Home based virtual rehabilitation for upper extremity functional recovery post-stroke

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ABSTRACT

After stroke, sustained hand rehabilitation training is required for continuous improvement and maintenance of distal function. An ideal home-based telerehabilitation system has to be low cost, easy to set up, effective in motivating the user to use it every day, generate progress reports to the user for self-tracking, and provide daily monitoring to remote clinicians. In this paper, we present a system designed and implemented in our lab: the NJIT Home-based Virtual Rehabilitation System (NJIT HoVRS). A single subject proof of concept study was conducted and demonstrated that this system is easy to access and effective in motivating subjects to train at home.

1. INTRODUCTION

Stroke remains the leading cause of serious, long-term disability in the United States, with over 6.8 million stroke survivors (Go et. al., 2014). Although the incidence of death from stroke has been decreasing due to new medical treatments during the acute episode, this still leaves a significant number of individuals permanently disabled. Only 10% of survivors recover completely, the majority have a long-term or lifelong need for help to perform activities of daily living and require further rehabilitation (CDC, 2007) as a result of a significant brain injury. Deficits in motor control affect the stroke survivors' capacity for independent living and economic self-sufficiency. The impact of even mild to moderate deficits in hand control in particular, affect many activities of daily living.

Intensity and progression have been proposed as key factors in successful stroke rehabilitation. A very recent article, offering a theoretical framework with which to develop future post-stroke clinical trials, proposed that intensity and progression are the active ingredients of a rehabilitation program that drive neural plasticity and lead to positive functional outcomes (Bowden, Woodbury, & Duncan, 2013). Studies have shown that sustained hand rehabilitation training is important for continuous improvement and maintenance of function (Hodics et al., 2006 , Page et al., 2004). If the amount of therapy is critical to rehabilitation, our current institutional limitations undermine the probabilities for successful outcomes. Time constraints and expensive personnel as well as the restricted length of stay in both acute care hospitals and rehabilitation restrain the provision of an adequate dose of training for persons with stroke. After discharge from the inpatient stay, access to rehabilitation therapy can be difficult for some patients. This is due in part to inadequate insurance, lack of transportation, and the patient's dependence on their caregiver. Having access to long-term rehabilitation training anywhere and at any time is necessary for sub-acute and chronic patients to continuously improve their functional abilities. There is a momentum building for increased attention to the development of technological interventions intended to support repetitive on-going home-based practice for better recovery of upper extremity motor function.

Innovative telerehabilitation systems have been developed using information and communication technologies to provide rehabilitation services at a distance. Many studies have developed video-game driven systems from commercially available gaming consoles such as Wii and Microsoft Kinect (Metcalf et al., 2013). Other groups have examined the use of custom-made tele-rehabilitation systems (Adamovich et al., 2005; Turolla et al., 2013). Most of these systems target arm or postural control, and require more space than may be available in the patient's home. These systems do not address hand rehabilitation. There is a vital need to explore intensive home-based upper extremity interventions that focus on the hand. An ideal home-based telerehabilitation system has to be low cost, easy to setup, able to motivate the user to use it every day, generate progress reports to the user for self-tracking, and provide daily monitoring to remote clinicians. Exciting new technologies have now made this approach possible and hold promise for long-term benefit. These technological advances - for the first time - allow for virtual reality simulations interfaced with discrete finger and hand tracking that is affordable and easy to use.

The NJIT Home-based Virtual Rehabilitation System (NJIT HoVRS) integrates the Leap Motion Controller and virtual reality technology to provide focused rehabilitation of wrist, hand, and finger movement. This paper presents the design concepts behind the NJIT HoVRS and the results of a proof of concept test. We believe that the NJIT HoVRS is a powerful tool that will give patients access to affordable, effective, and long-term rehabilitation in their home, allowing them to maximize and sustain stroke recovery, while increasing their overall quality of life.

2. SYSTEM DESIGN

NJIT HoVRS has two sub-systems to deliver home-based training: 1) a patient based platform to provide the training and 2) a server based online data logging and reporting system. In the patient's home, a cross platform virtual reality training application runs video games (developed in the Unity 3D game engine using the language C#) on their home computer. The Leap Motion Controller (LMC) infrared tracking device is used to capture motion of the hand and arm movement without requiring wearable sensors that may be difficult to put on independently or could potentially restrain movement.

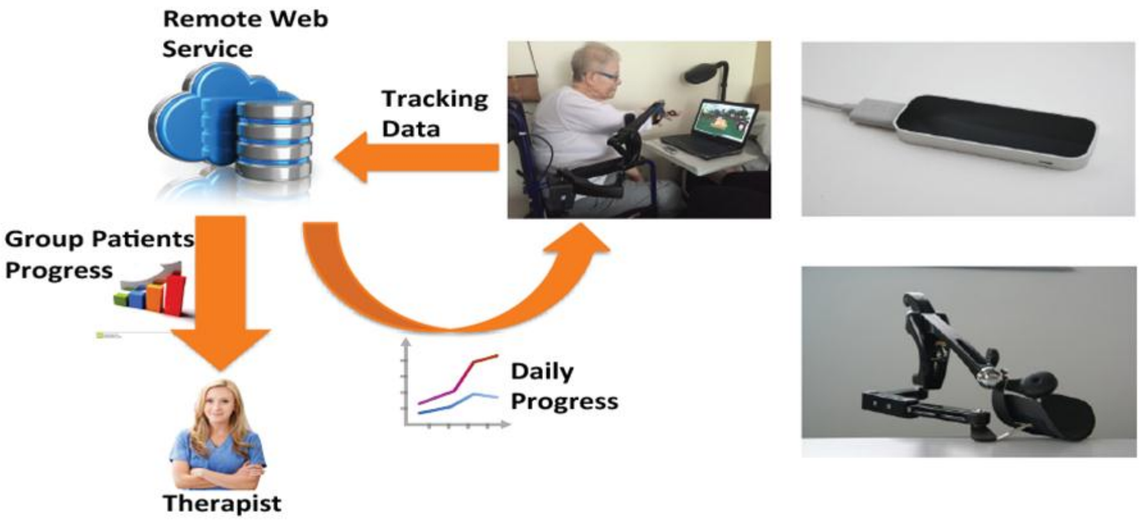

Figure 1. *Left: RAVR-Home architecture design. Upper right: Leap Motion Controller. Lower Right: Armon Edero™ arm support.*

2.1 Hardware

The Leap Motion Controller (LMC) (Figure 1) is a $50 computer hardware sensor that captures detailed hand movement as well as hand gestures. The heart of the device consists of two cameras and three infrared LEDs. A data validation study showed the LMC to be accurate and reliable as long as the target is within its visual area (±250 mm of the LCM center) (J Guna et. al., 2014). The device's USB controller reads the sensor data into its own local memory and performs any necessary resolution adjustments. This data is then streamed via USB to the Leap Motion image API. From there, we programmed the system to feed tracking data into virtual reality activities by calling the Leap Motion API.

If the patient's arm is severely impaired and he/she cannot support the hand against gravity above the Leap Motion Controller, the Armon™ Edero, a spring compensation system, can be provided to the subject (Figure 1**).** The Edero provides 12 different levels of passive support allowing it to accommodate a wide range of patient sizes and strength levels. It requires a single, setting that can be provided during the patient's initial evaluation. Minimal instruction is required to teach patients to readjust support levels on their own

2.2 Software

A user-friendly GUI interface lists all of the training activities allowing patients to choose which activity they want to begin with using just one mouse click.

Currently twelve games have been developed, each one designed to focus on training a specific hand or arm movement such as wrist rotation or finger individuation. (Figure 2). An avatar is at the corner of all game environments to provide verbal praise and encouragement as therapists usually do in real world. Therapists configuration page can be enabled by pressing “T” for game condition pre-setup, such as work space size, game challenge level, etc. (Figure 3a). All games are downloadable via HoVRS website.

- **Maze**: Player controls the movement of the virtual character through their hand location. The score is defined by the number of spheres the character intercepts along the maze path. The character falls if he deviates from the defined path. As the game level increases in difficulty; the platforms and bridges that the character is guided over become narrower and sharp turns become more frequent.
- **Whack-A-Mole**: The player controls the position of the hammer through arm movement in the horizontal plane. Rotation of the hammer is controlled by pronation/supination. Success score is defined by the amount of moles hit.
- **Soccer Goalie**: The player controls the position of the virtual hand to block the approaching soccer balls from hitting the goal.
- **Bowling**: The player reaches forward and extends their fingers to apply force to the ball to knock over the pins.
- **Fruit Picking**: The player must reach and use a pinch movement with their thumb and forefinger to pick apples and oranges from trees and sort them into the correct basket to increase the score.
- **Fruit Catching:** To catch the fruit, the player controls location of a collection basket through horizontal arm movement. To increase the score, the player uses forearm pronation/supination to drop the collected fruit into a second basket. The frequency of falling fruit decreases when the player misses 25% of the falling fruit
- **Car Game:** The player practices opening and closing their hand to control the car speed. Closing the hand slows the car down allowing it to maneuver over speed bumps.
- **Hand Flying:** The plane speed is constant. The player controls vertical position of the plane by opening and closing their hand. Success score is defined by the number of floating spheres intercepted.
- **Wrist Flying:** The plane speed is constant. The player controls vertical position of the plane by changing the pitch of their hand at the wrist. Success score is defined by the number of floating spheres intercepted.

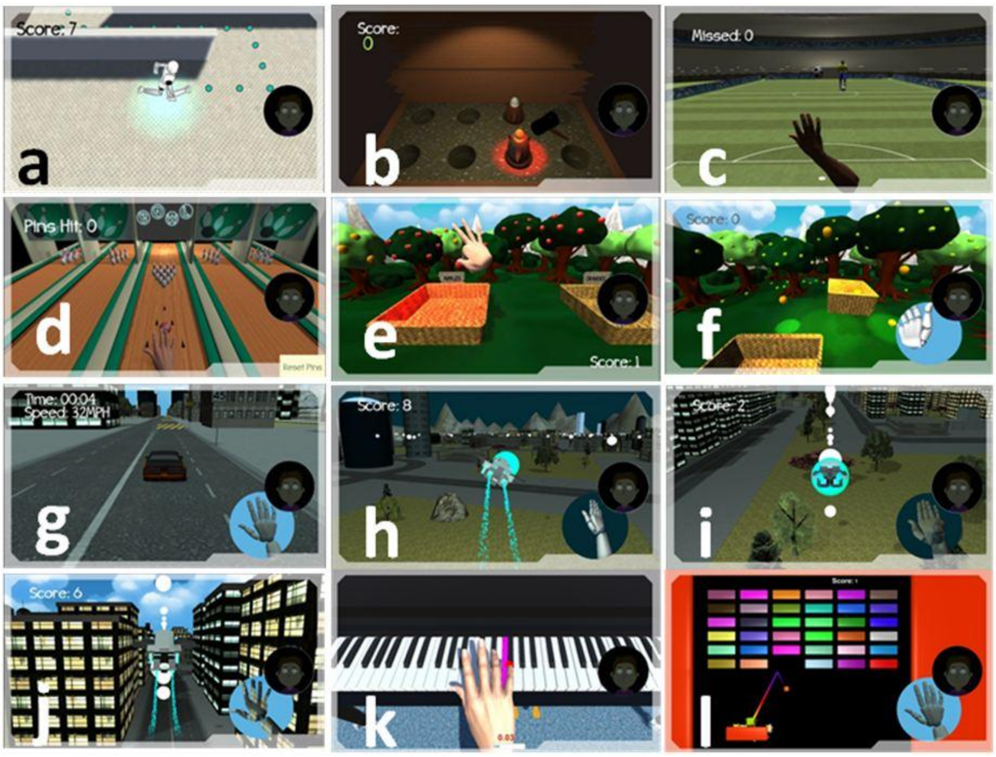

Figure 1. *Left: RAVR-Home architecture design. Upper right: Leap Motion Controller. Lower Right: Armon Edero™ arm support. Figure2. a: Maze, b. Whack-A-Mole, c. Soccer Goalie, d. Bowling, e. Fruit Picking, f. Fruit Catching, g. Car game, h. Hand Fly, i. Wrist Fly, j. Arm Fly, k. Piano, l. Breakout.*

- **Arm Flying:** The plane speed is constant. The player controls the horizontal position and roll of the plane by moving their arm left and right and pronating/supinating their forearm. Success score is defined by the number of floating spheres intercepted.
- **Piano:** The player plays a song by pressing the highlighted key with the indicated virtual finger. The amount of finger individuation required to successfully press any keys increases as the player progresses. However, it scales back down when they are unable to hit the key for 6 seconds.
- **Breakout:** The paddle used to direct the ball follows the palm position of the player. The ball is directed by bouncing off the paddle and hitting the bricks above to clear the screen.

2.3 System Calibration and Hand Position correction

A comprehensive calibration procedure (Figure 3b) is used to measure each subject's active range of motion within the LMC visual area and this range is scaled to fit into the video game virtual environment. To create greater ease of use, games have been designed to display a red frame (Figure 3c) to guide the subject back to the LMC visual area whenever his/her hand deviates from the calibrated range.

Figure 3. *a. Therapist setup interface; b. Calibration interface; c. Hand not visible warning.*

2.4 Data Collection

Performance and kinematic data collected during rehabilitation training using the NJIT HoVRS is securely transferred to Amazon Simple Storage Service (S3) at the end of the each training session for offline analysis. Patient data is automatically processed to produce daily progress reports. Therapists can securely access the reports through a password protected website, which will also host system updates.

3. SYSTEM VALIDATION

In order to evaluate NJIT HoVRS' ease of use and reliability, a 45 year old female patient with moderate hemiparesis of the upper extremity (UEFMA = 45) due to a cortical stroke was recruited. She was a police detective prior to the stroke and was able to return to full time deskwork 6 months after the event. She lives alone but her family lives nearby and gave her a lot of support during her rehabilitation. She had little to no video game experience prior to this training. The system was placed in her home. Without help from the therapist or engineer, she successfully finished 7 thirty minutes training sessions utilizing all twelve of the games at least twice (Figure 4).

3.1 Car Simulation

As shown in Figure 5 (left panel), the subject was able to maintain her hand above the Leap Motion and control virtual car speed by opening and closing her hand. As the simulation went on, she gradually opened her hand more than she was capable of during the initial calibration.

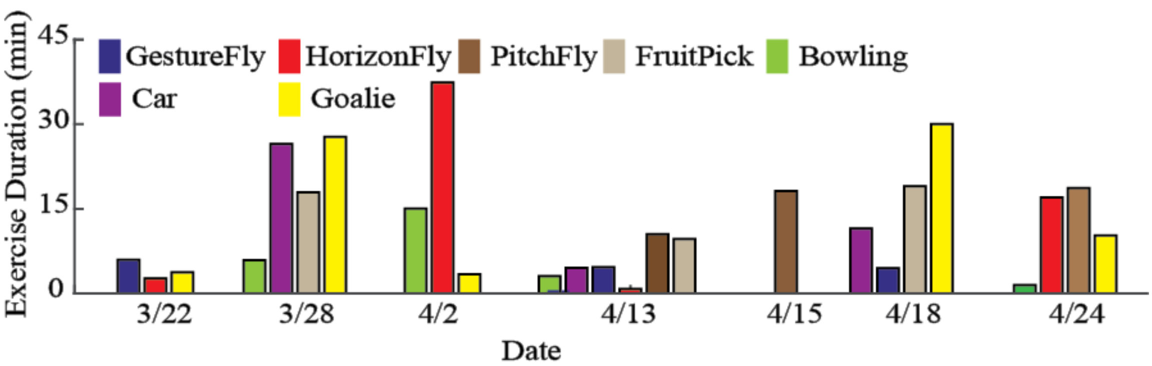

Figure 4. *Exercise duration for each gaming activity over one month of therapy, as reported by the HoVRS website.*

3.2 Maze Simulation

In the Maze simulation (Figure 5, right panel), after successfully reaching the target, the subject will advance to a higher level that requires more hand stability. If the subject fails to reach the target, the score collected from the current level will be deducted and the subject starts again from the beginning of the current level. As shown in Figure 5 right, our subject was able to successfully pass the first four easy levels. However, as difficulty level increased, the subject started to slow down and make multiple attempts to complete fifth level.

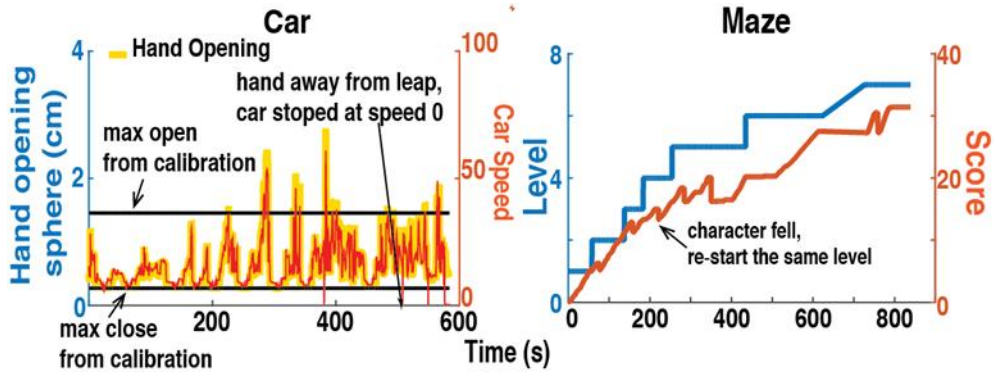

Figure 5. *Performance during a single session of Car (Left) and Maze (Right) simulations. Left panel: Two horizontal lines indicate maximum hand closing and opening during initial calibration. Arrow indicates moment when hand tracking was lost and the car speed dropped to zero. Right panel: Arrow indicates moment when the avatar fell off the maze plane and the game restarted at the beginning of the level.*

3.3 Questionnaire

In a post-training questionnaire, the subject noted the system's ease of use and a desire to incorporate the system as part of her on-going therapy. Subject felt that this therapy system was engaging. In her comments, she said that the system is easy to use, and she almost forgot that she was participating in rehabilitation training while she was focusing on trying to complete the computer tasks. Her arm was tired after doing the training, but not her hand. She felt this system would improve her hand motion. She wished it could have been part of her original therapy and wanted it to be part of her on-going therapy. Subject said most of the games were engaging. She was able to understand the requirements and learn how to play them quickly. The easiest game for her was the Car simulation because it had a one-dimensional control requiring only hand opening and closing to manipulate the car's speed. Her favorite game was the Arm Flying simulation because its soothing music made her relax and enjoy the training. The most difficult game for her was the piano because it required both arm stability and finger individuation. The most confusing game was Whack-A-Mole because different lighting and random appearance of the moles provided too much information and caused confusion about how to proceed. The most non-intuitive game was Soccer Goalie because the orientation of the virtual hand and the real hand did not match. The virtual hand displayed in the virtual environment was vertical with the palm facing forward, while the real hand was horizontal with the palm facing down.

3.4 System Server for Data Monitoring and Visualization

All training data could be accessed remotely from the data server via HoVRS website. The therapist can access daily training data of a specific subject for a specific game activity via website. As shown in Figure 6, therapist chose to display daily maximum hand opening value from game GestureFly on website. The therapist sent a short text messages to the patient whenever there was new training data shown on the server side as a way to praise her effort and encourage continued participation. The data showed that repeated performance of several simulations resulted in increased finger opening as measured by the system.

4. DISCUSSION

We intend to bring a "wellness" approach to the achievement of independent upper extremity manipulation and function for people post-stroke. The National Wellness Institute (mailto:http://www.nationalwellness.org) encourages "a conscious, self-directed and evolving process of achieving full potential." Through the development of an easy to use and engaging home-based virtual reality exercise program we modeled the wellness concept of continual self-directed exercise to allow people with hand and upper extremity motor deficits to achieve their full potential. NJIT HoVRS is a low cost, easy to setup, reliable and engaging home-based hand rehabilitation system. Virtual reality simulations are engaging and the subject was motivated to play them for a long period of time. Currently, there is little available for home-based hand therapy (Hayward, Neibling, & Barker, 2015). The advantage of this home-based system is its focus on hand-based simulations. Our objective was to provide markerless hand tracking (LEAP) and simple support of arm motion in 3-dimensional space to allow the patient to move freely, while it helps them keep their hands over the LEAP's effective range. Clear online directions, delivered visually and aurally through imaginative avatars allow the individuals to practice independently. Novel algorithms provide safe and effective interactions with the serious games. Despite this complexity, the use of novel technologies makes this affordable system easy to use. Compliance with home-based exercise programs is low. We believe strongly that the NJIT-HoVRS home-based system will effectively deal with compliance issues through the engaging games, the easy to use system (no donning and doffing difficulties), the enticing encouraging avatars, the success algorithms and the instant availability of daily achievement graphs. This self-paced, independent home practice is consistent with a "wellness" approach that should empower stroke survivors to take an active self-directed approach to their rehabilitation.

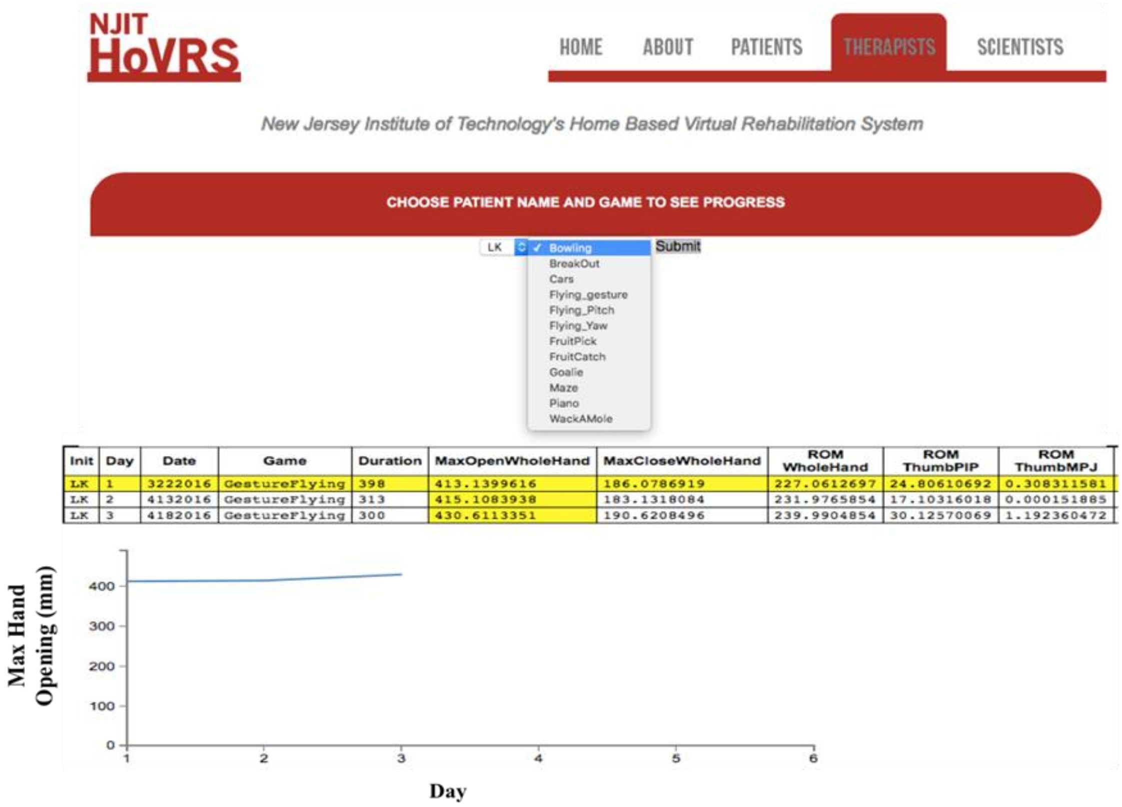

Figure 6. *Therapist can monitor subject's daily progress via HoVRS website. Plot shows the sum of distances between the palm and five fingertips.*

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