CYBERPSYCHOLOGY & BEHAVIOR
Volume 8, Number 3, 2005

Virtual Environments for Motor Rehabilitation: Review

MAUREEN K. HOLDEN, Ph.D.

ABSTRACT

In this paper, the current "state of the art" for virtual reality (VR) applications in the field of motor rehabilitation is reviewed. The paper begins with a brief overview of available equipment options. Next, a discussion of the scientific rationale for use of VR in motor rehabilitation is provided. Finally, the major portion of the paper describes the various VR systems that have been developed for use with patients, and the results of clinical studies reported to date in the literature. Areas covered include stroke rehabilitation (upper and lower extremity training, spatial and perceptual-motor training), acquired brain injury, Parkinson's disease, orthopedic rehabilitation, balance training, wheelchair mobility and functional activities of daily living training, and the newly developing field of telerehabilitation. Four major findings emerge from these studies: (1) people with disabilities appear capable of motor learning within virtual environments; (2) movements learned by people with disabilities in VR transfer to real world equivalent motor tasks in most cases, and in some cases even generalize to other untrained tasks; (3) in the few studies ($n = 5$) that have compared motor learning in real versus virtual environments, some advantage for VR training has been found in all cases; and (4) no occurrences of cybersickness in impaired populations have been reported to date in experiments where VR has been used to train motor abilities.

INTRODUCTION

IN RECENT YEARS, the field of virtual reality (VR) has grown immensely. Practical applications for the use of this technology encompass many fields, from aviation training and military applications, to industrial training in machine operation, to medicine, where surgeons can be trained in surgical techniques using VR systems.

One of the newest fields to benefit from the advances in VR technology is that of medical rehabilitation. In the space of just a few years, the literature has advanced from articles which primarily described the *potential* benefits of using such technology, to articles that describe the development of actual working systems, testing of prototypes, and early clinical results with patients who have used some of these systems.

In this article, a brief overview of the equipment typically used in VR training systems is provided. There follows a review of the scientific rationale and the potential advantages of using VR systems in the field of rehabilitation. Finally, the "state of the art" for VR applications in motor rehabilitation is reviewed. The application topics have been organized by diagnostic or task specific categories for ease of reference by the reader. The focus in this paper has been restricted to the field of motor rehabilitation.

EQUIPMENT FOR VR SYSTEMS IN MOTOR REHABILITATION

A virtual environment (or virtual reality) is a simulation of a real world environment that is generated through computer software and is experienced

Department of Brain and Cognitive Sciences, McGovern Institute for Brain Research, Massachusetts Institute of Technology, Cambridge, Massachusetts.

by the user through a human–machine interface. A wide variety of hardware and software devices can be utilized to create VR simulations of varying degrees of complexity. Whereas in the real world we gain knowledge about our environment directly through our senses—vision, hearing, touch, proprioception, smell—in the virtual world, we utilize these same senses to obtain information about the virtual world through a human–machine interface (e.g., head-mounted visual display). The human– machine interface can provide information specific to one or more senses, depending on the type of devices that have been selected for use. The information gathered about the virtual environment through the interface is then used to guide interactions of the participant within the virtual world. Input from the virtual environment can also be combined with natural sensory inputs from the real environment, to create a hybrid input to the central nervous system (CNS).

A variety of equipment can be utilized to create different kinds of virtual environments with different capabilities and purposes. Several available books provide complete and detailed descriptions of available VR equipment[1–3]; therefore, only cursory descriptions will be provided here. The basic components for VR systems are a computer, usually with a special graphics card that will allow fast computation and drawing of three-dimensional (3-D) images, display devices through which the user views the virtual environment, hardware devices that can be used to monitor movement kinematics, or provide simulations of haptic and force feedback to participants, and, of course, specially written software that enables all these components to work in synchrony. More immersive virtual environments provide the user with the perception that the environment is real and 3-D, a quality referred to as *presence.* Less immersive virtual environments provide less of a sense of presence and are more akin to looking through a window at a scene. While it might seem intuitive that more immersive virtual environments would be best for motor training, this may not actually be the case, in part because of a practical difficulty. Such immersive virtual environments can generate cybersickness (a constellation of motion-sickness like symptoms) in many participants.[4,5] Common symptoms of cybersickness include nausea, vomiting, headache, somnolence, loss of balance, and altered eye–hand coordination. These are obviously undesirable events, particularly in participants with impaired function in the CNS. Most of the studies on cybersickness to date have been on normal participants but it is reasonable to assume that patients with neurological impairments would be susceptible to cybersickness with similar (if not higher) frequencies than normal participants. It is important to note, however, that none of the studies reviewed in this paper that have used VR to train impaired participants have reported any incidence of cybersickness. All these studies have used less immersive desktop or wall screen displays. Although newer equipment, in theory, should greatly decrease the incidence of cybersickness,[6] the effects of different immersive systems on patient populations is an area still in need of investigation. Lewis and Griffen[7] have provided a comprehensive description of key issues to be considered in such investigations.

Display devices

The simplest visual display device is a desktop computer monitor, using an enhanced 2-D graphics display. Although such displays will not be as realistic as a true-stereo 3-D display, the sense of depth can be enhanced through the use of depth cues such as perspective, relative motion, occlusion, and aerial perspective.[1] Use of a liquid crystal display (LCD) projector and large wall screen as the monitor will also enhance the sense of depth perception (and thus sense of presence) in the user. Such set-ups are convenient, easy to use, require no glasses or headset with wires, and allow both the therapist and patient to view the same scene with ease. These displays have been preferred in clinical studies to date, as they are relatively cheap and easy to use, and there have been no reported occurrences of cybersickness in studies using such systems with clinical populations.

To move toward a more immersive virtual environment, one needs a display that can provide true 3-D stereo. This can be done inexpensively with flicker glasses which display alternating right/left views of the picture synchronized to the frame rate; or more expensively with a head-mounted visual display (HMD), which allows stereo viewing via small monitors mounted in front of each eye and linkage of the VR viewpoint with head movements; or large screen stereo projection systems, which provide compelling stereo with lightweight polarizing glasses. At the very high end, the CAVE™ system, developed at the University of Illinois at Chicago,[8,9] provides a multi-person, room-sized, high-resolution, 3-D video and audio virtual environment.

Interface devices

In addition to the standard mouse and joystick interfaces that are routinely used to navigate large 3-D worlds, a variety of devices will allow simulation of movement kinematics and sensory feedback such as touch, pressure, or force. In theory, any type of motion tracking device could be used to monitor movement or simulate movements in a virtual world. In practice, electromagnetic tracking devices are frequently utilized to monitor head, trunk, arm, and leg movements. They are lower in cost and impervious to optical occlusion problems. However, they can be susceptible to signal distortion from large metal objects or from electromagnetic fields generated by electronic devices.[10]

For capture of the more detailed kinematics of hand movements, an instrumented glove may be used. Inexpensive haptic feedback can be provided with newly developed contact feedback devices, for example, small vibration devices attached to the fingertips that become active when the participant has "touched" a virtual object and turn off when the object is released. For higher fidelity haptic feedback, a robotic arm, which generates 3 or 6 degrees of freedom forces (e.g., PHANToM™), can be used. To utilize this kind of feedback in VR training, a hand-held stylus is usually attached to the robotic arm, and the forces are translated to the participant through the stylus. This type of set-up has been used to train surgical techniques,[11,12] but has not been used to date in rehabilitation. To feel more realistic force feedback on different fingers and thumb, or throughout the arm, an exoskeleton type device is required. One such device, which applies forces to resist finger flexion, has been developed by Burdea and colleagues.[13] Commercial devices which can apply force feedback to the fingers and thumb ("CyberGrasp") or the entire arm ("CyberForce") are also now available but expensive <www.immersion.com/3d/products/cyber_grasp.php>.

Auditory input can also be utilized in VR to enhance spatial orientation and localization. For example, the CAVE system uses multiple speakers mounted in the room to create direction and distance effects in the virtual world.[8,9]

SCIENTIFIC RATIONALE AND ADVANTAGES OF VR USE FOR REHABILITATION

The discussion of the scientific rationale and advantages for VR use in rehabilitation will focus on a few key concepts relevant to motor learning. More extensive discussion of these issues may be found elsewhere.[14–17] The key concepts to be discussed are repetition, feedback, and motivation. We know that repetition is important both for motor learning and the cortical changes that instantiate it. But it is not just repetition alone that produces motor learning. The repeated practice must be linked to incremental success at some task or goal. In the normal nervous system, this is achieved by trial and error practice, with feedback about performance success provided by the senses (e.g., vision, proprioception). But to practice movements over and over, participants must be motivated. Most people can recall the extensive practice that was necessary when learning to ride a bicycle. In this case, the motivation to tolerate the extensive practice period was provided by the anticipation of later fun to be experienced while riding the bike.

VR provides a powerful tool with which to provide participants with all of these elements—repetitive practice, feedback about performance, and motivation to endure practice. In particular, in a virtual environment, the feedback about performance can be augmented—that is, enhanced relative to feedback that would occur in real world practice. A wide variety of methods have been used to exploit aspects of VR technology to enhance motor learning in people with disabilities through real time feedback (i.e., concurrent with task performance) and/or "knowledge of results" feedback. Knowledge of results feedback occurs immediately following a trial or block of trials. Feedback has been extensively investigated and there is general agreement that it improves learning rate.[18]

Since feedback is central to motor learning in a virtual environment, it is important to examine the neurophysiological processes that are evoked by feedback and discuss their relevance to the relearning of motor skills. There is extensive evidence that the proprioceptive and exteroceptive feedback associated with the execution of skilled tasks (in addition to internal feedback) induces profound cortical and subcortical changes at the cellular and synaptic level. For example, evidence derived from recording the activity of single cells from the primary motor cortex of intact primates has indicated that protracted use of the digits leads to an enlargement of the cortical representation. Nudo et al.[19] showed that cortical area M1 was alterable by use throughout the life of an animal. Use-dependent alterations of cortical organization have also been found in auditory, visual, and somato-sensory areas.[20–24]

Direct evidence for the development of new patterns of activity in the cells of the motor areas of the frontal lobe during the acquisition of a new motor skill has also been reported in a series of experiments in primates.[25–27] The most striking result in these experiments was the gradual recruitment of previously silent cortical neurons in area M1 during learning; these neurons displayed activity related to the production of forces that compensated for externally imposed disturbances. Similar results have been reported by Wise et al.[28] using the same technique of single-cell recordings with a different behavioral paradigm. Co-occurrence of functional and structural plasticity within the same cortical regions has also been described for rats.[29]

Studies by Greenough et al.[30] and Kleim et al.[31] have revealed some of the mechanisms underlying the functional reorganization in the motor cortex following motor learning. Rats trained on a complex motor task had larger dendritic fields and an increased number of synapses in cortical motor cells in the hemisphere opposite to the trained limb. There is also experimental evidence that synaptic efficacy in the motor cortex may be modified by the induction of long-term potentiation.[32,33] It has also been shown in the rat[29] and the primate[34] that functional reorganization of the motor cortex ("remapping") occurs only in response to the development of skilled forelimb movements, and not simply to increased forelimb use.[29,35] These studies provide neurophysiological evidence that motor repetition alone is not enough to induce cortical correlates of motor learning.

Substantial functional reorganization also takes place in the motor cortex of adult primates after a focal ischemic infarct.[36] The retraining of skilled hand-use in these animals results in reorganization in the adjacent intact cortex. Thus, the undamaged motor cortex may play an important role in motor recovery.[37,38] Interestingly, Nudo et al. found that, in the absence of post-infarct training, the movements formerly represented in the infarcted area do not automatically reappear in adjacent cortical regions, but do so only in response to specific motor re-training activities.[36,37]

Real versus virtual practice

As will be seen in the latter part of this paper, augmented feedback about motor performance can readily be provided in a virtual environment. And, as outlined above, scientific evidence suggests that augmented feedback about performance will enhance the cortical changes associated with motor learning. But one might argue, most of the cited studies have been conducted on animals, and the animals were not trained using VR. What sort of evidence exists about motor learning for human participants trained in virtual environments? And, have any studies compared training in a real vs. virtual world environment?

On the first point, there exists a fair amount of evidence that humans can learn motor skills in a virtual environment[39–42] and that they can then transfer that motor learning to a real world environment.[43–45] Evidence that people with disabilities can learn motor skills in VR and transfer this learning to real world performance will be presented in the various sections to follow. In general, it can be said here that people with disabilities do seem able to both learn motor skills in VR and transfer these abilities to the real world. But how does learning in a virtual environment compare to that which occurs in a real environment? On this second point, few studies exist. And this issue is an important one for those in the rehabilitation field, who inevitably ask when discussing the use of VR in rehabilitation: "Why bother with all that equipment; why not just practice the real task? Wouldn't that work better anyway, and cost less?" Of course, proponents of VR believe that outcomes will be enhanced following practice in VR because of the ability to make tasks easier, less dangerous, more customized, more fun, and of course easier to learn because of the salient feedback that can be provided during practice. To date, however, only five studies have examined this issue in a controlled fashion. All five studies provide some experimental evidence that motor learning in a virtual environment may be superior.

In the first of these studies, Todorov et al.[46] found that healthy participants who practiced a table-tennis stroke in a virtual environment, with augmented feedback from a virtual teacher, performed better following training than did participants who had practiced the table tennis stroke with feedback from an expert coach, or just practiced on their own. (Participants were tested on a real world performance test.)

A second study of motor learning in VR trained normal participants to move a hand held metal ring over a curved wire ("steadiness tester") in either a real or a virtual environment.[47] Participants received virtual training, real training or no training on the steadiness task. Prior to and following training, all participants were tested on the real task. The results were that both virtual and real training groups improved significantly ($p < 0.001$) post-training, but the no training group did not. The performance, as measured by number of errors, was equivalent ($p = 0.22$) between those who received virtual or real training. These results support the transfer of motor training in VR to real world performance, in concert with the findings of others reported earlier. Next, these same participants performed a second post-test on the steadiness tester, but were required to simultaneously carry out either a motor interference or a cognitive interference task. The motor Interference group was asked to tap on a Morse code key in time with a pre-recorded tempo. The cognitive interference group was asked to listen for the names of fruits interspersed within a string of pre-recorded words and say "yes" when they occurred. These concurrent tasks lasted for the duration of the steadiness test. The results were that the motor interference task had a significantly greater effect on the steadiness test than did the cognitive interference task ($p < 0.01$). However, the very interesting result was that participants who had trained on the virtual task were significantly less impaired ($p < 0.05$) by the interference task than those who had trained on the real task. This finding is in concert with the results of Todorov et al.[46] and implies an advantage or improved efficiency for the virtual training.

In the third study which compared real and virtual practice, Brooks et al.[48] found that an amnesic patient was able to learn two routes around a real world hospital rehabilitation unit following training in a VR simulation of these routes for 15 min per day for 3 weeks. An errorless learning[49] method was used. Seven untrained routes were also tested; performance on these routes showed no improvement. Later, the patient was trained on two additional routes in the same rehabilitation unit—one in VR and one in the real world. After 2 weeks of training, she had learned the route trained in VR, but not the route trained in the real world. Thus, in this case, training in the virtual environment proved to be superior to training in the real world. It is also interesting to note that the patient easily transferred the learned performance from VR to the real world, despite the fact that the motor activity in VR consisted only of manipulating a joystick, whereas in the real world, actual walking was of course required. Obviously, the motor patterns of the two tasks varied considerably, implying that the learning was at a more abstract or conceptual level.

In a fourth study, Webster et al.[50] evaluated the effectiveness of using a VR-based wheelchair training program in improving real world wheelchair use in a group of patients with stroke and unilateral neglect syndrome. A second group of patients who had participated in a prior study of unilateral neglect served as a control group (i.e., non-randomized). Both groups received standard rehabilitation wheelchair training, but only the experimental group received the VR training. The results showed that the patients who had received the VR training made fewer errors and hit significantly fewer ($p < 0.000$) obstacles with their wheelchair during the real world obstacle avoidance test than did participants in the control group, who had not received this training. In addition, the number of falls during their inpatient hospital stay was fewer for the VR-trained participants ($p < 0.02$) compared to control participants.

A fifth study compared training to avoid obstacles during walking using VR-based vs. real world training in a randomized controlled study of patients with chronic stroke.[51] Investigators reported that, although both groups improved on most of the outcome measures, participants in the VR group showed greater improvement ($p < 0.001$) in a fast paced velocity test post-training.

Taken together, the results of these five studies comparing different types of motor learning in a virtual versus real environment support the idea that motor learning following training in a virtual environment may be superior to that following real world practice. Obviously, further work is needed to confirm these findings, in particular with motor-impaired patient populations, where only one randomized controlled study has been published to date.[51]

Other factors that may enhance motor learning in VR

In addition to the important factors discussed above (augmented feedback, facilitation of cortical plasticity through guided practice), a few other ideas that may enhance motor learning in VR should be mentioned. For instance, there is psychophysical evidence that humans derive the specifications of a movement by tracking the trajectory of the end-point of the limb.[52,53] The precise definition of "end-point" depends on the task itself and can vary from the tip of a held object, to a finger, or to the entire hand. By explicitly showing this end-point trajectory to the participant via an animated VR display, learning may be enhanced, especially in the initial phase.[14,15,54]

VR also allows us to program into the display a virtual teacher, who performs the task repeatedly. The powerful visual input of the teacher performing the movement over and over may provide enhancement of "learning by imitation" through direct input to M1 via mirror neuron inputs.[55] Mirror neurons are cells which have been discovered in the monkey premotor cortex that fire when a movement is observed and when it is performed.[56] They may provide a neurophysiological underpinning to "learning by imitation" in VR. This feature of learning by imitation is not only an important way to provide enhanced visual feedback, but also a way to develop, through repetition, the formation of the correct pattern of cellular activity in the CNS.[25,26]

VR offers the unique capability for real time feedback to the participant during practice in a very intuitive and interpretable form. Patients can see their own movement attempts in the same spatial frame of reference as that of the "virtual teacher" (unlike practice with a real coach or therapist). Also, the task can be simplified in the early stages of learning, allowing the learner to focus on key elements. In contrast, in the real world situation, many potential distracters exist and may slow down learning as the participant attempts to distinguish, through trial and error, the key aspects of the task on which to focus. (This factor of reduced distractibility may have enhanced learning for the amnesia patient in the study by Brooks et al.[48]) Training environments can also be customized for different therapeutic purposes and the system designed to help the learner detect and correct errors more rapidly.

New methodology

Finally, even if it proves to be the case following further study that VR offers no performance advantage over real world practice for patients with motor impairments, there will still be a significant place for VR use in rehabilitation. It is a powerful new tool that can be utilized to test different methods of motor training, types of feedback provided, and different practice schedules for comparative effectiveness in improving motor function in patients. The technology provides a convenient mechanism for manipulating these factors, setting up automatic training schedules and for training, testing, and recording participants' motor responses.

USE OF VR FOR STROKE REHABILITATION

Upper extremity

Several groups of researchers have been working to develop VR systems for upper extremity (UE) rehabilitation in patients with stroke, using a variety of approaches.

MIT group. Holden and colleagues, based at Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, were the first to report successful use of VR to retrain movement in patients with stroke.[57] The VR motor re-training system they have developed is centered around the concept of "learning by imitation" of a virtual teacher,[55] and allows the user to retrain a wide variety of arm movements (including shoulder, elbow, wrist, and hand) in any part of the UE workspace, within the context of functional or goal-directed tasks. A brief system description is provided below; further details may be found in Holden and Todorov,[15] and Holden and Dyar.[14]

System description. The system consists of an electromagnetic motion tracking device (Polhemus, Inc.), desktop computer display, and VR software. The VR software contains a basic 3-D graphics editor which allows the user (therapist) to create "scenes" designed to be therapeutically meaningful to the targeted patients. Usually, a scene shows some simple task (e.g., place an envelope in a slot, hit a nail with a hammer, move a ball through a ring, or lift a cup to the mouth). To date, approximately 20 scenes, each with multiple levels of difficulty, have been developed and tested with patients, making a total of approximately 50 training scenes. Following the basic scene creation, the motion tracking device is used to pre-record normal participants performing the desired activities, within the context of the VR scene. These prerecorded trajectories (6 degrees of freedom (DOF); translation and orientation) then serve as the "virtual teacher" for the patient to watch and copy during the VR therapy practice. The entire limb or only the endpoint of the limb (i.e., hand or held object) and its trajectory may be displayed. The teacher display may also be hidden from view if desired.

During training, the same motion tracking device used to record the "virtual teacher" is attached to the patient. The arm movements of the patient can then be monitored and displayed in real time in the context of the virtual scene, along with the prerecorded movements of the virtual teacher. The degree of match with the teacher trajectory provides augmented feedback in a visual context to the participant during practice. The amount of match may also be quantified to provide augmented knowledge of results feedback following each trial. This feedback is presented to the participant as a "score," or paired with verbal cues, such as "Very good!" The scoring algorithm is flexible, allowing the therapist to specify weights for different aspects of performance as needed for particular patients. For example, displacement error, orientation error, angular or linear velocity, smoothness, and other factors may be weighted to emphasize one or more of these factors during training. A more complete description of the score algorithm may be found in a forthcoming paper.[58]

Although the desktop display allows only enhanced two-dimensional (2-D) displays, 3-D display is possible if stereo headsets, flicker glasses, or large screen polarizing projectors are used. To date, however, the desktop has been the preferred choice for these initial clinical studies, both because of lower cost and to minimize any risk of cybersickness in these impaired participants. Recently, a telerehabilitation version of the system has been developed and deployed. Two disadvantages of the system developed by Holden and colleagues are that it presently lacks a full hand model (fingers and thumb) and haptic feedback capability. However, the group is presently working to add these features to their system.

Study results. In the first study reported by Holden et al.,[57] the purpose was to assess whether participants with stroke would even be able to use a virtual environment to practice motor tasks, and if so, whether any movements that they learned in VR would generalize to performance in the real world on similar and untrained tasks. Two participants with stroke (3.5 and 1.5 years post-stroke; one with right hemiparesis and aphasia; one with left hemiparesis, parietal lobe symptoms, left side inattention and hemianopsia; initial Fugl-Meyer [FM] Motor Scores = 31.5 (max = 66) for both participants) were trained on a complex reaching task on their involved side, requiring shoulder flexion with external rotation, elbow extension, and forearm supination combined with grasp. During training, each participant held a (real) Styrofoam envelope using a lateral grasp. The envelope was fitted with a sensor, which recorded the endpoint trajectory of the patient's reaching movements, which in turn was displayed to the patient in the context of a VR scene. In the VR scene, a "teacher" animation placed an envelope in the slot of a virtual mailbox. Six levels of difficulty for this scene were devised (near and far reach with different hand orientations). Participants practiced for 1-hr sessions at a frequency of once or twice a week, for a total of 16 sessions. Before and after training, participants were assessed on their reaching ability using a 3-D kinematic test performed in the real world. The kinematic test was repeated three times at 1-week intervals, prior to and following training. In the test, participants held an envelope in their hand and attempted to place it in a real "mailbox" slot. The box and slot were placed in nine different locations, only one of which had been trained in VR. Participants were also tested using two standard clinical tests: the FM Test of Motor Recovery for Stroke,[59] and the motor task section of the SAILS test of UE function.[60]

Results for the kinematics test indicated that, not only could participants transfer what they learned in VR practice to the real world, but also, that they generalized the motor learning to untrained spatial locations. Both participants showed significant improvement for distance errors to the target across both trained and untrained locations (64% reduction in error for P1, 50% reduction for P2, when averaged across all target locations). Hand orientation errors improved for P1 in the trained location and for five of eight untrained locations; however, no improvements in hand orientation were seen for P2. As expected, the control of hand orientation while reaching and grasping proved more difficult to learn than control of reach with no constraint on hand orientation. The clinical tests also showed some improvement, greater for P1: FM motor test improved by 17% for P1; 5% for P2. Neither participant improved on the SAILS test, probably due to poor fine motor control of hand for both participants. However, P1 reported that he gained the ability to perform three new functional tasks with the right arm following the VR training.

In a second study, the issue of motor generalization was examined in greater depth. The study provided further evidence that movements trained in VR in patients with stroke can be generalized to similar real world tasks and to certain types of untrained tasks. Preliminary results from the first seven participants have been reported and will be reviewed here.[14,61,62] Final results of this study, including a more extensive analysis of kinematic data, additional participants and statistical analyses will be presented in a forthcoming paper.

In this study, two movements were trained in a virtual environment using the same system as in the first study, but with the addition of quantitative feedback about trajectory match with the virtual teacher that could be presented in the form of a score following each trial. Specific and non-specific motor generalization was assessed. Specific generalization was defined as transfer of learning from VR to the real world measured during real world performance of 14 tasks designed to assess the following six types of generalization: (1) same task generalization; (2) spatial generalization; (3) gravitoinertial force (GIF) generalization; (4) combined spatial plus GIF generalization; (5) generalization to tasks requiring novel recombination of trained movement elements; and (6) control tasks with untrained elements. Non-specific generalization was defined as transfer of learning from VR to the real world as measured by change in clinical tests of motor recovery and function following the VR training.

Participants (n = 7) with cortical and/or subcortical stroke were tested (mean duration post-stroke was 20.4 months, mean age 52.6 years; four had left hemiparesis, three had right; five were male, two female). Initial FM UE motor scores ranged from 18 to 54; mean score was 32 (maximum = 66). All participants primarily used the uninvolved UE for activities of daily living (ADL) tasks and were no longer receiving therapy for the arm.

Participants were trained on two tasks in a virtual environment using a series of scenes that simulated the tasks at increasing levels of difficulty. The first scene was the mailbox scene, which elicited forward reach with grasp; the second scene required the participant to reach smoothly out to the side (abduction to 45 degrees) with open hand and elbow extension, by moving the hand from its start position resting on a table in front of participant at midline, through a series of rings arranged along the trajectory of the hand path, approximately in a semicircle, to the final position out to the side. (Such a movement would be useful to catch one's balance, use hand for postural support, or to reach for objects located lateral to participant.) Each scene displayed a virtual "teacher" performing the correct movement. Augmented feedback about error, based on degree of match with the teacher trajectory, was provided during movement practice, initially at high frequency, then faded to a lower frequency as sessions progressed. Participants received 30 sessions in total, 1 hr each, at a frequency of three sessions per week.

During the specific generalization tests, 3-D kinematics of the arm and trunk were measured using an electromagnetic tracking device. Spatial errors (distance from movement endpoint to target) and number of velocity peaks were calculated for each trajectory. Non-specific generalization was assessed using the FM test of motor recovery, the Wolf Motor Test for UE function,[63,64] and two strength tests. The test battery was administered prior to and after the VR training.

Five of the seven participants showed quantitative evidence of generalization, defined as a >25% reduction in spatial error (range = 25–98%) or >25% reduction in the number of velocity peaks (range = 25–97%) for the test movements following training. Larger generalization effects were found for same task, spatial, GIF, and combined spatial plus GIF tasks than for novel recombination and untrained tasks.

Results for the clinical testing (non-specific generalization) of these participants (plus one additional participant [n = 8][14]) showed that the mean values post-training were significantly higher on both the FM Motor and FM Total scores, indicating improvement (p = 0.008 and p = 0.048) for FM Motor and Total scores, respectively. These results indicate that most of the improvement was in motor function, but some participants also had decreased pain, increased range of motion and improved sensory scores post-training. Individually, all participants showed some level of improvement on the Motor subtest; the range was 2.5%–42%; the mean across participants was 15% ± 14.8%. Individually, three of the eight participants improved by >20% on the FM Motor test.

Results for the Wolf Motor Test of UE Function indicated improvement, with lower Total Time scores post-training (p = 0.021). Average improvement was 31% ± 25.7% (range, 1–83%). Individually, six of the eight participants improved by >20%. Of note is that the participants who showed little change on the FM measure all had large improvements on the Wolf Motor test of UE Function. Conversely, the two participants who showed little change on the Wolf Motor test showed larger changes (>20%) on the FM test.

Two strength tests, for shoulder flexion and for grip strength, also improved after VR training. The differences for shoulder flexion strength (mean increase 118%) were statistically significant (p = 0.02), and the differences for grip strength (133%) were close to significance (p = 0.058). Considered individually, six of the eight participants increased either shoulder flexion or grip strength, or both, by >20%.

Taken together, these improvements in three standard clinical tests of function were surprising, given that participants practiced only two movements during VR training and that most of the tasks tested were untrained. These results are also encouraging, as they imply that something more general than one specific movement is being trained by these VR methods, and thus VR may be an efficient way to train a set of "basis functions," which in turn allow the execution of a variety of more skilled movements.

A third study on patients with stroke conducted by this group will be described in the last section entitled Telerehabilitation. In this study, a wider variety of training scenes (8–10 per participant) were used, and the scenes were designed to address specific deficits displayed by each participant.

Rutgers group. A second group, Burdea and colleagues, based at Rutgers University and the University of Medicine and Dentistry of New Jersey, has centered their development around the hand. (The Burdea group has done extensive engineering development for a variety of VR rehabilitation applications.)

System description. Their UE system makes use of the commercially available Cyberglove™ to monitor hand position and to provide feedback about kinematics of hand movement during training, and a laboratory-built glove, Rutgers Master II, to provide haptic monitoring and feedback combined with position sensing.[13,65] Four types of hand exercise routines have been developed: (1) range of motion (ROM); (2) speed; (3) fractionation; and (4) strength.

In the ROM exercise, participants begin with their fingers in extension, and attempt to move either the thumb or the four fingers into flexion. As they do so, a picture is revealed on the screen, with the amount revealed roughly equivalent to the amount of flexion ROM. For the speed exercise, participants again begin in extension, seeing their open "virtual" hand on the screen. Then a butterfly begins to flutter around the hand, and the participant attempts to rapidly flex the fingers in order to "catch" the butterfly. The fractionation exercise is designed to help participants practice isolated finger control. In this exercise, participants see a piano keyboard on the screen, with the virtual hand on the keys. The patient tries to depress a single key using a single finger (flexion), while maintaining the other fingers in extension. If successful, the key turns green; errors cause keys to turn red. For the strength exercise, a different glove is used (Rutgers Master II),[13] which has small pneumatic pistons in the palm, with movable rods fixed to the fingertips. The participant practices with thumb and each finger separately, depressing the piston against a force applied via the computer. On the screen, the participant sees a virtual hand, with virtual pistons in the palm. The pistons are red at the start of each trial, but turn green if the target force level is achieved by the patient. For all of these exercises, participants receive immediate visual feedback about their ongoing performance by viewing the virtual hand on the screen. In addition, following each trial, participants receive a numerical score which provides quantitative information about their performance.[65,66]

Study results. The Rutgers group has used their hand rehabilitation system in two clinical studies with chronic stroke patients. The first study used the system on three participants with right hemiparesis.[65,67] In this initial study, the VR treatment was combined with another type of treatment for UE rehabilitation, constraint-induced (CI) therapy.[68,69] The participants ranged in age from 54 to 83 years, were 3–6 years post-stroke, and had a fairly high degree of motor recovery, as they met the criteria used for inclusion in CI studies (i.e., active wrist extension of 20° and 10° of active MP extension).

Participants were treated for 5 hr per day for 9 days, with one 2-day break. The majority of the time (approximately 3.5 hr/day) was spent in CI therapy, while the remainder was spent in VR therapy (approximately 1.5 hr/day). Because two different treatments were used in combination, it is not possible to determine whether, or to what extent, the VR therapy contributed to the changes found in the participant's post-training.

Participants' progress following this combined therapy was measured using quantitative measures of ROM, speed, fractionation, and work, derived from the VR training data (performance of first 2 days vs. last 2 days). In addition, a clinical test of hand function (Jebsen)[70] and dynamometer measures of grip strength were performed. Results for the measures derived from the VR training data showed a variable pattern, with all three participants showing improvement on at least some of the measures. The ROM changes were small (approximately 10° finger flexion; 20° thumb flexion). However, changes for fractionation and speed, seen in two of the three participants, were larger (25° for fractionation; speed increases of 16–69% for thumb and 21–52% for fingers). Mechanical work capacity improved by a small amount across participants (9–25%). For the clinical test, two participants improved (+11%, +29%), while the third participant got worse (−7%). All three participants increased their grip force (range, 13–59% increase). However, two participants showed similar rates of grip force increase on their non-involved side, so some of the change seen following training may have been due to the simple practice of the dynamometer grip rather than to specific effects of either the CI or VR training.

In the second study reported by Burdea and colleagues,[66,71] eight participants with stroke were treated using the VR system alone. Preliminary results from the first four of these participants are presented in the first report,[66] while results for all eight participants are presented in a more recent report.[71] Data from the second report is reviewed here. Participants ranged in age from 50 to 81 years, six were male; two female; seven had a right hemiparesis, and one had a left hemiparesis. Although initial clinical scores are not reported, all had a fairly high degree of motor recovery, as they met the minimum criteria of active wrist extension of 20° and active MP extension of 10°. Treatment sessions were 2 hr in length, conducted 4–5 times per week for 3 weeks (total = 13 sessions, or approximately 26 hr). The VR exercises were the same as those in the prior study (i.e., ROM, speed, fractionation, and strength). Each exercise was repeated 40–60 times, for a total of approximately 160–200 movement repetitions per session. As in the prior study, participants received feedback about performance both during and after every trial. Results were measured by assessing the percent improvement in performance in VR (first 2 days vs. last 2 days of training). In addition, participants performed a clinical test (Jebson test of hand function[70]) and a real world grasping task using the Cyberglove, to assess transfer to real world performance.

For the quantitative VR measures (ROM, speed, fractionation, and work), results are not averaged across participants; rather, they are presented for each participant individually, as "each participant showed improvement on a unique combination of movement parameters." The most impressive areas of change seem to be for thumb ROM (four of eight participants improved by >40%) and for fractionation where six of eight participants improved by >40%). The changes for speed and work are small and likely not clinically significant, though the authors report "statistical significance" based on results of unpaired *t*-tests, performed individually for each participant. For example, on the speed measure, only three of 16 cases (16 = 8 finger + 8 thumb measures) had >20% improvement, and only three of the eight participants had >20% change on the work measure. For the Jebson test of hand function, results were pooled across participants, and a 15% improvement was found. However, since these data were pooled across participants, it is not clear whether the 15% change reflects a large improvement by a few participants, or a smaller change by most participants.

For the grasping task, hand kinematic data were analyzed in terms of movement time, averaged across participants. No change in movement time was found for the transport phase, but an 18% decrease in movement time was found for the grasping phase, although three of the eight participants did not decrease their grasp movement time. Although the authors report that they performed a discriminant analysis on the hand kinematic data as a way to assess hand preshaping during the evolving movement, the results of this analysis are presented for only one participant's data in graphical form. For this participant, classification errors from the discriminant analysis are shown to decrease as the movement evolves, indicating an improvement in the timing of hand preshaping during the grasping task.

Groups in Sweden, United Kingdom, and Italy. A group in Sweden has described the use of another VR system, consisting of a Reachin Technologies AB 3.0 system with haptic force feedback provided by a PHANToM device and stereoscopic vision provided by CrystalEyes CE-2 glasses in a single case study of one stroke patient.[72] The participant was a 59-year-old man with left hemiparesis, 11 weeks post-stroke, with normal spatial competence and body awareness. He trained using a computer game developed by Reachin Technologies, in which the participant strikes a ball, which in turn knocks over bricks, and gives a score. He was treated three times per week for 4 weeks for a total of 12 sessions and progressed through four levels of difficulty (based on faster ball velocities), using a performance criterion. It was unclear whether he was also receiving additional therapy. The use of telemedicine was mentioned, but it was not clear whether the patient was using the VR system in the laboratory, with the telemedicine system employed as an adjunct to communicate response to the treatment from home, or whether the entire VR system was installed in the patient's home, and the treatment was conducted via a telemedicine set-up.

The patient was evaluated using three tests: (1) Purdue pegboard; (2) hand grip using a dynamometer; and (3) a laboratory-developed reaching test, using the PHANToM to record data. Following the training, he increased the number of pegs from six to eight on the Purdue test, increased grip strength from 68 to 264 N, and improved somewhat on selected kinematics measures derived from his reach trajectory data. For example, path length of the trajectories decreased (by 0–11 cm, depending on direction), movement time decreased (by approximately 0.5 sec), and movement velocity increased (by ~10 cm/sec for one direction).

A group at the University of Nottingham[73] explored the use of VR in stroke rehabilitation via a "user centered design approach" that involved consultation with stroke survivors, therapists and stroke researchers. Based on input from these groups, the activity of making a hot drink was selected for development and study. This group used a different approach for their VR system. They began by building a real ("tangible") interface for the task, consisting of a series of instrumented objects. To conduct training in the task of making a hot drink, the real objects and VR are integrated in a unique fashion. For example, the computer first instructs the patient verbally to place the kettle under the tap. Once the movement has been sensed from the instrumented real kettle, a signal is sent to the computer and the VR plays a simulation of the activity (e.g., participant hears water running and sees a kettle filling). Then the next subtask in the sequence is suggested verbally by the computer. If the patient performs the incorrect task, the computer corrects the participant and the user cannot proceed until the correct task is performed using the correct real world hardware. This procedure is repeated until the 16 subtasks for this activity have been completed.

Seven participants tried out this system in a pilot test. The participants were community dwelling stroke patients, all with right hemiparesis and aphasia. Six of the seven had "little to no use" of the involved arm. (Although not specifically mentioned, this would imply that participants were using their non-involved extremity to complete the task, making it more a cognitive training than a motor training tool for these particular participants.) Observations were made as participants used the system, and notes were taken on both participant and system performance. Through this process, problems were identified and potential solutions were discussed. The two main points, which are planned for implementation in future models of the system, were to let the user imitate the virtual task, and to provide feedback about performance using the VR system in order to enhance learning of the task. (Note that the system developed by Holden and colleagues[14,15,55] already does this.) While this device appears to be a good training system, its effectiveness has yet to be tested. It also seems labor intensive in terms of its development (especially if additional tasks were to be trained), and it is not clear whether training on this one task would generalize to other real world tasks.

Others have described the usefulness of VR systems in the assessment of arm motor deficits following stroke or brain injury.[74] Piron et al. describe how a VR system was used to provide a more sensitive, precise and objective measure of progress in rehabilitation settings. Twenty patients with chronic stroke (mean, 8.2 months post-stroke) were treated with "standard" rehabilitation therapy for 1 hr per day, 5 days per week (20 sessions total). Before and after the therapy, patients were tested with the FM Test of Motor Recovery[59] and two kinematic measures (movement duration and average velocity), which were derived from 20 repetitions of a reaching movement, performed in a virtual environment. The changes in the kinematic measures following therapy were statistically significant (average movement duration was 4.4 sec prior to and 3.5 sec following treatment; average velocity changed from 19.6 cm/sec before therapy to 26.3 cm/sec after therapy). In addition, the kinematic measures were found to correlate significantly with the FM test[59] (Pearson correlation = -0.82 to -0.97 for duration, and 0.82 to 0.97 for velocities, all at $p < 0.01$). The VR test was thought to be useful for evaluating the results of rehabilitation treatments, as it was faster and easier to perform than the FM test.

Several of the research groups whose work is described above are also developing telerehabilitation applications of their VR systems.

Lower extremity/gait

Burdea and colleagues have also developed a VR haptic device for use in training ankle control, the "Rutgers Ankle."[75–77] The details of the engineering design are well described in these articles, so only a brief description is provided here. The system consists of a Stewart platform-type haptic interface that provides 6 DOF resistive force to the patient's foot, in response to his or her performance in a game-like VR exercise. The patient is treated in the sitting position, with the foot attached via a footplate to the device. Two exercise games have been developed. In the first, the patient pilots a virtual airplane, by using the foot, through a virtual sky. As the plane moves forward, a series of open square hoops are presented on the screen. The goal is for the participant to maneuver the plane through the hoops without hitting the sides. This is done by mapping the ankle kinematics to the flight path (e.g., ankle dorsiflexion causes the nose of the plane to point upward, eversion causes the plane to go toward the left). Difficulty level can be adjusted by changing the number and placement of hoops, airplane speed, and the amount of resistance provided by the haptic interface. A second game calls for the participant to pilot a virtual speedboat over the ocean while avoiding buoys, again by moving the ankle up/down or in/out. A recent addition to these games is the ability to apply task-related haptic effects such as a "jolt" when a buoy or hoop is hit, or to change the environmental conditions by adding turbulence to the air or water (implemented by generating a low-frequency side-to-side vibration of the platform[75]).

To date, the system has been used in two pilot studies with stroke patients, the first a single case report[77] and the second involving three patients.[75,76] In the first study, a 70-year-old patient with left hemiparesis, 11 months post-stroke, was treated. Concurrent with the experiment, the patient was also receiving outpatient physical therapy twice a week. That therapy was focused on improving the use of the affected hand, strength and coordination of affected leg, and on balance and coordination training in standing. Thus, it is difficult to know which treatments may have contributed to the changes noted after the VR treatment. The patient received six sessions of VR training, with testing and training in sessions 1 and 6. The amount of time spent working in the VR exercise ranged from 13 to 26 min over the sessions. The patient practiced ankle movements by interacting with the airplane scenario, guiding the plane through the hoops, at increasing levels of difficulty, as described earlier. Following training, the participant had gained 10 degrees of plantarflexion ROM, increased torque production for ankle inversion and eversion (by 3 Nm), and ankle power from 200 W in session 1 to 550 W in session 6. The largest changes were seen for accuracy, as measured by the number of hoops entered (whether on not sides were hit); this increased from 32% in session 1 to 95% in session 6 for the dorsiflexion/plantarflexion movement. Clinically, a large decrease was seen in time required to climb four stairs, which was 90 sec in session 1 and 20 sec in session 6.

In the second study,[75,76] three patients with stroke, mean age 52 years, 1–8 years post-stroke, were treated three times per week for 4 weeks, for 1-h sessions (total = 12 sessions, with total exercise time ranging from 20 to 50 min per session). It is not mentioned whether these patients were receiving any additional concomitant therapy. The patients demonstrated increased power, as measured by the system, as well as increased muscle strength, as measured by a hand-held dynamometer (range of increase across the four muscle groups, 0.5–13 N). Although increases in gait speed are reported, the only value presented is for one participant, who increased his score on the 6 min walk test by 9%. The changes in strength seen for selected muscles for some participants were large, especially considering the relatively small amount of time spent in treatment. The Rutgers Ankle system has also been pilot tested with orthopedic patients.

These authors are currently developing a substantial enhancement to this system, which will allow training in standing and also virtual walking.[78,79] The new system will add a locomotor haptic interface to two linked Stewart platforms (one for each foot). It will be able to withstand higher loads and apply 6 DOF force and torque to the feet, thus simulating different surface support conditions (such as ice, gravel, normal sidewalk). VR simulations for use with the device are being developed, one for crossing a street, and another for walking on a park path.

Another group of researchers, located at the Palo Alto Veterans Administration, have recently described the use of VR technology to train obstacle avoidance during walking in chronic post-stroke patients,[51] and reported an advantage for the VR method. In this study, 20 participants with hemiparesis (10 right, 10 left, mean age, 60.7 years; mean time post-stroke 3.8 years) were randomly assigned to receive training in obstacle avoidance during walking via either a real world scenario or a virtual world scenario. Both groups received six sessions of 1 hr in duration, given over a 2-week period (6 hr of total training). Each session consisted of 12 walking trials. During each trial, a series of 10 objects had to be "stepped over." Participants in the real world scenario practiced stepping over (real) foam objects placed along their walking path at distances approximating their stride length. Participants began with small (2″ × 2″) objects and progressed to larger objects based on their performance. Participants in the virtual training scenario walked on a treadmill at a self-selected comfortable velocity and viewed virtual obstacles through a head-mounted display (HMD). The virtual objects were superimposed on a real time lateral video view of their foot and leg as they attempted to clear the object. The software was programmed with collision detection, and if the foot "touched" the virtual object, a tone was heard, and a vibrotactile signal was applied to the participant's toe or heel, to provide enhanced feedback as to the location of the error. In addition, the participant could see their foot on the video. Although the view was rotated 90º from the normal walking viewpoint, there were no reports of ill effects or confusion on the part of participants (perhaps because it was an HMD, and no conflicting visual input from a different perspective could be seen). There were also no complaints of cybersickness from any of the participants. Virtual training participants practiced with 10 steps over virtual objects per trial, as in the real world condition. Participants were allowed to hold on to the side rails of the treadmill, and as an additional precaution, wore an overhead safety harness to protect against possible falls.

Although both groups improved on most of the outcome measures used, participants in the VR training showed greater improvement ($p < 0.001$) in fast paced velocity post-training. There also seemed to be an advantage for the VR group in improvements in obstacle clearance and step length of the non-paretic side, but these differences were not statistically significant. A 2-week follow-up test showed that participants in both groups had retained the improvements they had made, with some measures showing continued improvement. Given the relative brevity of the training and low number of repetitions, and the duration post-stroke of the participants, these results are impressive, and lay the groundwork for further work in this area.

Spatial and perceptual-motor training in stroke

Connor et al.[80] have experimented with the use of an active force-feedback (AFF) joystick to train a perceptual motor skill in the *un*involved UE of 12 stroke patients. These authors wished to test whether errorless learning (EL), a method proven to be effective in teaching new information to participants with memory problems,[81,82] could prove useful in re-training perceptual motor deficits. Error*ful* (EF) learning (movement practice, allowing errors, and standard knowledge of results feedback) was used as a control training method. Twelve community dwelling stroke patients were recruited, all >1 year post stroke, age 38–83 years. All had some form of visuospatial processing deficit, ranging from minor to profound. A within-participant, cross-over design, randomized to sequence was used. Group 1 received EF first; Group 2 received EL first. Participants were treated once a week for 4 weeks for each method, with a 3-week washout period in between. During training, participants sat at a computer and used an AFF joystick with their *un*involved hand. A series of letters or numbers were randomly dispersed on the computer screen, together with a variable number of distracter objects. The participant's task was to connect the sequential items by moving a cursor on the screen using the joystick, then pressing the button on the joystick when they felt the cursor was in the correct location. In the EL condition, a "force field valley" was defined which prevented movements to incorrect targets on the screen, but allowed correct movement. Thus, when participants moved, no "errors" were made. In the EF conditions, no forces were applied, so participants could make errors, which they saw visually on the screen.

Participants were tested weekly, before, during and after training. Five sets of different target combinations were used. Data were analyzed for response time and for maximal deviation from a straight trajectory for each target link. The results showed no difference for EL versus EF. Overall, five of 12 participants improved on response time; only one improved in the trajectory error measure. Group 1 (EF first) did better than Group 2 (EL first) in that four participants versus one participant increased response speed. However, these differences may also have been due to differences in participant impairment levels. Although these results are not dramatic, they do indicate the feasibility of the treatment approach. The authors speculate that better participant selection, more frequent and more individualized treatment might improve the results in the future with this method.

In another study, Rose et al. evaluated the effects of a VR exposure on spatial memory and object recognition memory.[83] Forty-eight patients with brain injury of vascular etiology (stroke), with equal numbers of young and old, left and right hemisphere involvement, participated. Mean age was 61 ± 17 years. Forty-eight unimpaired control participants, mean age 36 ± 11 years. were also included. Patients and control participants were randomly assigned to an active or passive VR group. A virtual bungalow, consisting of four interconnected rooms, was created and displayed on a desktop computer. The virtual rooms could be navigated using a joystick. In addition, a total of 20 objects were embedded in various locations throughout the four rooms. Participants in the active group were told to enter the house and use the joystick to find a route through the rooms. At the same time, they were instructed to study the various objects and to try to find a toy car. Participants in the passive group watched a recording of the last active participant's path through the house (this was a clever control for exposure time), but received the same instructions regarding the embedded objects. All participants received only one trial of the task. Following this single VR exposure, participants completed two tests: (1) a spatial recognition test, in which they guided reconstruction of the bungalow by the experimenter, using real 2-D cardboard elements; and (2) an object recognition test, in which participants were randomly presented with photographs of the 20 test objects that had been in the bungalow, and 20 ruse objects, and had to report whether they recognized the objects as having been in the virtual house. Since the idea was to test incidental memory, no instructions were given in advance as to what would be tested following the VR exposure.

The results showed that for the spatial reconstruction test, active VR use improved the performance as compared to passive VR use, for both patients and controls. Considering that participants received only a single exposure to the VR bungalow, these results are quite impressive. They suggest that one way to enhance spatial learning/memory in patients with stroke may be to use motoric encoding to tap into spared procedural memory. VR can provide a convenient way to do this. For the object recognition task, however, active/passive VR made no difference to patients' scores, whereas for the control participants, performance was better following the passive VR condition. This finding was interpreted for control participants as having been due to having more time available during the passive exploration condition to view objects in the virtual house (e.g., less attention to actual control of the joystick). The fact that a similar effect did not occur in the stroke participants was attributed to their memory deficit (relative to controls) and to having had no enforced procedural component in the active exploration VR condition (such as touching each object) that might have facilitated procedural learning.

Children with severe motor disabilities often have poorly developed spatial awareness.[84] One significant contributing factor to this deficit is thought to be the reduced ability to explore the environment in an active way secondary to the mobility impairment. VR technology has been proposed as a way to offer such children a chance for active, independent spatial exploration. Wilson et al.[85] have tested whether such training in VR would result in improved spatial knowledge in a comparable real world setting. The authors used a desktop VR system to train large-scale spatial knowledge of a two-story building. Participants (n = 10) were children with a variety of disabling conditions, including spina bifida, cerebral palsy, and muscular dystrophy. All relied on a wheelchair as their prime method of mobility, though three participants could walk short distances with a walker. They ranged in age from 7 to 11 years. A control group of eight healthy adults, mean age of 23 years, received no VR training, but underwent the same testing as the children. Children received one training session. They explored a virtual model of the actual building in which the experiment was conducted, with the goal of finding the fire extinguishers and the fire exit door. Immediately following VR training, they were tested on knowledge of the fire extinguishers and fire door locations in the real building in two ways. First, while still in the training room with the computer, participants used a pointer to aim at the expected location. This was followed by a wheelchair tour of the real building, during which participants were asked to guide the experimenter to two specific locations. Results showed that all the participants were able to point to and find the desired locations in the real world, and to do so significantly better than control participants who received no training.

Broeren et al. in Sweden have used a VR system to measure neglect in patients following stroke.[86] The system utilized a Reachin 3.0 system, stereo vision with Crystal Eyes, and a PHANToM to provide haptic feedback. In this paper, they describe the development of a VR test to measure neglect, and compare the results with those from standard clinical measures of neglect. Four patients with stroke, mean age 51.5 years, 7–36 weeks post-stroke were evaluated. All were right handed, with left hemiparesis, and had shown evidence of neglect at 2–5 weeks post-stroke. A reference group of nine healthy participants, mean age 53 years, was also tested. Participants completed two clinical tests of neglect, the Star Cancellation test,[87] and the Baking Tray Test,[88] and the VR test developed by the authors.

The authors found a reasonable correspondence between the tests, and they found that the new VR test was at least as sensitive as the clinical tests in detecting neglect. In addition, the VR test was able to measure additional variables that might enhance its sensitivity relative to the clinical tests. For example, target detection time, and search strategy patterns showed abnormalities in Participant 1, who had scored within the normal range on the standard clinical tests.

Another group is working on improving wheelchair mobility in patients with stroke who have unilateral neglect.[50] This study is discussed in the Wheelchair Mobility and Functional ADL Training section.

ACQUIRED BRAIN INJURY: MOTOR TRAINING

Most rehabilitation efforts using VR with this population have involved cognitive rehabilitation, a topic reviewed elsewhere in this issue (Brooks et al., this issue). There have been few attempts to work with motor retraining in the acquired brain injury (ABI) population using virtual environments. One group that has done so is Holden and colleagues.[89,90] In this study, eight patients with ABI (seven male, one female; mean age 27.3 ± 8.8 years, mean duration post-injury 9.5 ± 7.0 years) were trained in the functional task of pouring from a cup, within a virtual environment. The VR system used was the same one described previously for use with stroke patients, but the scenes used were different. Participants had primarily a hemiparetic deficit (five right, three left) and received training on the involved arm. All participants received a block of 16 one-hour treatment sessions, at a frequency of three times per week. Four of the eight participants received a second block of 16 VR sessions, making a total of 32 sessions. Prior to and following each treatment block, participants received an evaluation battery of tests. The battery was administered twice, at a 2-week interval. Four measures of UE motor performance were included: (1) the FM Test of Motor Recovery;[59] (2) the Wolf Motor Test;[63,64] (3) strength tests for shoulder flexion and grip; and (4) a behavioral kinematic test of pouring skill. This last test consisted of measuring the 3D kinematics of trunk and arm movements during a pouring task performed in the real world. During testing, participants held a cup filled with oatmeal, then at the start signal, lifted the cup and poured the contents into a second cup, located on a table in front of them. Six target locations were used; only one or two of these locations were trained during the VR sessions. The end-point trajectories (path of the cup) were analyzed to assess progress.

Following VR training, both the Wolf Motor Test and the FM Total UE scores improved ($p = 0.010$, $p = 0.034$, respectively), and the FM Motor subscore showed a trend toward improvement ($p = 0.068$). Strength did not change significantly. These results indicate a significant amount of generalization of the motor training received in VR to functional ADL tasks. The term "generalization" is used here because these clinical tests consist primarily of tasks that were not specifically trained in VR during the experiment. Analysis of the pour trajectory data indicated that the time spent to accomplish the pouring task and the size of the spatial volume encompassed by the cup path during pouring (an indication of stability of the hand during pouring and the precision of the pouring movement) decreased for most participants following training. Quantitative measures derived from the pouring trajectories, averaged across participants, suggested some reductions in length of hand path, trunk movements, response times and number of velocity peaks following training. However, for the most part, these changes did not reach statistical significance. When data for individual participants were evaluated, it was found that some participants improved more on the transport phase of the movement, while others improved more on the precision of the pouring movement. Thus, when data from these two types of participants were averaged together, these positive effects cancelled each other out, and mean improvements appeared low.

The study served to demonstrate that even participants with significant motor and cognitive impairment are capable of at least some learning within a virtual environment, and that it is feasible to use VR to teach functional tasks, such as pouring from a cup, which would be inconvenient or messy in the real world.

A group from Sweden has reported early results from a project designed to evaluate the potential usefulness of VR in brain injury rehabilitation.[91] In this paper, the authors describe the broad spectrum of tasks that need to be re-learned by patients following brain injury. Such tasks require learning on a variety of levels, from physical to cognitive. Three broad categories of tasks which present challenges for participants with brain injury were identified: preparing food, managing finances, and finding one's way from one place to another. Specific VR applications were developed to train tasks from each of these categories. The tasks selected were (1) kitchen-based training (making coffee, setting a table); (2) using vending machines, specifically an automated teller machine (ATM); and (3) wayfinding, specifically using two prototype virtual environments representing the local hospital and university buildings. Although no clinical data or training data are reported, the article does present useful and relevant information about the development of such a system for this population.

Researchers from Texas have begun to evaluate the use of VR as a diagnostic tool for ADL skills following ABIs.[92] They have developed a virtual kitchen environment and a test task, that of making soup and a sandwich, to serve as an evaluation tool. This meal preparation task was broken down into 81 subtasks; each subtask received a rating with the sum of ratings as the total score. This test tool has been evaluated for reliability and validity. To assess these attributes of the test, 54 participants with ABI were evaluated. Participants ranged in age from 18 to 69 years, with the majority of participants (63%) between 18 and 35 years old. Forty-six had been in a coma following injury, with a mean duration in coma of 11 days. All had total Functional Independence Measure (FIM) scores of >60 and FIM cognitive domain sub-scores of >20. Each participant performed the virtual kitchen test on two occasions within a 3-week period. They also performed an actual kitchen test, similar to the virtual test, on two occasions. In addition, they received a single occupational therapy (OT) evaluation for meal preparation and for cognitive skills, and up to 12 different neuropsychological tests.

An intraclass correlation coefficient (ICC) test was used to evaluate test-retest reliability and revealed an r value of 0.76, indicating good reliability. A Pearson test was used to assess validity, revealing an r value of 0.63 for the virtual kitchen test with the actual kitchen test ($p < 0.01$). Significant correlations were also found for the virtual kitchen performance with eight other tested variables (range of r values 0.30–0.56, $p < 0.05$). A regression model was constructed, using the tested variables, to assess which tests were the strongest predictors of actual kitchen performance. Although the model was statistically significant, the R^2 was not overwhelming ($R^2 = 0.34$). Two variables in the model had significant beta weights: the virtual kitchen performance ($\beta = 0.35$, $p = 0.014$) and OT meal preparation score ($\beta = 0.45$, $p = 0.007$).

VR USE IN PARKINSON'S DISEASE

One of the primary symptoms of Parkinson's disease (PD) is akinesia, or difficulty in the initiation and continuance of motions, in particular during ambulation. These symptoms tend to worsen as the disease progresses. Although the symptoms can be mitigated by drugs such as L-dopa, over time these drugs can become less effective and may produce unwanted side effects, such as correaform and athetotic movements. Thus, an alternative method to treat akinetic gait in PD could offer patients a way to delay or reduce drug use while still maintaining or improving function

Such a method is being developed and tested by a group of researchers led by Weghorst and Riess. The method is based on an interesting phenomenon associated with patients with PD termed "kinesia paradoxa." Patients with PD, who are unable to ambulate, or even initiate a step on open ground are, paradoxically, able to step over objects placed in their path with little difficulty. Weghorst and colleagues have conducted a number of studies to ascertain whether VR technology could provide a way to take advantage of this phenomenon and facilitate walking in PD patients by presenting virtual objects overlaid on the natural world.

In the first study, investigators attempted to determine which aspects of the stimuli accounted for the "kinesia paradoxa" effect.[93] For example, could non-tangible objects elicit it? If a virtual environment was used to provide the cue, how would factors such as eye dominance, field of view, location within field of view, and image realism affect the response? Testing was done with both a simple laser pointer and with a Virtual Vision Sport, a display device with a visor and small lens mounted in front of one eye reflecting a liquid crystal display (LCD). The authors found that spatial stabilization of the cue was a critical factor in its effectiveness. The cue had to appear stable in the external world (i.e., a virtual cue had to move relative to the participant). The realistic nature of the cue was found not to be important; robust effects were obtained with both the laser pointer and small yellow squares in the VR display. The vertical field of view was found to be important, as both a cue near the body, and two or three cues, corresponding to 2–3 paces ahead, were needed. The cue near the body was associated with gait initiation, but the far cues were required to continue gait. The laser pointer proved to be inconvenient, as it had to be moved, and turned on and off, to facilitate the gait. As well, in outside light, the laser pointer was not visible.

Two patients with PD were evaluated with the VR technique. The first participant had a dramatic increase in stride length, from 3 to 26 in. This participant also learned, after 2 h of practice using the laser pointer as a cue, to initiate and sustain gait without a cue. This effect was maintained (though fragile) for 2–3 months. The second participant had a smaller increase in stride length (8%), and was unable to learn to initiate and continue gait in the absence of cues.

In later articles, the system features are described in more detail.[94–97] One report mentions that the prototype system was found to work with "more than 20 patients in early testing," but specific results, such as standard gait measures, are not reported.[96] The authors refer to the use of "augmented VR" in the system, by which they mean technology that combines the real world view with the virtual environment view. Initially, see-through head-up information displays that fuse the natural scene with physically registered graphical overlays were used in combination with a head position tracker to achieve a "space-stabilized" image. However, these displays were not bright enough to compete with ambient light. The solution was to partially occlude the visual field, using a field-multiplexed display, which projects an image near optical infinity superimposed on the real- world image. A portion of one visual field is occupied by an occlusive and collimated reflection of a small LCD panel mounted in the brow piece. Continuous virtual objects (bars) scroll downward in the participant's visual field, giving the illusion of objects that are stable relative to the ground. This induces participants with PD to "step" over them. The lower part of the field of view has been found to control the gait initiation response, while the upper part of the field of view is linked with sustaining the gait. Another key factor in success of the technique was found to be the movement speed of the virtual cues, which must be linked to the user's gait speed, so that virtual cues are spaced at apparent stride length.

With further testing, the investigators have also found that the greater the impairment of the participant, the more realistic the virtual cues need to be. However, the realism required is not photorealism, but "interactive" realism (i.e., the run-time modifications of cue spacing to adjust to different walking speeds and stride lengths, as well as perspective changes with head tilt). Further work is now being done to investigate the relative importance of a variety of factors on the effectiveness of the visual cues ability to elicit the "kinesia paradoxical" effect.[95,97]

Riess is currently working on the development of a sunglasses-like commercial device to deliver these visual stimuli to PD patients. He has also reported that similar visual cues can have a profound calming effect on the dyskinesia induced by long term use of L-dopa.[95]

A group in Italy has reported on the potential usefulness of VR as a way to evaluate deficits in ADL in participants with PD.[98] In this paper, they report preliminary findings on two participants with PD who navigated in a virtual flat using a joystick and were then tested on three performance measures: (1) a speed test ("walking" from living room to bathroom; (2) a pointing task (object identification); and (3) an incidental memory task (object recall). Ten normal participants were also tested. The participants with PD also received a battery of six standard neuropsychological tests, the results of which were in the normal range. The results for the VR tests, however, suggested some differences from those of the normal participants, especially for the speed test and, to a lesser extent, the incidental memory test.

WHEELCHAIR MOBILITY AND FUNCTIONAL ADL TRAINING

A computer-assisted training (CAT) program for the treatment of unilateral neglect has been developed by Webster et al.[50] In a recent study, they examined whether use of the CAT system in combination with a wheelchair simulator device would be effective in improving real world performance on a wheelchair obstacle course in a group of patients with stroke and unilateral neglect syndrome. In addition, they examined whether this training influenced the number of falls experienced by participants during their inpatient hospital stay.[50] Forty patients (38 men, two women) with right hemisphere stroke participated. All were right handed and showed evidence of unilateral neglect, defined as specific scores on two standard tests of neglect, the Random Letter Cancellation Test[99] and the Rey-Osterrieth Complex Figure test.[100]

Twenty of the patients received the CAT treatment for neglect. The remaining 20 patients, who had participated in a prior study of unilateral neglect, served as controls. Both groups received a standard inpatient rehabilitation program, including real world wheelchair training to improve mobility and obstacle avoidance skills. Participants in the VR experimental group also received 12–20 sessions of CAT. Sessions were 45 min in length, delivered five times per week during the inpatient rehabilitation stay. The control participants did not receive additional training of any kind beyond the standard rehabilitation care (thus, as measured by time, the amount of therapy was unequal between the two groups). Extensive testing was performed on participants. All participants received the previously mentioned neglect tests as part of screening procedure. Participants in the VR-CAT group were tested on two virtual tests, a video tracking test and a video obstacle course test, before and after the CAT training to assess their virtual world learning. The main outcome measures, assessed for both groups, were the number of falls during participants' inpatient stay (obtained from a review of incident reports), and scores on a wheelchair obstacle course test performed in the real world.

The training method employed by the investigators is very well thought out, logically progressed, and highly relevant to the deficits one sees in such patients. Their method is fully described in their article, but will be briefly summarized here. Patients view a virtual wheelchair on a large, wall size LCD screen. They navigate the chair using either a hand controller or wheelchair simulator, through various scenes that involve turns and obstacle avoidance. Five modules were developed that began with simple task components, and then progressed to more complex task control based on participant's performance. The five modules were (1) scanning the full frontal environment; (2) coordinating scanning with right UE movements; (3) detection of stimuli in left hemi-space; (4) wheelchair simulation; and (5) additional training on obstacle avoidance. Extensive software features of many types were used to provide feedback about performance and guide correct movement.

The results showed that the patients who had received the VR-CAT training made fewer errors, and hit significantly fewer ($p < 0.000$) obstacles with the left side of their wheelchair during the real world wheelchair obstacle course test than did participants in the control group, who had not received this training (1.3 vs. 5.1 collisions, respectively). In addition, participants in the VR-trained group sustained significantly fewer falls ($p < 0.02$) than those in the control group (two of 19 patients in CAT group; eight of 19 in the control group). Results for the virtual performance tests, conducted on participants in the CAT group, showed that performance had improved post-training for both the video tracking and VR wheelchair obstacle test, indicating that learning in the virtual world had occurred.

Although this study has some flaws (participants were not randomized to the treatments; experimental and control participants received differing amounts of total therapy time), the results are still impressive. It is one of the few studies in the VR literature in the rehabilitation field with reasonable numbers of participants and at least an attempt to provide a control group. The findings are important, not only because they seem to indicate that symptoms of neglect can be remedied by virtual world training, but also because they show significant generalization from virtual world practice to real world performance, that is, fewer collisions during actual wheelchair use, and fewer falls during everyday activities.

Another group has been working on the development of different interface options for driving electric wheelchairs and on VR applications that can be used to train patients in how to drive electric wheelchairs.[101] This work addresses an important problem, as one study estimates that 40% of people who need electric wheelchairs cannot presently use them because they are unable to control them sufficiently using currently available controls.[102] The authors first developed an isometric joystick as an alternative to the standard position sensing joystick. Then, both devices were interfaced with a VR wheelchair mobility training module. Ten participants with disabilities (predominantly spinal cord injury) were tested; all were experienced electric wheelchair users (mean 10 years experience). Participants were tested in both VR based tasks and real world tasks which involved wheelchair mobility control using both interface devices. The results indicated no differences for the type of joystick interface in either time or RMS error (i.e., error indicating deviation from a straight path), for all tasks combined, and few differences when individual tasks were evaluated. A significant correlation was found for performance in VR versus real world tasks, as measured by RMS error (r^2 = 0.81 for position joystick, p = 0.008; r^2 = 0.72 for isometric joystick, p = 0.02). This finding indicates VR could serve as a good training tool for electric wheelchair control, as performance in the two environments was fairly comparable.

A third group, from Singapore, has developed a more generic VR system that can be used to train a variety of ADL skills.[103] The system contains an authoring tool than can be utilized to construct a variety of training scenarios. A virtual hand is displayed within the virtual scene and is able to interact with 3-D objects placed in the scene. In this article, they describe two specific scenes that they have developed, a pick and place task, designed to improve spatial skills, and a virtual kitchen, which can be utilized to practice tasks such as making a cup of coffee, using a stove, or making a microwave meal. However, no patient data have been collected or analyzed as yet with this system.

Researchers in Canada have developed and tested a VR program designed to teach safe street-crossing ability to children.[104,105] Although the system was tested on normal children, it is reported here as it would appear to be a useful tool for retraining adults with acquired brain injury or stroke in similar skills. A virtual environment was first developed that consisted of a virtual city, moving vehicles, people, and different intersections. Then, modules were designed to teach various key skills, such as stopping at the curb, looking left-right-left before crossing, and so on. Following development, 95 children were randomly assigned to receive either the VR street crossing training (three trials), or a control treatment, which consisted of practice on an unrelated VR program. Children were evaluated in the real world by observers who rated actual street crossing behavior of the children, 1 week before and 1 week after the intervention.

Performance in the virtual environment was also tested. While all children improved their performance in the virtual environment, only children from a suburban school showed improved performance in actual street crossing; urban school children did not make the transfer from virtual to real performance. The authors speculate that, with further training, transfer may have been achieved.

BALANCE TRAINING

A group from Israel has been working on balance training and related skills in participants with a variety of neurological disabilities, using a laboratory-adapted version of VividGroup's Gesture Xtreme projected VR scenarios.[106] In this article, they describe the development of the adaptations they employed for training, and pilot results for patients who have used the system thus far. The participants included patients with stroke (n = 3), spinal cord injury (n = 4), and cerebral palsy with mental retardation. Although specific treatment details (e.g., number of sessions, length of treatment) and performance data are not provided in this preliminary report, the authors do say that all patients responded positively to the treatment, felt a sense of presence, made more effort during the VR training than during standard training, and made gains in their mobility.

Another preliminary report on the use of VR in balance training has been provided by Whitney et al.[107] The authors describe a VR system they have developed for use in balance training of participants with vestibular disorders, which they term the "Balance Near Automatic Virtual Environment" (BNAVE). Persons with peripheral vestibular disorders frequently suffer from disequilibrium during standing and walking, and visual blurring during head movements. They are often treated in vestibular rehabilitation programs by exposure to situations that stimulate their symptoms in order to promote habituation. Typically, patients are taken through a graded type exposure that progressively adds situations and positions that provoke and increase their symptoms (e.g., dizziness, motion sickness, loss of balance). Such training is an ideal type of therapy to deliver via VR, as large immersive visual fields can be created and changed easily to suit patients needs, and stimuli applied to patients can be carefully controlled and measured.

The BNAVE system developed by Whitney et al. is a spatially immersive, stereoscopic, projection-based VR system that encompasses a participant's entire horizontal field of view, and most of the vertical field of view, when looking forward (view angle, 200º horizontal, 95º vertical). The validity of the system's immersion was tested in a pilot study using five participants. Two participants had peripheral vestibular disorders (more than 1 year post-onset and well compensated), and three were healthy normal participants. Each participant was exposed to three conditions, while standing on a force platform in the center of the virtual "room": (1) normal room lighting, nothing on VR screens; (2) infinite tunnel with checkerboard pattern moving at a sinusoidal velocity; and (3) infinite tunnel with a constant velocity profile (pulsed). The anterior-posterior movement of the participant's center of foot pressure and head movement were measured. Both normal and vestibular-impaired participants responded to the visual stimuli provided by the BNAVE system with substantial increases in head movements (range, 100–300% increase) and body sway movements (3.3 vs. 9.2 cm) in synchrony with the visual motion. The results confirmed the robust effect of the visual stimuli provided by the system on postural responses.

Keshner and Kenyon[108] have used an immersive virtual environment, produced by a CAVE™ system, a multi-person, room-sized, high-resolution, 3-D video and audio environment [8,109] to study the organization of dynamic postural responses in normal participants. In this study, normal participants were exposed to constant velocity motion or sinusoidal motion of the visual scene in either a 3-D stereoscopic scene (Experiment 1, $n = 3$) or a random dot pattern (Experiment 2, $n = 3$) while attempting to maintain static posture or walk a short distance (Experiment 3, $n = 4$). Their results support the idea that postural controllers in the nervous system may set limits of motion at each body segment rather than be governed solely by the perception of visual vertical. For example, with pitch plane stimulation, the upper body appeared to respond to visual-vestibular signals with changes at the hip; in contrast, ankle movements appeared more linked to segmental proprioceptive inputs and inputs from ground reaction forces. Although this work is more theoretical in nature, it is mentioned here as presumably it may lead in the future to new therapeutic intervention methods for participants with postural instability.

ORTHOPEDIC REHABILITATION

The Rutgers Ankle system described earlier has also been pilot tested on patients with orthopedic disorders.[110–112] In the first of these papers,[110] the system is described in detail, and results from a proof-of-concept trial are reported. Four patients with ankle problems participated, two with hypermobility and two with hypomobility. Each participant was seen once, experienced the system, and had their ankle ROM and torque evaluated.

Patient reactions to the system were evaluated through use of a questionnaire. Patient reactions were positive and the device was able to discriminate a difference between the involved and uninvolved ankle torque and ROM in the two participants for whom both ankles were tested. In the second paper,[111] the system is described further, and six patients with orthopedic disorders were tested in order to evaluate the system's capabilities and its potential use as an evaluation tool. However, data for only one patient is presented; these data demonstrated a difference in torque values between the involved and uninvolved sides.

In the third paper, a pilot study conducted on three patients with ankle injuries is described. Case 1 was a 14-year-old patient, 2 weeks after Grade 1 ankle sprain. Case 2 was a 15-year-old patient, 5 months after Grade 2 ankle sprain. Case 3 was a 56-year-old patient, 2 months after bimalleolar fracture. Patients received five treatment sessions over a 2-week period, sessions were 30 min, delivered two to three times per week. A sixth session was used for the post test. The treatment consisted of piloting a virtual airplane through hoops, at progressive levels of difficulty, as described earlier for the stroke patients. Cases 1 and 3 were also receiving concomitant physical therapy for their ankle problem. Case 2 received only the VR therapy. Each case is discussed separately, and different measures are presented for each participant. The authors report that all three participants improved. However, only for participant 2 could these changes be attributed to the VR treatment, as the other participants were receiving additional therapy at the same time. The most consistent improvement across the three participants was in task accuracy, defined as the number of hoops entered versus missed. All were able to reach 100% accuracy, from a start point of 40%, 65%, and 25%, respectively, for cases 1, 2, and 3. Improvements of varying amounts in ankle ROM and torque production, one leg stance time, stair descent time, and speed of target hoop acquisition were also noted in one or more participants.

TELEREHABILITATION

Rosen,[113] in his extensive review of the newly developing field of telerehabilitation, identified access to and quality of care as key factors in the rationale for the developments in this field. The unfortunate reality is that many patients who have completed their acute in-patient rehabilitation following a stroke or other injury may have limited access to out-patient rehabilitation upon their return home to rural communities. Even many patients in urban settings have poor access to transportation, or may find travel to a clinic too tiring because of the added effort imposed by their disability. Such patients could benefit from telerehabilitation services, in particular those aimed at the provision of direct therapeutic services over the internet.

Several groups have been working to develop such telerehabilitation applications for VR technologies in rehabilitation. Some have focused on truly home-based systems[58,114–117] while others are working to develop clinic to clinic connections.[118,119] Holden and colleagues have recently expanded the functionality of their original VR system[14,15,54,55] to include telerehabilitation capability. Their telerehabilitation system can provide real-time interactive treatment sessions in the patient's home with a therapist who is located remotely at a clinic.[58,114,120,121] Both the patient and therapist see a simultaneous display of the VR program on one monitor and can communicate via video-conferencing on a second monitor. The system can be used to train a wide variety of arm movements in any part of the UE workspace.

Initial results from an ongoing study designed to develop and test the clinical feasibility of the system on patients with stroke, have demonstrated clinically meaningful improvements (range, 17–67% p = 0.003–0.05) on a variety of outcome measures. Following 30 1-hr VR sessions, delivered in the home via the internet, patients with stroke showed statistically significant improvements on the FM test of Motor Recovery, Wolf Motor Test of UE Function, Strength tests for shoulder and hand grip,[114,121] and kinematic measures of arm movement trajectories recorded during real world functional movement tasks.[58,121] Piron et al.,[116] working in Italy, have also reported success with home-based telerehabilitation, finding a significant improvement in the mean values for clinical and VR trajectory measures of the first five participants tested, following four weeks of daily therapy via telerehabilitation. (The VR software used by this group was developed at MIT by Holden and colleagues.)

Burdea and colleagues have developed a VR-based telerehabilitation system that focuses on hand rehabilitation using force feedback, and tested the system on orthopedic patients.[118,119] Reinkensmeyer and co-workers[117] have developed a web-based telerehabilitation system that the patient can access independently, and with which he or she can practice simple movements using an adapted computer joystick with force feedback. These systems appear to be designed mainly for independent work by the patient, with the networking component being used to send data to the therapist for later evaluation. Although a video-conferencing link was included in one of these systems,[119] it was too slow to support real time interactive therapy. Thus, as presently configured, only highly constrained movements in a very small workspace can be practiced using these systems. Both of these telerehabilitation systems have proven feasible in pilot testing on a single patient. In contrast to results reported by Holden et al.[114] and Piron et al.,[116] neither of the patients tested by Popescu et al.[119] or Reinkensmeyer et al.[117] were reported to show significant improvement on standard clinical tests of UE function following training. However, some changes in force production,[118,119] movement, and speed[117] on selected test items were seen.

CONCLUSION

This review details the wide variety of clinical applications for which VR systems are now being developed and tested. The published clinical studies, for the most part, still consist of small studies without control groups, geared toward feasibility or proof of concept testing. However, this type of design is appropriate for testing a new technology in the early stages of its application. As the reader examines the wide variety of VR systems that have been or are being developed, it is important to keep in mind that VR is not really a treatment in itself—and thus cannot be found to be "effective" or not for motor rehabilitation. Rather, VR is only a new technological tool that can be exploited to enhance motor retraining. But how well the new VR systems work in this regard will depend very much on how familiar the developers and users are with the scientific rationale behind motor learning as well as the specific details of the motor impairments presented by different clinical populations. This understanding will be key to designing appropriate system features and successful VR treatment interventions. Conversely, considerable engineering knowledge is required to understand the potential capabilities of the various technologies and which functions are necessary for the various applications.

Thus, to be maximally successful, experiments in this area require collaborative efforts among a team of clinicians, engineers, and neuroscientists—not a trivial task. In terms of the types of clinical problems that have been investigated in studies of VR applications to motor rehabilitation, patients with stroke have received most of the attention. The record of success in this area to date has been good (e.g., see results for UE training, gait training, and wheelchair mobility training), and the potential for further success in this area appears quite promising. The potential to apply VR to training patients with vestibular disorders is great, but the equipment set-up for this type of application is quite expensive, and may limit its widespread use. In contrast, standard balance training could be widely applied to general rehabilitation populations with comparatively less expensive equipment. The potential for applications in PD appears quite promising, but will require further system development and testing. Motor rehabilitation has been undertaken in patients with acquired brain injury with some success, but the cognitive deficits displayed by this population may remain the best area of potential application for VR in this population. Finally, the field of telerehabilitation is in its infancy, but has great potential, especially if system cost can be reduced.

Much work remains to be done in such areas as identifying which types of patients will benefit most from VR treatment, which system features are critical, and what types of training routines will work best. However, a few findings appear to be solidly emerging from the VR work to date, as they have appeared repeatedly in multiple studies by different research groups. These findings are that: (1) patients with disabilities appear capable of motor learning within virtual environments; (2) movements learned in VR by patients with disabilities transfer to real world equivalent motor tasks in most cases, and in some cases even generalize to other untrained tasks; (3) in the few studies (n = 5) that have compared motor learning in real versus virtual environments, some advantage for VR training has been found in all cases; and (4) no occurrences of cybersickness in impaired populations have been reported to date in experiments where VR has been used to train motor abilities.

ACKNOWLEDGMENTS

This work was supported by NIH grants nos. HD40959, HD40959–02S1, and M01-RR-01066.

REFERENCES

1. Durlach, N.I., & Mavor, A.S. (eds.). (1995). *Virtual reality: scientific and technological challanges*. Washington, DC: National Academy Press.
2. Burdea, G.C., & Coiffet, P. (2003). *Virtual reality technology*. Hoboken, NJ: John Wiley & Sons, Inc.
3. Stanney, K.M. (ed.). (2002). *Handbook of virtual environments: design, implementation and applications*. Mahwah, NJ: Lawrence Erlbaum.
4. Nichols, S. (1999). Physical ergonomics of virtual environment use. *Applied Ergonomics* 30:79–90.
5. Stanney, K.M., Kennedy, R.S., Drexleer, J.M., et al. (1999). Motion sickness and proprioceptive after effects following virtual environment exposure. *Applied Ergonomics* 30:27–38.
6. Riva, G., Wiederhold, B., & Molinari, E. (eds.). (1998). *Virtual environments in clinical psychology and neuroscience: methods and techniques in advanced patient–therapist interaction.* Amsterdam: IOS Press, Section I, pp. 1–59. Online: http://www.cybertherapy.info/pages/book2.htm
7. Lewis, C.H., & Griffen, M.J. (1997). Human factors consideration in clinical applications of virtual reality. In: Riva, G. (ed.), *Virtual reality in neuro-psychophysiology*. Amsterdam: IOS Press, pp. 35–56.
8. Cruz-Neira, C., Sandin, D.J., DeFanti, T.A., et al. (1992). The CAVE automatic virtual environment. *Communications of the ACM* 38:64–72.
9. Cruz-Neira, C., Sandin, D.J., & DeFanti, T.A. (1993). Surround screen projection–based virtual reality: The design and implementation of the CAVE. *Computer Graphics: Proceedings of SIGGRAPH* 135–142.

10. Nixon, M.A., McCallum, B.C., Fright, W.R., et al. (1998). The effects of metals and interfering fields on electromagnetic trackers. *Presence* 7:204–218.
11. Gor, M., McCloy, R., Stone, R., et al. (2003). Virtual reality laparoscopic simulator for assessment in gynaecology. *BJOG* 110:181–187.
12. Ali, M.R., Mowery, Y., Kaplan, B., et al. (2002). Training the novice in laparoscopy. *Surgical Endoscopy* 16(12):1732–1736.
13. Bouzit, M., Burdea, G., Popescu, G., et al. (2002). The Rutgers Master II—new design force-feedback glove. *IEEE/ASME Transactions on Mechatronics* 7: 256–263.
14. Holden, M., & Dyar, T. (2002). Virtual environment training: a new tool for neurorehabilitation. *Neurology Report* 26:62–71.
15. Holden, M., & Todorov, E. (2002). Use of virtual environments in motor learning and rehabilitation. In: Stanney, K. (ed.), *Handbook of virtual environment technology*. London: Lawrence Erlbaum, pp. 999–1026.
16. Rizzo, A.A., Buckwalter, G., & van der Zaag, C. (2002). Virtual environment applications in clinical neuropsychology. In: Stanney, K. (ed.), *Handbook of virtual environment technology*. London: Lawrence Erlbaum, pp. 1027–1064.
17. Rose, F.D., Attree, E.A., Brooks, B.M., et al. (1998). Virtual environments in brain damage rehabilitation: a rationale from basic neuroscience. In: Riva, G., Wiederhold, B.K. & Molinari, E. (eds.), *Virtual environments in clinical psychology and neuroscience*. Amsterdam: IOS Press, pp. 233–242.
18. Bilodeau, E.A., & Bilodeau, I.M. (1962). Motor skills learning. *Annual Reviews of Psychology* 13:243–280.
19. Nudo, R.J., Milliken, G.W., Jenkins, W.M., et al. (1996). Use-dependent alterations of movement representations in primary motor cortex of adult squirrel monkeys. *Journal of Neuroscience* 16:785–807.
20. Merzenich, M.M., Nelson, R.J., Stryker, M.P., et al. (1984). Somatosensory cortical map changes following digit amputation in adult monkeys. *Journal of Comparative Neurology* 224:591–605.
21. Miller, K.D., Keller, J.B., & Stryker, M.P. (1989). Ocular dominance column development: analysis and simulation. *Science* 245:605–615.
22. Allard, T., Clark, S.A., Jenkins, W.M., & Merzenich, M.M. (1991). Reorganization of somatosensory areas 3b representations in adult owl monkeys after digital syndactyly. *Journal of Neurophysiology* 66: 1048–1058.
23. Recanzone, G.H., Merzenich, M.M., Jenkins, W.M., et al. (1992). Topographic reorganization of the hand representation in cortical area 3b of owl monkeys trained in a frequency discrimination task. *Journal of Neurophysiology* 67:1031–1056.
24. Dinse, H.R., Recansone, G.H., & Merzenich, M.M. (1993). Alterations in correlated activity parallel ICMS-induced representational plasticity. *NeuroReport* 5:173–176.
25. Padoa Schioppa, C., Li, C.-S.R., & Bizzi, E. (2002). Neuronal correlates of kinematics-to-dynamics transformation in the supplementary motor area. *Neuron* 36:751–765.
26. Li, C.-S.R., Padoa Schioppa, C., & Bizzi, E. (2001). Neuronal correlates of motor performance and motor learning in the primary motor cortex of monkeys adapting to an external force field. *Neuron* 30:593–607.
27. Gandolfo, F., Li, C.-S.R., Benda, B.J., et al. (2000). Cortical correlates of learning in monkeys adapting to a new dynamical environment. *Proceeding of the National Academy of Sciences* USA 97:2259–2263.
28. Wise, S.P., Moody, S.L., Blomstrom, K.J., et al. (1998). Changes in motor cortical activity during visuomotor adaptation. *Experimental Brain Research* 121:285–299.
29. Kleim, J.A., Barbay, S., Cooper, N.R., et al. (2002). Motor learning–dependent synaptogenesis is localized to functionally reorganized motor cortex. *Neurobiology of Learning & Memory* 77:63–77.
30. Greenough, W.T., Larson, J.R., & Withers, G.S. (1985). Effects of unilateral and bilateral training in a reaching task on dendritic branching of neurons in the rat motor-sensory forelimb cortex. *Behavioral and Neural Biology* 44:301–314.
31. Kleimm, J.A. Lussnig, E., Schwarz, E.R., et al. (1996). Synaptogenesis and FOS expression in the motor cortex of the adult rat after motor skill learning. *Journal of Neuroscience* 16:4529–4535.
32. Hess, G., & Donoghue, J.P. (1994). Long-term potentiation of horizontal connections provides a mechanism to reorganize cortical motor maps. *Journal of Neurophysiology* 71:2543–2547.
33. Keller, A., Iriki, A., & Asanuma, H. (1990). Identification of neurons producing LTP in the cat motor cortex: intracellular recordings and labeling. *Journal of Comparative Neurology* 300:47–60.
34. Plautz, E.J., Milliken, G.W., & Nudo, R.J. (2000). Effects of repetitive motor training on movement representations in adult squirrel monkeys: role of use versus learning. *Neurobiology of Learning & Memory* 74:27–55.
35. Kleim, J.A., Cooper, N.R., & VandenBerg, P.M. (2002). Exercise induces angiogenesis but does not alter movement representations within rat motor cortex. *Brain Research* 934:1–6.
36. Nudo, R., & Milliken, G.W. (1996). Reorganization of movement representations in primary motor cortex following focal ischemic infarcts in adult squirrel monkeys. *Journal of Neurophysiology* 75:2144–2149.
37. Nudo, R., Wise, S.P., SiFuentes, F., et al. (1996). Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct. *Science* 272:1791–1794.
38. Nudo, R. (2003). Adaptive plasticity in motor cortex: implications for rehabilitation after brain injury. *Journal of Rehabilitation Medicine* 41:7–10.
39. Goldberg, S. (1994). Training dismounted soldiers in a distributed interactive virtual environment. *U.S. Army Research Institute Newsletter* 14:9–12.
40. Lampton, D.R., Knerr, B.W., Goldberg, S.L., et al. (1994). The virtual environment performance as-

sessment battery (VEPAD): development and evaluation. *Presence* 3:145–157.
41. Regian, J.W., Shebilske, W.L., & Monk, J.M. (1992). Virtual reality: an instructional medium for visual spatial tasks. *Journal of Communication* 7:131–145.
42. Theasby, P.J. (1992). The virtues of virtual reality. *GEC Review* 7:131–145.
43. Lintern, G., Roscoe, J.M., Koonce, J.M., et al. (1990). Transfer of landing skills in begining flight simulation. *Human Factors* 32:319–327.
44. Lintern, G., Roscoe, J.M., Koonce, J.M., et al. (1990). Display principles, control dynamics and environmental factors in pilot training and transfer. *Human Factors* 32:299–317.
45. Bliss, J.P., Tidwell, P.D., & Guest, M.A. (1997). The effectiveness of virtual reality for administering spatial navigation training to firefighters. *Presence: Teleoperators and Virtual Environments* 6:73–86.
46. Todorov, E., Shadmer, R., & Bizzi, E. (1997). Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. *Journal of Motor Behavior* 29:147–158.
47. Rose, F.D., Attree, E.A., Brooks, B.M., et al. (2000). Training in virtual environments: transfer to real world tasks and equivalence to real task training. *Ergonomics* 43:494–511.
48. Brooks, B., McNeil, J.E., Rose, F.D., et al. (1999). Route learning in a case of amnesia: a preliminary investigation into the efficacy of training in a virtual environment. *Neuropsychological Rehabilitation* 9:63–76.
49. Baddeley, A.D., & Wilson, B.A. (1994). When implicit learning fails: amnesia and the problem of error elimination. *Neuropsychologia* 32:53–68.
50. Webster, J.S., McFarland, P.T., Rapport, L.J., et al. (2001). Computer-assisted training for improving wheelchair mobility in unilateral neglect patients. *Archives of Physical Medicine and Rehabilitation* 82: 769–775.
51. Jaffe, D.L., Brown, D.A., Pierson-Carey, C.D., et al. (2004). Stepping over obstacles to improve walking in individuals with post-stroke hemiplegia. *Journal of Rehabilitation Research and Development* 41:283–292.
52. Morasso, P. (1981). Spatial control of arm movements. *Experimental Brain Research* 42:223–227.
53. Flash, T., & Hogan, N. (1985). The coordination of the arm movements: an experimentally confirmed mathematical model. *Journal of Neuroscience* 7:1688– 1703.
54. Bizzi, E., Mussa-Ivaldi, F.A., & Shadmehr, R. (1996). System for Human Trajectory Learning in Virtual Environments. U.S. patent no. 5,554,033. Cambridge: Massachusetts Institute of Technology.
55. Holden, M.K. (2001). Neurorehabilitation using "learning by imitation" in virtual environments. In: Smith, J.S.G., Harris, D., & Koubek, R.J. (eds.), *Usability evaluation and interface design: cognitive engineering, intelligent agents and virtual reality*. London: Lawrence Erlbaum, pp. 624–628.
56. Rizzolatti, G., Fadiga, L., Fogassi, L., et al. (1999). Resonance behaviors and mirror neurons. *Archives Italiennes de Biologie* 137:85–100.
57. Holden, M., Todorov, E., Callahan, J., et al. (1999). Virtual environment training improves motor performance in two patients with stroke: case report. *Neurology Report* 23:57–67.
58. Holden, M.K., Dyar, T., Schwamm, L., et al. (2005). Virtual environment-based telerehabilitation in patients with stroke. *Presence: Teleoperators and Virtual Environments* (in press, 14[2] April).
59. Fugl-Meyer, A.R., Jaasko, L., Leyman, I., et al. (1975). The post-stroke hemiplegic patient: a method for evaluation of physical performance. *Scandanavian Journal of Rehabilitation* 7:13–31.
60. Mahurin, R.K., Debettignies, B.J., & Pirozzolo, F.J. (1991). Structured assessment of independent living skills: preliminary report of a performance measure of functional abilities in dementia. *Journal of Gerontology* 46:58–66.
61. Holden, M.K., Dyar, T., Callahan, J., et al. (2001). Quantitative assessment of motor generalization in the real world following training in a virtual environment in patients with stroke. *Neurology Report* 25:129–130.
62. Holden, M.K., Dyar, T., Callahan, J., et al. (2000). Motor learning and generalization following virtual environment training in a patient with stroke. *Neurology Report* 24:170–71.
63. Morris, D.M., Uswatte, G., Crago, J.E., et al. (2001). The reliability of the Wolf motor function test for assessing upper extremity function after stroke. *Archives of Physical Medicine and Rehabilitation* 82: 750–755.
64. Wolf, S.L., Catlin, P.A., Ellis, M., et al. (2001). Assessing the Wolf motor function test as an outcome measure for research with patients post-stroke. *Stroke* 32:1635–1639.
65. Jack, D., Boian, R., Merians, A.S., et al. (2001). Virtual reality–enhanced stroke rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 9:308–318.
66. Boian, R.F., Sharma, A., Han, C., et al. (2002). *Virtual reality–based post-stroke hand rehabilitation: medicine meets virtual reality.* Newport Beach, CA. IOS Press.
67. Merians, A.S., Jack, D., Boian, R., et al. (2002). Virtual reality–augmented rehabilitation for patients following stroke. *Physical Therapy* 82:898–915.
68. Wolf, S.L., Blanton, S., Baer, H., et al. (2002). The emergence of repetitive task practice in upper extremity neurorehabilitation of patients with stroke: a critical review of constraint induced movement therapy and mechanisms related to TMS. *The Neurologist* 8:325–338.
69. Taub, E., & Wolf, S.L. (1997). Constraint induction techniques to facilitate upper extremity use in stroke patients. *Topics in Stroke Rehabilitation* 4:38–61.
70. Jebsen, R.H., Taylor, N., Trieschmann, R.B., et al. (1969). An objective and standardized test of hand function. *Archives of Physical Medicine and Rehabilitation* 50:311–319.
71. Adamovich, S.V., Merians, A.S., Boian, R., et al. (2003). A virtual reality–based exercise system for

hand rehabilitation post-stroke. Presented at the 2nd International Workshop on Virtual Rehabilitation, Piscataway, NJ.
72. Broeren, J., Georgsson, M., Rydmark, M., et al. (2002). Virtual reality in stroke rehabilitation with the assistance of haptics and telemedicine. Presented at the 4th International Conference on Disability, Virtual Reality & Associated Technologies, Veszprem, Hungary.
73. Hilton, D., Cobb, S., Pridmore, T., et al. (2002). Virtual reality and stroke rehabilitation: a tangible interface to an everyday task. Presented at the 4th International Conference on Disability, Virtual Reality & Associated Technologies, Veszprem, Hungary.
74. Piron, L., Cenni, F., Tonin, P., et al. (2001). Virtual reality as an assessment tool for arm motor deficits after brain lesions. *Studies in Health Technology and Infomatics* 81:386–392.
75. Boian, R.F., Deutsch, J.E., Lee, C.S., et al. (2003). Haptic effects for virtual reality-based post-stroke rehabilitation. Presented at the 11th Symposium on Haptic Inerfaces for Virtual Environments and Teleoperator Systems, Los Angeles.
76. Boian, R.F., Lee, C.S., Deutch, J.E., et al. (2002). Virtual reality–based system for ankle rehabilitation post stroke. Presented at the 1st International Workshop on Virtual Reality Rehabilitation (Mental Health, Neurological, Physical, Vocational), VRMHR 2002, Lausanne, Switzerland.
77. Deutsch, J.E., Latonio, J., Burdea, G.C., et al. (2001). Post-stroke rehabilitation with the Rutgers Ankle system: a case study. *Presence* 10:416–430.
78. Boian, R.F., Kourtev, H., Erickson, K., et al. (2003). Dual Stewart-platform gait rehabilitation system for individuals post-stroke. Presented at the 2nd International Workshop on Virtual Rehabilitation, Piscataway, NJ.
79. Yoon, J., Ryu, J., & Burdea, G. (2003). Design and analysis of a novel virtual walking machine. Presented at the 11th Symposium on Haptic Interfaces for VE and Teleoperator Systems, Los Angeles.
80. Connor, B.B., Wing, A.M., Humphreys, G.W., et al. (2002). Errorless learning using haptic guidance: research in cognitive rehabilitation following stroke. Presented at the 4th International Conference on Disability, Virtual Reality & Associated Techologies, Veszprem, Hungary.
81. Wilson, B.A., Baddeley, A.D., Evans, J.J., et al. (1994). Errorless learning in the rehabilitation of memory impaired people. *Neuropsychological Rehabilitation* 4:307–326.
82. Wilson, B.A., & Evan, J.J. (1996). Error-free learning in the rehabilitation of individuals with memory impairments. *Journal of Head Trauma Rehabilitation* 11:54–64.
83. Rose, F.D., Brooks, B.M., Attree, E.A., et al. (1999). A preliminary investigation into the use of virtual environments in memory retraining after vascular brain injury: indications for future strategy? *Disability and Rehabilitation* 21:548–554.
84. Foreman, N., Orencas, C. Nicholas, E., et al. (1989). Spatial awareness in seven to 11-year-old physically handicapped children in mainstream schools. *European Journal of Special Needs Education* 4:171–178.
85. Wilson, P.N., Foreman, N., & Tlauka, M. (1996). Transfer of spatial information from a virtual to a real environment in physically disabled children. *Disability and Rehabilitation* 18:663–637.
86. Broeren, J., Lundberg, M., Molen, T., et al. (2003). Virtual reality and haptics as an assessment tool for patients with visuospatial neglect: a preliminary study. In: Burdea, G., Thalmann, D., & Lewis, J.A. (eds.), *2nd International Workshop on Virtual Rehabilitation.* Piscataway, NJ: Rutgers University, pp. 27–32.
87. Halligan, P.W., Marshall, J.C., & Wade, D.T. (1989). Visuospatial neglect: underlying factors and test sensitivity. *Lancet* 2:908–911.
88. Tham, KT.R. (1996). The baking tray task: a test of spatial neglect. *Neuropsychological Rehabilitation* 6: 19–25.
89. Holden, M.K., Dettwiler, A., Dyar, T., et al. (2002). Virtual environment training improves functional movement in patients with acquired brain injury. Presented at the American Society of Neurorehabilitation, Philadelphia.
90. Holden, M., Dettwiler, A., Dyar, T., et al. (2001). Retraining movement in patients with acquired brain injury using a virtual environment. In: Westwood, H.M.H., Mogel, G.T., Stredney, D., et al. (eds.), *Medicine meets virtual reality.* Newport Beach, CA: IOS Press, pp. 192–198.
91. Davies, R.C., Lofgren, E., Wallergard, M., et al. (2002). Three applications of virtual reality for brain injury rehabilitation of daily tasks. Presented at the 4th International Conference on Disability, Virtual Reality & Associated Technologies, Veszprem, Hungary.
92. Zhang, L., Abreu, B.C., Seale, G.S., et al. (2003). A virtual reality environment for evaluation of daily living skill in brain injury rehabilitation: reliability and validity. *Archives of Physical Medicine and Rehabilitation* 84:1118–1124.
93. Prothero, J. (1993). The treatment of Akinesia using virutal images [Master's thesis]. Seattle: University of Washington.
94. Weghorst, S., Prothero, J., Furness, T., et al. (1994). Virtual images in the treatment of Parkinson's disease akinesia. *Proceedings of Medicine Meets Virtual Reality II* 242–243.
95. Weghorst, S. (1997). Augmented reality and Parkinson's disease. *Communications of the ACM* Aug: 47–48.
96. Emmett, A. (1994). Virtual reality helps stead the gait of Parkinson's patients. *Computer Graphics World* 17–18.
97. Riess, T.W.S. (1995). Augmented reality in the treatment of Parkinson's disease. In: Morgan, K., Satava, M., Sieburg, H.B., et al. (eds.), *Interactive technology and the new paradigm for healthcare*. Amsterdam: IOS Press pp. 298–302.
98. Albani, G., Pignatti, R., Bertella, L., et al. (2002). Common daily activities in the virtual environment:

a preliminary study in parkinsonian patients. *Neurological Sciences* 23:S49–S50.

99. Mesulam, M.M. (1985). *Principles of behavioral neurology*. Philadelphia: F.A. Davis.
100. Rey, A. (1941) L'examen psychologique dans le cas d'encephalopathie traumatique. *Archives of Psychology* 28:296–340.
101. Cooper, R.A., Spaeth, D.M. Jones, D.K., et al. (2002). Comparison of virtual and real electric powered wheelchair driving using a position sensing joystick and an isometric joystick. *Medical Engineering & Physics* 24:703–708.
102. Fehr, L., Langbein, W.E., & Skaar, S.B. (2000). Adequacy of power wheelchair control interfaces for persons with severe disabilities: a clinical survey. *Journal of Rehabilitation Research and Development* 37:353–360.
103. Gourlay, D., Lun, K.C., Lee, Y.N., et al. (2000). Virtual reality for relearning daily living skills. *International Journal of Medical Infomatics* 60:225–261.
104. McComas, J., & Sveistrup, H. (2002). Virtual reality applications for prevention, disability awareness, and physical therapy rehabilitation in neurology: our recent work. *Neurology Report* 26:55–61.
105. McComas, J., MacKay, M., & Pivik, J. (2002). Effectiveness of virtual reality for teaching pedestrian safety. *CyberPsychology & Behavior* 5:185–190.
106. Kizony, R., Katz, N., Weingarden, H., et al. (2002). Immersion without encumbrance: adapting a virtual reality system for the rehabilitation of individuals with stroke and spinal cord injury. Presented at the 4th International Conference on Disability, Virtual Reality & Associated Technologies, Veszprem, Hungary.
107. Whitney, S.L., Sparto, P.J., Brown, K.E., et al. (2002). The potential use of virtual reality in vestibular rehabilitation: preliminary findings with the BNAVE. *Neurology Report* 26:72–78.
108. Keshner, E.A.K. (2000). The influence of an immersive virtual environment on the segmental organization of postural stabilizing responses. *Journal of Vestibular Research* 10:207–219.
109. Kenyon, R.V., DeFanti, T.A., & Sandin, D.J. (1995). Visual requirements for virtual environment generation. *Journal of Soc. Inform. Display* 3:211–214.
110. Girone, M., Burdea, G., Bouzit, M., et al. (2000). Orthopedic rehabilitation using the "Rutgers Ankle" interface. In: *Medicine Meets Virtual Reality.* Newport Beach, CA: IOS Press, pp. 89–95.
111. Girone, M., Burdea, G., Bouzit, M., et al. (2001). A Stewart Platform–based system for ankle telerehabilitation. *Autonomous Robots* 10:203–212.
112. Deutsch, J.E., Latonio, J., Burdea, G.C., et al. (2001). *Rehabilitation of musculoskeletal injuries using the Rutgers Ankle haptic interface: three case reports.* Eurohaptics Conference, Birmingham, UK, pp. 11–16.
113. Rosen, M. (1999). Telerehabilitation. *NeuroRehabilitation* 12:11–26.
114. Holden, M.K., Dyar, T., Schwamm, L., et al. (2003). Home-based telerehabilitation using a virtual environment system. In: Burdea, G., Thalmann, D., Lewis, J.A. (eds.), *2nd International Workshop on Virtual Rehabilitation.* Piscataway, NJ: Rutgers University, pp. 4–12.
115. Dyar, T.A., & Holden, M.K. (2005). Telerehabilitation system for motor training: design and development. *Journal of Rehabilitation Research and Development* (in review).
116. Piron, L., Tonin, P., Atzori, A., et al. (2003). A virtual reality–based motor tele-rehabilitation system. In: Burdea, G., Thalmann, D., Lewis, J.A. (eds.), *2nd International Workshop on Virtual Rehabilitation.* Piscataway, NJ: Rutgers University, pp. 21–26.
117. Reinkensmeyer, D.J., Pang, C.T., Nessler, J.A., et al. (2002). Web-based telerehabilitation for the upper extremity after stroke. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 10: 102–108.
118. Burdea, G., Popescu, V., Hentz, V., et al. (2000). Virtual reality–based orthopedic telerehabilitation. *IEEE Transactions on Information Technology in Biomedicine* 8:430–432.
119. Popescu, V.G., Burdea, G.C., Bouzit, M., et al. (2000). A virtual-reality–based telerehabilitation system with force feedback. *IEEE Transactions on Information Technology in Biomedicine* 4:45–51.
120. Holden, M.K., Dyar, T., Schwamm, L., et al. (2003). Telerehabilitation: development and initial testing of a remotely operated computerized motor training system to provide patients with home-based therapy via the Internet. *Neurology Report* 26:198.
121. Holden, M.K., Dyar, T., Dayan-Cimadoro, L., et al. (2004). Virtual environment training in the home via telerehabilitation. *Archives of Physical Medicine and Rehabilitation* 85(8):E12. Available: <www.archives-pmr.org>.

Address reprint requests to:
Dr. Maureen K. Holden
Department of Brain and Cognitive Sciences
McGovern Institute for Brain Research
Massachusetts Institute of Technology
Cambridge, MA 02139

E-mail: holden@mit.edu