Chapter 7
Rehabilitation Applications Using Virtual Reality for Persons with Residual Impairments Following Stroke

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Objective To describe current clinical evidence for the effectiveness of VR applications on upper limb recovery in individuals who have had a stroke.

7.1 Introduction

According to the World Health Organization, 15 million people worldwide suffer a stroke each year, leaving 5 million survivors permanently disabled. In most developed countries, the incidence of stroke is declining due to control of hypertension and cardiovascular disease. However, the overall rate of stroke remains high due to the aging of the population http://www.strokecenter.org/patients/about-stroke/stroke-statistics/. People post-stroke exhibit paresis of the upper and lower extremities. This consists of a group of coexisting sensorimotor impairments such as weakness, spasticity, decreased ability to isolate movements, diminished range of motion, as well as higher order cognitive and motor planning functions. When a person with paresis uses their upper extremity (UE) for purposeful movement, the paretic movements differ from normal movements in that they are slower, less accurate, have delayed or reduced force, and are uncoordinated in terms of magnitude and timing of the movement (Sathian et al., 2011). People post-stroke are often unable to perform actions, tasks, and activities needed for self-care, home management, employment, and social activities. Therefore, rehabilitation of movement dysfunction is confronted with multiple and complex challenges.

This chapter focuses on VR interventions for the UE of people post-stroke. Existing physical and occupational therapy interventions are the foundation for

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treatment of the residual movement dysfunction exhibited by people after a stroke. Currently, the management of these interventions within the patient/client relationship usually follows the framework developed by the World Health Organization ICF model, a disability classification for use in health and health-related sectors. In general, the classification describes three levels of human function, at (1) the body level, (2) the whole person level, and (3) the level of the whole person in a social context. More specifically, disability at the body level refers to impairments to body function and structure (physiological functions and anatomical parts), at the whole person level to limitations in activity (execution of a task or action by an individual) and at the social context level to participation in a life situation (Jette, 2006; World Health Organization, 2002). (http://www.who.int/classifications/icf/training/icfbeginnersguide.pdf.)

In the clinical environment, therapeutic interventions are designed to address problems in each of these three areas of function. The construction of virtual environments used to rehabilitate motor deficits has progressed from simple two-dimensional visual experiences to more complex three-dimensional gaming and functional environments that are integrated with haptics, electromyography, and fMRI. These complex environments are being designed to address the multiple sensorimotor impairments that remain a pervasive problem for patients with motor dysfunction post-stroke with recent studies demonstrating evidence of the potential for these VR-based interventions to benefit patients with disordered movement due to neurological dysfunction. Known neurophysiological and behavioral benefits of movement observation (Buccino, Solodkin, & Small, 2006; Celnik et al., 2006), imagery (Butler, Blanton, Rowe, & Wolf, 2006), repetitive massed practice and imitation therapies (Gaggioli, Meneghini, Morganti, Alcaniz, & Riva, 2006) used to facilitate voluntary production of movement can be easily incorporated into a virtual environment (see Chap. 3). This allows the clinician to use sensory stimulation through VR as a tool to facilitate targeted brain networks, such as the motor areas, critical for neural and functional recovery. The potential for functional recovery can be optimized by tapping into a number of neurophysiological processes that occur after a brain lesion, such as enhanced potential for neuroplastic changes early in the recovery phase and stimulation of sensorimotor areas that may otherwise undergo deterioration due to disuse (see Chap. 2).

If repetition and skill learning are important for motor learning and recovery of function after stroke what does VR technology add over and above real-world task practice? What can training within an interactive virtual environment contribute to skill learning and improved motor control in people who have had a stroke? Are these technological interventions able to model and incorporate accepted rehabilitation practices? Is there a relationship between the elements of practice and sensory input available through interventions delivered within virtual environments and the clinical therapeutic interventions designed to address the areas of dysfunction described by the ICF model (body function/structure, activity, or participation)? These are important and timely concerns. In this chapter we summarize the published outcomes of UE rehabilitation studies utilizing the ICF model as a framework and then explore the motor learning principles used in physical and occupational therapy interventions such as (1) intensity and dosing of interventions, (2) knowledge of results and knowledge of performance, (3) adaptive scaling of task difficulty, (4) visual and auditory feedback, and (5) attentional focus, describing how each of these approaches have been utilized in VR simulations and interventions, specifically with respect to recovery from stroke. The chapter concludes with a case study that explores how to effectively use VR/robotic technology for an individualized treatment intervention. The intervention follows a patient/client management model that reflects the clinical decision making process and demonstrates the implementation and manipulation of several of the principles discussed in this chapter.

7.2 VR Interventions Within the ICF Framework

The ICF model describes three levels of function, all of which can be negatively impacted by a cerebrovascular accident. Body level impairments result in activity limitations and subsequent participation restrictions. Virtual environments can be used to intervene at all three of these levels of function. For more than a decade, simple environments used to provide feedback and expand the motivation of persons performing exercises designed to correct intrinsic aspects of active movement such as range of motion and strength have been used in the rehabilitation of people who have had a stroke (Holden, 2005; Sveistrup, 2004). Controlled trials of systems described in these reviews have demonstrated comparable (Piron, Turolla, Agostini, Zucconi, Cortese, et al., 2009) or larger (Piron, Turolla, Agostini, Zucconi, Ventura, et al., 2009; Yavuzer, Senel, Atay, & Stam, 2008) improvements in active range of motion strength than traditional therapy. A systematic review of these studies described a significantly larger effect on measurements of UE impairment when comparing virtually simulated repetitive task practice (RTP) to dose-matched programs of traditional therapy (Laver, George, Thomas, Deutsch, & Crotty, 2011). Other impairment-level interventions have combined simple, non- or semi-immersive virtual environments with robots to add interaction forces allowing participants to train grip strength (Merians, Poizner, Boian, Burdea, & Adamovich, 2006), shoulder strength (Adamovich, Fluet, Merians, Mathai, & Qiu, 2009), shoulder–elbow disassociation (Acosta, Dewald, & Dewald, 2011; Volpe et al., 2008), and finger disassociation (Stein, Bishop, Gillen, & Helbok, 2011). These studies were all uncontrolled pilot studies with the exception of Volpe et al., who compared their intervention to a time-matched dose of occupational therapy, finding no difference in adaptation to these two regimens. Because body function level impairments often contribute to activity limitations and participation restrictions, several uncontrolled pilot studies have used activity level simulations and have demonstrated improvements at the activity level (Boian et al., 2002; Piron et al., 2003, 2005). One study comparing a program of virtual reality based RTP and a time-matched program of traditional occupational therapy demonstrated no significant difference between activity level outcomes for the two interventions (Yavuzer et al., 2008). Saposnik et al. (2010) compared a program of game-based UE rehabilitation activities presented in VR with a program of game based Recreational Therapy. The rehabilitation activity subjects demonstrated larger improvement measured at the participation level than the Recreation Therapy group.

Some more recent interventions performed at the body function level are investigating how VR affects recovery at the neural level and have used specific feedback manipulations to upregulate hypoactive areas of the brain caused by damage due to stroke (Adamovich, Fluet, Mathai, et al., 2009; Adamovich, Fluet, Merians, et al., 2009; Adamovich, Fluet, Tunik, & Merians, 2009; Merians, Tunik, & Adamovich, 2009). The study of rehabilitation activities incorporating these manipulations and their ability to make longer term modifications in properties of brain networks are being initiated. The negative impact of a stroke on UE function seems to extend beyond the sum of individual impairments. A particularly discouraging study describes a lack of improvements in activity limitations related to hemiparetic upper extremities despite amelioration of impairments including strength and range of motion (Dromerick et al., 2006). This lack of improvement may be secondary to the complex, varied, and interdependent nature of normal UE function and may require interventions and practice at the activity level. Simulations in virtual environments have now progressed from simple target reaching activities to more complex activity level interventions. Examples of simulations that have been developed at the activity level include, cleaning a stove top, grocery shopping, playing basketball (Housman, Scott, & Reinkensmeyer, 2009) placing cups on a haptically rendered shelf, or hammering a haptically rendered nail (Merians et al., 2011). These systems expand the ability of therapists to provide repetitive task practice interventions that are more time, resource and manpower efficient than traditionally presented programs of rehabilitation (Adamovich, Fluet, Tunik, et al., 2009), allowing for the performance of large volumes of practice using complex movement activities required to elicit neuroplastic adaptations (Birkenmeier, Prager, & Lang, 2010). Multiple studies of virtually simulated repetitive task practice (RTP) demonstrate activity-level improvements using standardized measurements of UE function (Saposnik & Levin, 2011). It is interesting to note that two studies of virtually simulated RTP demonstrated large treatment effects compared to controls in untrained ADL ability (Piron et al., 2007; Piron, Turolla, Agostini, Zucconi, Ventura, et al., 2009). Another study comparing the effects of virtually simulated RTP on grip strength demonstrated comparable effects with those of a program of traditionally presented rehabilitation activities that included strength training (Housman et al., 2009). In addition, two other uncontrolled studies of virtually facilitated RTP, which did not directly train strength also describe improvements in grip strength (Broeren, Rydmark, Bjorkdahl, & Sunnerhagen, 2007; Connelly et al., 2010).

A smaller group of studies has examined interventions designed to limit the impact of participation restrictions. To date these interventions have consisted of training activities related to the use of power wheelchairs, the use of simulations to train persons with stroke to use hand controls to drive automobiles (Archambault, Chong, Sorrento, Routhier, & Boissy, 2011; Erren-Wolters, van Dijk, de Kort, Izerman, & Jannink, 2007) and navigating through a series of activities required to use the public train system (Lam, Man, Tam, & Weiss, 2006). Allowing subjects to trial these activities and or train during the earlier stages of recovery is significantly expanded because of the safety of practicing these activities in virtual environments. Another group of virtual rehabilitation activities have been designed to address the sensory processing and cognitive demands of participation in activities such as shopping (Rand, Katz, & Weiss, 2009). Virtual environments offer multiple advantages for rehabilitation at the participation level by allowing subjects to practice these functions safely and repeatedly, including elimination of the time demands associated with transportation to and from shopping centers, decreasing the burden of supervision of these activities and the ability to grade the complexity of the sensory presentations that participants are required to manage with great precision.

7.3 VR as a Tool to Provide Intensive Intervention Dosing

One of the difficulties in designing rehabilitation programs congruent with the literature supporting repetitive task practice is the labor-intensive nature of these interventions. Difficulties in the provision of adequate training volumes for persons with stroke are well documented (Lang, Macdonald, & Gnip, 2007). Typical rehabilitation programs do not provide enough repetitions to elicit neuroplasticity. In a study of 36 outpatient therapy sessions for persons with strokes, Lang, Macdonald, et al. (2007) observed that subjects performed an average of 27 repetitions of functional activities during these sessions. This volume of intervention stands in stark contrast to training volumes of 500–600 repetitions of tasks performed by animal subjects in stroke rehabilitation studies (Lang, Macdonald, et al., 2007) and the 600–800 repetitions of activity per hour (Housman et al., 2009; Krebs et al., 2008; Lum, Burgar, & Shor, 2004) reported in virtual rehabilitation and robotic studies. Dose of treatment can be described in terms of number of repetitions per session or total hours of intervention. A 2011 review by Saposnik and Levin indicated that the duration of VR sessions in most of the 12 studies included in their review was 1 h with a range of 30 min to 2.5 h, with total number of sessions ranging between 6 and 30. However, they did not indicate the average number of repetitions performed. The impact of the total volume of activity performed during UE rehabilitation interventions and its impact on outcomes is not completely clear. One meta-analysis has identified a minimum of 16 h of non-automated training as being necessary to improve ADL function in persons with stroke (Kwakkel et al., 2004). A Cochrane Report (Laver et al., 2011), based on 19 studies found that interventions providing less than 15 h of practice had a non-significant effect but interventions providing more than 15 h of practice showed a moderate effect on ADL outcomes. There seems to be a rate of diminishing returns subsequent to training after approximately 20 h of UE training have been performed (Fig. 7.1). Studies by Saposnik & Levin (2011), Fischer et al. (2007) and Merians et al. (2010) demonstrate a correlation between intervention time and outcome. This effect does not seem to continue when training times increase beyond 23 h. Studies by Wolf et al. (2006) and Lo et al. (2009) that use considerably longer periods of training do not demonstrate

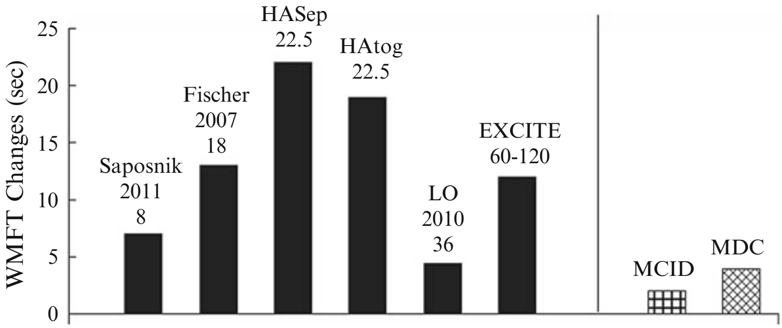


Fig. 7.1 *Left panel* indicates Wolf Motor Function Test (WMFT) outcomes based upon number of hours of repetitive task practice in both virtual and real-world environments. *Right panel* indicates published Minimal Clinical Important Difference (MCID) and Minimal Detectable Change (MCD) for the WMFT

substantially better outcomes. While the studies presented in Fig. 7.1 did not consider a perfectly homogenous group of subjects—subjects in the Saposnik study were in the acute phase of recovery and also received concurrent inpatient rehabilitation, and the subjects in Lo et al. (2009) had a greater level of upper extremity impairment—the argument that more training time will always produce better outcomes is clearly not supported and that the consideration of other factors to explain differences in outcome must continue to be entertained.

7.4 Manipulation of Elements in VR to Facilitate Motor Skill Development

7.4.1 Activity Scaling

A skilled movement is characterized by consistency, stability, flexibility, and adaptability. These features are achieved through practice-dependent changes in kinematic and force errors (Krakauer, 2006). With practice, one progresses through the stages of skill acquisition, eventually achieving a movement that is autonomous with fewer errors. Evidence suggests that repetitive practice resulting in "actual motor skill acquisition, or motor learning" may be a more potent stimulus for "driving representational plasticity in the primary motor cortex," than the simple repetition of activities that are well within the movement capabilities of a subject (Plautz, Milliken, & Nudo, 2000; Remple, Bruneau, VandenBerg, Goertzen, & Kleim, 2001). Thus activity scaling is a critical issue related to neuroplasticity when considering the need for continuous skill development. In some virtual environments, movement characteristics may be similar to those for movements made in the physical environment (see Chap. 5). Such virtual environments may be particularly well-suited to the systematic scaling of movements and activities. The intensity of practice (time and/or number of repetitions), the visual,

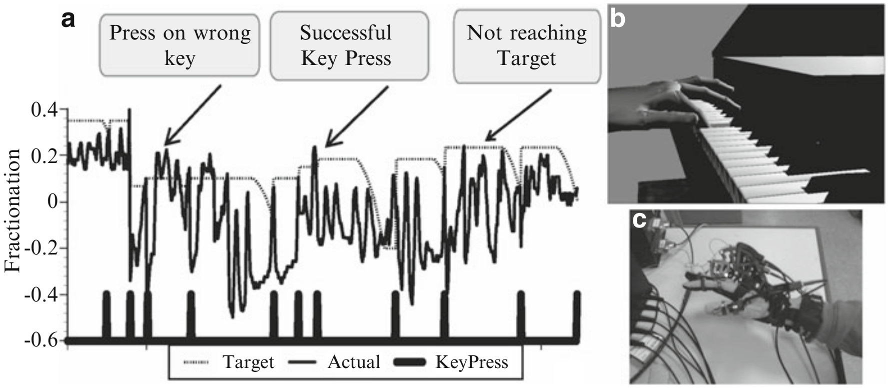
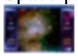
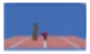
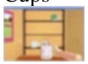


Fig. 7.2 (**a**) Representative example of the adaptive algorithm used in the Virtual Piano simulation showing the adjustable fractionation target based on an individual subject's actual ability to isolate their finger movements at each attempted key press. The *dotted line* indicates the target fractionation, the *thin line* is the actual fractionation and the *thick line* indicates when the key is successfully pressed. The *left section* shows the scenario when the subject reaches the target fractionation but the finger is not aligned with the correct key. The *center section* indicates a successful key press. The *right section* shows the scenario when the subject fails to reach the target fractionation and the target is lowered. (**b**) Screenshot of the Virtual Piano simulation. (**c**) The Cybergrasp used with patient MP

auditory, and haptic feedback presented, the speed and range and force of the movement required to interact with task-related objects can all be manipulated to drive movement reeducation and skill development. In addition, kinematic and kinetic data on subjects' performance and learning history are available to provide definitive measurable data regarding the changes in motor behavior. Virtual workspaces, target sizes, and activity speeds and forces can be increased in minute gradients allowing for an infinite range of difficulty for any task. This provides an opportunity for persons with stroke to develop and refine skills steadily throughout a rehabilitation session. Physical fatigue during large volume training sessions also presents challenges to persons with strokes. Motor fatigue can be easily addressed in VR training through VE modifications (Fluet et al., 2012).

It has been proposed that a favorable learning experience occurs when the task in neither too difficult nor too easy (Cameirao, Badia, Oller, & Verschure, 2010; Jack et al., 2001). In the Cameirao study, a reaching task in which moving spheres moved toward the participant who had to intercept them, the speed of the moving spheres, the interval between the appearance of the spheres and the horizontal spread of the spheres could all be manipulated based upon patient success rate. In this study the difficulty was increased by 10 % when the participant intercepted more than 70 % of the spheres and was decreased when less than 50 % of the spheres were intercepted (Cameirao et al., 2010). In a study of robotically facilitated UE training in virtual environments, task difficulty was manipulated over the 2-week training period through the use of online algorithms and changes in the dimensions of the workspace (Merians et al., 2011). A Virtual Piano simulation (Fig. 7.2b and Table 7.1) consisting of a complete virtual piano that played the appropriate notes as they were pressed by

Table 7.1 Describes each simulation, the performance measure used to track progress, and the approach to increasing the intensity of the activity

Virtual reality simulation	Impairment	Game	Strategies	Metric
Space pong 	Decreased finger extension modulation	Subject 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.	Decrease proportion of subject movement (finger extension) to paddle movement if accuracy does not improve with practice. Increase proportion when accuracy increases.	Accuracy
Hammer 	Decreased shoulder stabilization	Subject 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.	Decrease the size of the target as time to hammer pegs decreases.	End point deviation Time to hammer pegs
Hammer 	Decreased shoulder–elbow isolation	Subject hammers peg into the floor by pronating his forearm. Robot holds hammer stable over the target peg.	Decrease proportion of subject movement (pronation) to hammer movement as time to hammer pegs decreases.	Peak pronation range of motion Time to hammer pegs
Piano 	Decreased finger individuation	Subject plays scales and simple songs. Each key is cued and the finger to press it designated.	Algorithm sets fractionation target based on performance. Utilize CyberGrasp™ to teach movement pattern if subject does not respond to algorithm.	Fractionation Time to press keys
Cups 	Decreased shoulder–trunk isolation	Subject attaches virtual hand to virtual mugs and places them on virtual shelves in a 3D workspace.	Increase volume of workspace as time to place cups on shelf decreases. Recalibrate workspace weekly.	Time to place nine cups on shelf Reaching trajectory length
Reach-touch 	Decreased shoulder AROM	Subject moves cursor to touch ten targets in a 3D workspace.	Increase size of workspace as duration decreases. Recalibrate workspace weekly.	Time to touch ten targets Trajectory length

the virtual fingers while the subject was wearing a CyberGlove, was designed to help improve the ability of subjects post-stroke to move each finger in isolation (fractionation). Fractionation was calculated as the difference in the amount of flexion in the metacarpophalangeal (MCP) joint between the cued finger and the most flexed non-cued finger. An adaptive algorithm used to shape fractionation required more isolated finger flexion to elicit a key press as participants succeeded and less fractionation if their performance diminished. Initial target fractionation was calculated based on each subject's actual fractionation. If the actual fractionation reached 90 % of target fractionation, the next initial target fractionation was increased by 8 % of the previous target fractionation If not, the next initial target fractionation was decreased by 10 % of the previous target fractionation. Figure 7.2a shows an example of the variation in the adjustable fractionation target based on an individual subject's actual ability to isolate their finger movements at each attempted key press. The dotted line indicates the target fractionation, the thin line is the actual fractionation and the thick line indicates when the key is successfully pressed. The left section of Fig. 7.2a shows the scenario when the subject reaches the target fractionation but the finger is not aligned with the correct key, the middle section shows a successful key press and the right section shows the scenario when the subject fails to reach the target fractionation and the target is lowered. In an uncontrolled pilot study, that trained ten subjects who had a stroke, the subjects performed the piano simulation described above for 30 min/day for 8 days in a 2-week period. At posttest the subjects significantly improved in fractionation showing on average a 39 % change pre-post training. There was also a significant improvement in the time to complete the task after training, showing a 19 % change without a subsequent change in accuracy, indicating that the subjects were able to do the task faster while maintaining their accuracy. This is thought to be consistent with motor learning (Krakauer, 2006). Further, it is interesting to note that in this study, the largest improvements demonstrated with the Virtual Piano were for finger fractionation. Subjects made larger improvements in fractionation than speed or accuracy that were not shaped with an algorithm or reinforced with feedback (Merians et al., 2011).

In an arm transport simulation in which the goal of the activity was to improve forward, sideways and overhead reaching ability, subjects reached to touch a series of ten targets placed randomly throughout the workspace. To adapt to the range of arm motion of each subject, the Reach-Touch simulation workspace size was calibrated for each subject on the first day of each training week according to their available range of motion in a single reach. To prevent fatigue and keep the game at a reasonably challenging level, training began at 60 % of the calibrated workspace volume, and gradually increased to a consistent 100 % of the volume at the end of the week. Figure 7.3 shows a graphic representation the change in workspace volume for one subject. Workspace size of day 3 and day 4 were 60 % and 80 % of the calibration range of the first week. Workspace size of day 5, day 7, and day 8 were 60 %, 70 %, and 90 % of the increased calibration range of the second week. The workspace volume gradually and continuously expanded throughout the training period. Another example of workspace modification is the Cup Placing simulation (Table 7.1).

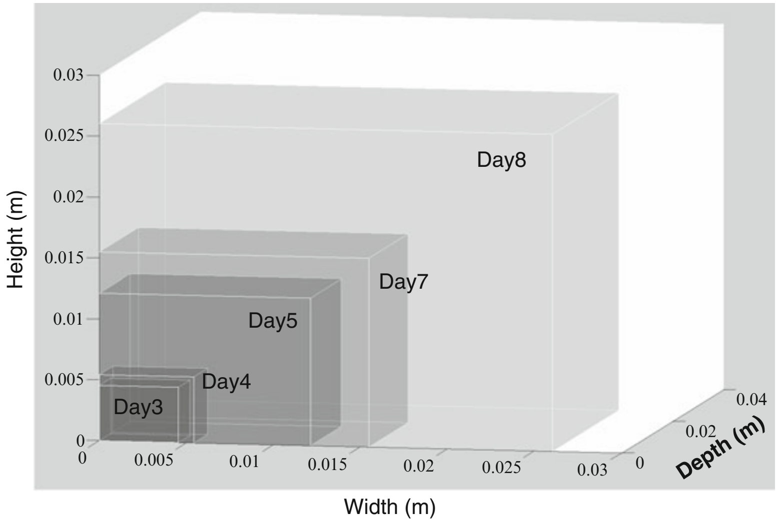


Fig. 7.3 Graphic representation of the changes in the three-dimensional workspace of a subject on training days 3, 4, 5, 7, and 8. The workspace gradually and continually expanded in height, width, and depth throughout the training

The shelf height on which the cups were placed was calibrated at the beginning of each week of the training, and the cups were placed further away and higher as the training proceeded (Merians et al., 2011).

7.4.2 Augmented Feedback

In addition to activity scaling, VR environments use both visual and auditory sensory input in the form of Knowledge of Results (KR) and Knowledge of Performance (KP) both for clarification of task parameters and for motivation. Simulations can provide immediate visual or faded KR in the form of scoring and timing incentives (e.g., number of successful repetitions, number of warriors eliminated, number of space ships destroyed in a set time limit) or when task performance scores exceed a predetermined limit (Piron, Turolla, Agostini, Zucconi, Cortese, et al., 2009; Weiss & Katz, 2004). Summary feedback is often given as a score after a group of trials. The IREX system is a video-capture system that captures the whole body movement of the user and immerses it into the virtual environment where they can interact with on-screen images and objects. This visual illusion is designed to enhance the sense of "presence" for the patient. In a study of ten patients using simulations in which reaching, lifting and grasping motions were performed, faded KR and KP feedback were provided that included error rate, speed, direction, joint position, and resistive force (Jang et al., 2005) Auditory feedback can be provided through music that impels continuous activity such as in Pong Games as well as through the inherent nature of the activity as found in the Virtual Piano Trainer that uses well known melodies (Adamovich, Fluet, Mathai, Qiu, Merians et al., 2009; Subramanian, Lourenco, Chilingaryan, Sveistrup, & Levin, 2013). KP has been used by both Holden (2005) and Piron, Turolla, Agostini, Zucconi, Cortese, et al. (2009). In an example of one type of KP used in a virtual reaching task, the patient moves a real object and sees a display of both their own trajectory and the trajectory of the "virtual teacher," thereby providing the subject with ongoing knowledge of their reaching hand path (Holden, Dyar & Dayan-Cimadoro, 2007).

7.4.3 Attentional Focus

Another factor to consider is that VR simulations structure the attentional focus of the subject. It has been shown in people with and without disabilities that the learning of a motor task is more effective when attention is focused on externally rather than on internally based instructions (Wulf, Landers, Lewthwaite, & Tollner, 2009; Wulf, McNevin, Fuchs, Ritter, & Toole, 2000). In many VR simulations, practice is directed to achieve action goals rather than performing specific movements. The instructions for the game, the feedback provided and the inherent structure of the simulations direct the attention of the player to the task to be achieved. In other words, the focus of attention is on the effect of one's movements rather than on the movement itself (Merians et al., 2011). VR can be a particularly effective tool for the rehabilitation of another type of attentional deficit, persons with unilateral spatial neglect secondary to stroke. The performance of large volumes of scanning or motor tasks directed into the impaired hemi-space is required to ameliorate the functional limitations and reduce subsequent activity limitations and participation restrictions. Virtually simulated activities are ideal for this type of training because the position and density of targets can be manipulated easily with precision (Tsirlin, Dupierrix, Chokron, Coquillart, & Ohlmann, 2009) and the activities can be presented in formats that are more engaging and entertaining, facilitating long periods of training (Smith, Hebert, & Reid, 2007). An example of this approach was implemented by Smith et al. (2007) who had subjects play computer games using a camera based VR system. Subjects played games requiring attention and movement of their upper extremities into their neglected hemi-space. Subjects improved in motor and sensory tasks subsequent to training and also reported improvements in their ability to perform activities of daily living. Another study examining the rehabilitation of persons with unilateral spatial neglect highlights one of the unique features of virtual environments that have also been used in other areas of rehabilitation—the ability to alter the visual feedback provided to participants. Glover and Castiello (2006) had subjects with stroke reach toward virtual targets located in their neglected space. The visual representation of the workspace was shrunk and translated into their intact visual hemispace. After practicing for several sessions with this translation, subjects were able to reach toward targets in their impaired space with decreased errors and were able to better attend to targets in their impaired hemispace during a non-motor transfer test, providing possible evidence of a “re-mapping” of the neglected hemi-space. The use of 3D VR has been suggested as a possible assessment tool to map out the full dimensions of the spatial deficit of a patient (Dvorkin, Bogey, Harvey, & Patton, 2006).

7.5 Commercially Available VR Exercise Systems

Many clinical settings have begun to use commercially available off-the-shelf, low-cost gaming systems that can be displayed on a standard TV monitor (e.g., the Wii (Nintendo; Redmond), EyeToy, PlayStation2, (Sony Computer Entertainment; Tokyo, Japan); and the Xbox Kinect, (Microsoft). These commercial applications include motivating environments, some of which are more functional (serving meals, cooking activities) but most use competitive gaming activities (tennis, boxing, soccer, baseball, bowling, golf). For a full review of the design, activity levels and energy expenditure associated with these systems see (Taylor, McCormick, Shawis, Impson, & Griffin, 2011). In a randomized controlled trial of 20 patients post stroke, all subjects received 1 h of conventional physical and occupational therapy but the 10 subjects in the EyeToy group received an additional 30 min of game playing. At posttest and at follow-up, the EyeToy group showed significantly more improvement in UE motor function as measured by the FIM (Functional Independence Measure) than the control group. No changes in the motor recovery of the paretic limb were found as measured by Brunnstrom arm and hand stages (Yavuzer, Senel, Atay, & Stam, 2008). Most research VR systems are extremely expensive and complex. This makes the commercial gaming systems attractive for rehabilitation. However, there are many unanswered questions related to their use. Are the changes reported by therapists and reported in the literature related to increased activity by the participants or importantly are there actual changes in motor recovery and in movement kinematics? Currently the commercial systems cannot provide kinematic data, nor can they be modified for individual patient impairment levels.

7.6 Integration of Vision and Haptics in VR

A newer generation of virtual environments incorporates tactile information and interaction forces into what had been an essentially visual experience. Traditional visual and auditory VE presentations are being interfaced with robots of varying complexity to provide haptic feedback that (1) adds physical task parameters, (2) enriches the sensory experience, and (3) provides global forces such as gravity that result in neuromuscular and biomechanical interactions with the VE that simulate real-world movement more accurately than visual only VEs. Haptic feedback gives cues on manipulated object weight, inertia, and solidity. Haptic interfaces allow users to touch, feel, and manipulate objects during VR simulations thus contributing to increased simulation realism. Haptic feedback can be used to add the perception of contact to skills like placing a cup on a shelf, hammering a peg (Merians, Tunik, Fluet, Qiu, & Adamovich, 2008), or kicking a soccer ball. Lam et al. (2008) describe a system that uses vibratory disks to simulate the feeling of impact between the foot and the object when kicking a soccer ball. The authors reported a greater degree of skill learning in a group of healthy subjects training with visual and haptic feedback than a group of subjects practicing with visual feedback alone (Lam et al., 2008). As previously described "virtual tutor trajectories" (Holden, Dyar, & Dayan-Cimadoro, 2007; Piron et al., 2005) have been used in subjects with hemiparesis due to stroke to model the appropriate movement path. Alternatively, collisions with haptically rendered objects can also be used to teach normal movement trajectories such as the action required to place an object on a shelf or navigating a space ship through space (Adamovich, Fluet, Tunik, et al., 2009). Using haptically rendered obstacles to indirectly shape trajectories may decrease the effects of the explicit cognitive processes associated with presenting a model, such as an "ideal" trajectory into what is usually an implicit process (Boyd & Winstein, 2006). Investigation into this potential advantage is necessary because of the significant increases in cost associated with adding haptic effects to virtual rehabilitation applications.

Haptic environments can also exert global forces on the user such as increased resistance, antigravity support or viscous stabilization forces. Anti-gravity and viscous stabilization allow persons with force generation impairments to perform reaching and object manipulation tasks in 3D space. These activities invoke muscular force synergies that are comparable to those exerted in real-world movements. Several authors employ these concepts in VR simulations designed to train reaching, grasping, and lifting. Wolbrecht, Chan, Reinkensmeyer, and Bobrow (2008) used a haptic robotic interface to provide anti-gravity assistance to subjects with chronic hemiparesis secondary to stroke as they performed reaching movements in virtual environments. In a single session, single group study, the as need assistance improved their reaching kinematics so they resembled more normal reaching patterns. Many important activities of daily living require interaction with tools to achieve movement goals like feeding and grooming. In the physical world, object manipulation produces an interaction between the user and the object that is unique (e.g., torques exerted on the wrist by the interaction between the subject's hand and a knife and a cutting surface). Haptics can simulate the interaction forces produced by tools in virtual environments. The left panel of Fig. 7.4 shows the changes in the reaching trajectory when the lifting force shown generated during the reaching movement (right panel Fig. 7.4) is modified by manipulating the load of the cup to be lifted onto the shelf. See description of cup simulation in Table 7.1. Lambercy et al. (2007) described a haptic knob that can be used to simulate rotational forces using a set of objects that vary in size and shape allowing for customization based on therapeutic goals. Haptic forces can also be synchronized with visual feedback to improve the sense of presence of the user in the virtual environment. In two small studies involving healthy subjects, this feedback combination was found to be more effective for skill learning than visual only feedback in healthy subjects (Huang, Gillespie, & Kuo, 2007; Singapogu, Sander, Burg, & Cobb, 2008).

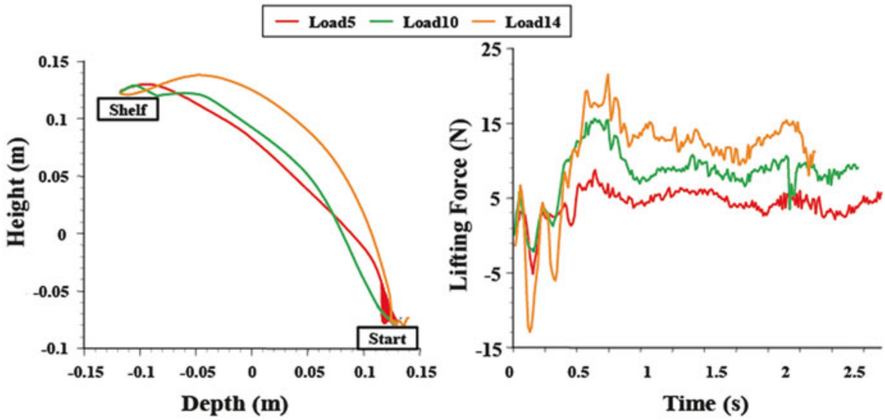


Fig. 7.4 *Left panel* shows the trajectory used to transport a haptic cup and place it on a shelf at three different haptic "weights" of the cup. Heaviest load is top line medium load is *middle line* lightest load is *bottom line*. *Right panel* shows how the force generated during the reaching movement, is modified based on the load of the cup to be lifted. To maintain the appropriate trajectory the force generated increases as the load on the cup increases. Force necessary to lift heaviest load represented by *top line*, medium load represented by *middle line*, lightest load generated by lowest line

7.7 Conclusions

The literature describing the efficacy of virtually simulated UE rehabilitation activities summarized in this chapter make a clear case for the effectiveness of this approach to treatment. The ability of simulated rehabilitation activities to address many of the requirements of motor learning and neuroplasticity in persons with a wide range of abilities seems to be central to this effectiveness. Virtually simulated rehabilitation treatments are inherently safe, time efficient and flexible, allowing for large volumes of training to be presented at appropriate levels of difficulty in a time efficient manner. Augmented feedback in the form of either KP or KR is known to enhance motor skill learning in normal adults (Lee, White, & Carnahan, 1990), in older healthy populations (Swanson & Lee, 1992) and in individuals post stroke (Winstein, Merians, & Sullivan, 1999) and Chap. 3. Both KR and KP can easily and systematically be delivered with specificity and predetermined frequency within virtual environments. Importantly it appears that VR interventions can be modeled on the clinical therapeutic framework described by the ICF model at the body function/structure level, as an activity based task or to enhance participation within social contexts.

Several areas of study are indicated to continue the development of this treatment approach for persons with stroke. The first would be to expand the study of virtual interventions to include persons in the acute phase of recovery. Further studies of the neural effects of VR sensory manipulations are needed. Future studies should include visuomotor discordance as a promising tool to enhance neuroplasticity. One of the examples described in the literature is mirror visual stimulation of the lesioned hemisphere controlled by the non-paretic hand in persons with no active movement of their hemiplegic upper extremities (Ramachandran & Altschuler, 2009; Tunik & Adamovich, 2009). Continued study of the manipulation of task difficulty using online algorithms is another area of study unique to simulated rehabilitation activities that should be pursued as well as the manipulation of the ratio of active patient movement to avatar movement. Two competing approaches to these manipulations use smaller avatar movements compared to subjects' movement to make them work harder in order to facilitate increased activity in the motor cortex, or large avatar movements compared to patient movement to allow patients with very little active movement to perform purposeful movements with their paretic upper extremity (Bagce, Saleh, Adamovich, & Tunik, 2011). An important next step toward translating the work done by researchers into clinical practice will be to design interventions that leverage the flexibility of virtually simulated environments. These interventions should be designed specifically for the impairment, activity, or participation level of the patient utilizing the patient management model. This chapter concludes with a case study that describes just such an intervention. The intervention includes task parameter scaling and gain scaling into a personalized rehabilitation program designed for an individual patient by a physical therapist utilizing the patient management model to inform decision making.

7.8 Case Study

Virtual environments have been used to facilitate the intensity and volume requirements of repetitive task practice in several studies (for recent reviews, see Henderson, Korner-Bitensky, & Levin, 2007; Laver et al., 2011; Merians et al., 2008; Saposnik & Levin, 2011). One of the strengths of virtually simulated rehabilitation systems is their ability to tailor activities to the unique motor abilities and rehabilitation goals of participants (Adamovich, Fluet, Tunik, et al., 2009). This case study will present a rehabilitation intervention customized to match the goals and clinical presentation of a gentleman with UE hemiparesis secondary to a chronic stroke. Detailed descriptions of the responses of the subject during the intervention and the modification of the intervention made by the therapist will be presented to demonstrate the ability of the technology to facilitate clinical practice.

7.8.1 Case Description: History and Systems Review

MP is an 85-year-old man with left hemiparesis secondary to an intracerebral hemorrhage and craniotomy 5 years prior to the interventions described in this case. Past medical history included an atrophic right kidney, recurrent urinary tract infections and several bouts of pneumonia and paroxysmal atrial fibrillation. Surgical history includes a permanent pacemaker placement, an abdominal aortic aneurysm repair and radical prostatectomy. Eleven years prior to this intervention, MP suffered a fall and incomplete spinal cord injury and a subsequent C3–C8 laminectomy and decompression from which he recovered from completely. Rehabilitation history following the stroke included 16 weeks of inpatient rehabilitation, 9 months of outpatient physical therapy (PT) and occupational therapy (OT), and 4 years of home therapy combining PT and OT that focused on ambulation, balance, transfers, sensory integration, and upper extremity function. MP performs bed mobility, transfers, grooming and feeding with supervision. He requires moderate assistance for toileting and upper body dressing and maximum assistance for lower body dressing. MP uses a power wheelchair for mobility but is able to walk up to 150 ft with contact guard using a cane. MP actively participates in his extended family and is on the board of several nonprofit organizations. His goals included improved use of the impaired upper extremity during transfers and dressing and improved use of the UE during eating, grooming, and computer activities.

7.8.2 Initial Examination and Outcome Measurements

A screening examination included active movements of his UE against gravity and several functional grasping movements to establish that MP had the motor ability necessary to participate in our study. This examination identified partially isolated, partial range of motion movement against gravity at all joints of the UE as well as gross and fine motor coordination impairments. Initial baseline data collection was performed prior to 4 weeks of biweekly home PT/OT sessions that were typical of the therapy performed by MP over the previous 18 months. A second data collection session immediately followed this period of home training and preceded a month of robotically facilitated training. A third data collection session was performed 4 days after completion of the robotically facilitated training period. To evaluate UE impairment at the body structure/function level we used the Upper Extremity Fugl-Meyer Assessment (FM) (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975) and the Reach-to-Grasp test (RTG), a kinematic analysis of untrained UE movement (Schettino et al., 2006). The Wolf Motor Function Test (WMFT) (Wolf et al., 2005), the Jebsen Test of Hand Function (JTHF) (Jebsen, Taylor, Trieschmann, Trotter, & Howard, 1969), and the Nine Hole Peg Test (9HPT) (Mathiowetz, Volland, Kashman, & Weber, 1985) were used to test for changes at the activity level. This combination was chosen in order to capture change in the ability to perform gross and fine motor movements. During the initial examination, we noticed that MP had difficulty flexing his trunk during reaching. We added the Modified Functional Reach Test (MFR) (Katz-Leurer, Fisher, Neeb, Schwartz, & Carmeli, 2009) to track changes in this skill. Changes at the activity level were also tested outside the laboratory by collecting UE accelerometer data for 24 h immediately after each testing session. Measurements included the ratio of impaired to unimpaired UE vertical plane activity, total vertical plane activity (Lang, Macdonald, 2007; Lang, Wagner et al., 2007; Uswatte et al., 2005), and total roll plane activity. Roll plane motion was chosen because pronation movements are associated with

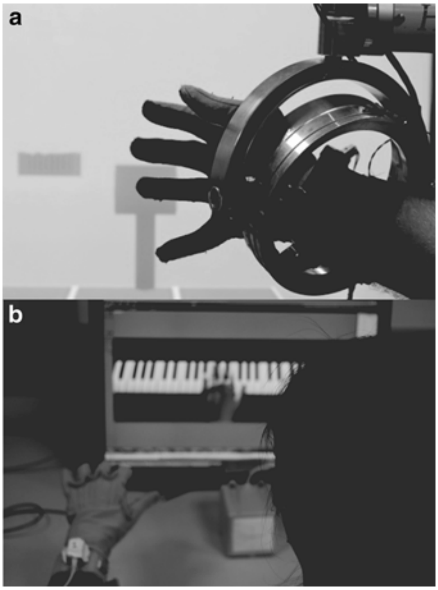


Fig. 7.5 (**a**) NJIT RAVR system. (**b**) NJIT Trackglove system

neurological recovery and tend to be associated with purposeful UE movement (Fan & He, 2006; Fan, He, & Tillery, 2006). MP completed the hand, mobility, activities of daily living, and social participation subscales of the Stroke Impact Scale (SIS; Duncan et al., 1999) to assess changes at the participation level.

7.8.3 Intervention

The VR intervention consisted of 12, 60 to 90 min sessions of training over 4 weeks with two virtual rehabilitation systems, the NJIT-RAVR system (Fig. 7.5a) and the NJIT TrackGlove system (Fig. 7.5b), which are described in detail elsewhere (Adamovich, Fluet, Mathai, et al., 2009; Adamovich, Fluet, Merians, et al., 2009; Merians et al., 2008). MP performed six simulated rehabilitation activities in each of 12 sessions.

7.8.3.1 Simulations

A brief description of each simulation, the therapeutic goals it was designed to address, the performance measure designed to track progress and the approach to increasing the intensity of the activity are described in Table 7.1. A discussion of the configuration and application of each simulation follows. MP had difficulty manipulating small objects due to an inability to flex fingers individually. The Virtual Piano

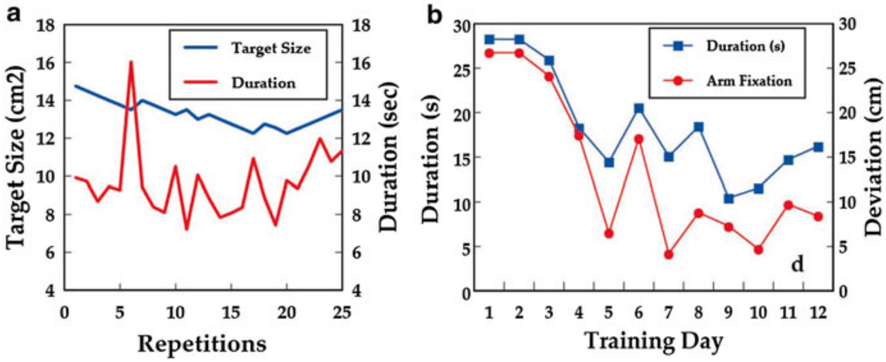


Fig. 7.6 (**a**) A representative example of 25 repetitions of MP performing the Hammer simulation in dynamic mode. The size of the peg to be hammered (*top line*) increases when the subject required more than 12 s to perform the task (*bottom line*) and decreased when he was able to hammer the peg in less than 12 s. (**b**) Average time to hammer a peg on each training day (*squares*) and average distance between peg and hammer during hammering (*circles*). This distance decreased as training progressed demonstrating improvements in MP's ability to stabilize his upper extremity during hammering

trainer simulation (Fig. 7.2 and Table 7.1) was used to address this impairment. MP played scales and drills with his hand in a stationary position and attempted simple songs with his hand moving across the entire keyboard. The program controlling the simulation measured the difference between the angle of the finger cued to press a key and the average of the non-cued fingers. When a predetermined difference between these two measurements was exceeded, the key was pressed. The algorithm previously described under "Activity Scaling" controlled the target difference. The Space Pong simulation (Table 7.1) addressed the difficulty controlling the aperture of the hand during grasping activities. MP played the Space Pong game using opening and closing of his hand to control the paddle. The Hammer simulation in dynamic mode (Table 7.1) was used to address difficulties with the manipulation of objects that were far from his body. MP reached to targets in a virtual space and hammered them using repetitive finger extension movements. We used an algorithm that increased target size, effectively decreasing proximal shoulder stabilization demands, when MP hammered targets slowly and decreased target size, increasing stabilization demands, when MP hammered targets quickly (Fig. 7.6a, b). We utilized the same hammer simulation in static mode to train a repetitive pronation movement in varying degrees of elbow extension and shoulder flexion (Table 7.1). MP demonstrated synergistic extension of his trunk during shoulder flexion making large excursion forward reaches difficult for him. We approached this impairment using two different simulations. The Reach-Touch simulation trained shoulder active range of motion with the trunk kept stationary (Table 7.1) and we used the Cup Reaching simulation to address shoulder elevation combined with active trunk movement (Table 7.1). During training with this simulation, MP attached his hand to a virtual cup near his body, reached forward and placed it in one of nine spaces on a virtual

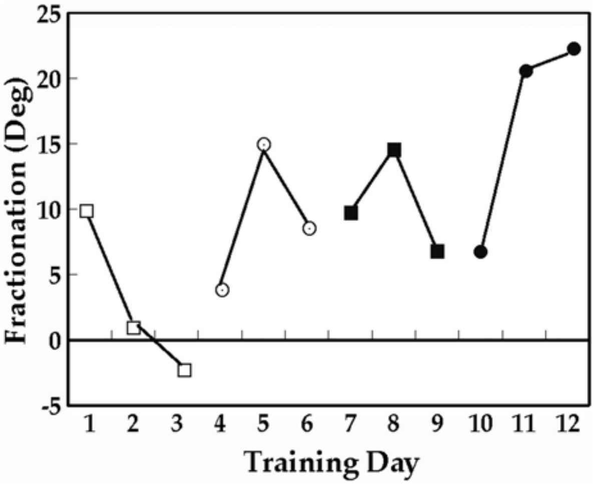


Fig. 7.7 Shows changes in MP's ability to isolate individual fingers during the training. These are the daily fractionation scores during the Virtual PIano simulation. The first 3 days (*open squares*) and the last 3 days (*open circles*) are performed without the Cybergrasp. Training days 4 through 6 (*solid squares*) are performed using the Cybergrasp 100 % of the time during the training session. Training days 7 through 9 (*solid circles*) are performed using the Cybergrasp for the first 5 min of each session

shelf. We set the height, width and distance of the shelves based on the maximal reaching distance of MP's arm which we measured weekly, with MP's trunk moving freely. We encouraged him to flex at the trunk to increase his forward reaching distance.

7.8.4 Responses and Modifications to Intervention

MP made little progress in the ability to flex his fingers during the Virtual Piano Trainer simulation performance as evidenced by his first three daily fractionation scores. We added the CyberGrasp™ (Fig. 7.2c), an exoskeleton robot, to assist MP in maintaining extension of the non-cued fingers while allowing flexion of the cued finger. Figure 7.7 shows the changes in MP's ability to isolate individual fingers (fractionation) during the training. MP used the CyberGrasp™ on training days 4 through 6 (Fig. 7.7 open circles). During training days 7 through 9 (Fig. 7.7 solid squares), MP used the CyberGrasp™ during the first 5 min of Virtual Piano trainer practice, and finished the 15-min block without the CyberGrasp™. He did not use the CyberGrasp™ at all during the final week (Fig. 7.7 solid circles). MP 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. After week 1, we

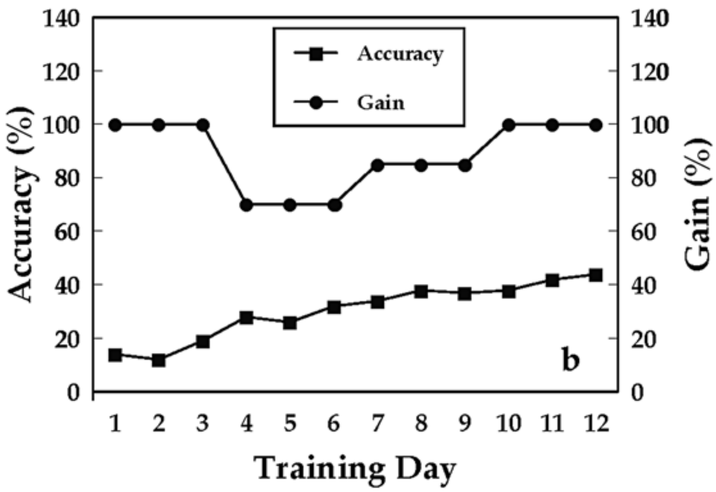


Fig. 7.8 Average accuracy scores for each training day demonstrated by MP during the Space Pong simulation (*circles*). Changes in the ratio of MP's finger movement and movement of the pong paddle (*squares*). This ratio was manipulated to allow MP to learn to more effectively control the opening and closing of his hand and play the game with a reasonable level of success

decreased the gain (Fig. 7.8 circles) from movement to virtual movement by 30 % which increased the amount of finger movement required to produce the paddle movement. This allowed MP to control his paddle accurately using the movement strategy available to him. The gain was increased by 15 % for training days 6 through 9 and back to 100 % for training days 10 through 12 as MP's accuracy scores increased (Fig. 7.8 squares). MP did not make significant improvements in his ability to pronate his forearm with his shoulder flexed and elbow extended during the use of the Hammer simulation in fixed mode (Table 7.1). We modified the relationship between the active pronation movement and the hammer swinging movement in an attempt to stimulate progress during this activity but none of these manipulations resulted in consistent increase in pronation excursion. MP made steady improvements in proximal stabilization while performing the Hammer finger extension simulation in dynamic mode during the first 2 weeks of the trial and maintained them in weeks 3 and 4. MP made small steady improvements in the time to touch all ten targets in the Reach-Touch simulation despite a steadily increasing workspace. In addition, the excursion of his forward reaching movement improved during performance of the Cup Reaching simulation while decreasing the movement time required to perform the activity. Prior to calibrating the workspace on training day 10, the PT managing the trial encouraged MP to challenge himself during the calibration process. This resulted in a much larger increase in reach excursion accomplished with a combination of trunk flexion and shoulder elevation. MP was able to use this strategy during the rest of the training period.

7.8.5 Outcomes

MP demonstrated no change in UEFMA after the month of home PT/OT (pretest 1 to pretest 2) and then a four-point improvement in the UEFMA after the month of robotically facilitated training (posttest). MP's improvements in UE activity measures were impressive as well. He made a small, 5 s improvement in JTHF time after the month of home therapy and an additional 35 s of improvement after the robotic intervention. MP demonstrated a 3 s decline in WMFT during his period of home training but a robust 44-s improvement subsequent to robotic training that greatly exceeds the published minimal clinical important difference of 2.7 s (Lin et al., 2009). There was no improvement in the NHPT following home training and a 14 s improvement following the VR training program. MFR distance increased 2 in. following home training and 10 in. following robotic training utilizing the strategy MP developed during the last week of training using the cup reaching simulation. MP also demonstrated improvements in all three 24-h activity measurements. Active vertical plane movement increased 1,538 s (26 min) which is consistent with those demonstrated during an acute rehabilitation stay (Lang, Macdonald, et al., 2007; Lang, Wagner, et al., 2007). Roll plane movement increased 789 s (13 min). Impaired arm movement to unimpaired arm movement ratio increased from 41 to 51 %, which is consistent with changes measured in a constraint induced movement therapy study of subjects post stroke (Uswatte et al., 2005). MP demonstrated an improvement of seven points on the hand scale of the SIS, eight points in the ADL scale and six points in the social participation scale. His caregivers confirmed MP's reports of increased use of his hand and arm during several activities of daily living.

7.8.6 Discussion

This case study presents the use of six VR simulations (four of them integrated with haptic robots) for the clinical management of a gentleman with hemiparesis due to chronic stroke. As in customary care, the intervention was specifically tailored for the patient and modified over time based upon the responses of the subject. The control systems governing the robotic interactions with the subject as well as the feedback presented by the VR simulations were adapted to address his specific impairments and functional limitations. Modifications in approach to training were made in four of the six simulations (Piano Trainer, Space Pong, Hammer Training, and Cup Reach) based on therapist observation. This resulted in dramatic improvements in performance in three of the four modified simulations, as well as robust improvements at the body structure/function, activity, and participation levels. 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. While highly standardized protocols are valuable in determining specific changes elicited by specific interventions, there is also a possibility that they result in an underestimation of the potential benefits of this technology as they fail to address the specific impairments of a heterogeneous patient population or leverage the flexibility of virtual environments as rehabilitation platforms.

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