Virtual Reality and Gaming Systems to Improve Walking and Mobility for People with Musculoskeletal and Neuromuscular Conditions

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Abstract. Improving walking for individuals with musculoskeletal and neuromuscular conditions is an important aspect of rehabilitation. The capabilities of clinicians who address these rehabilitation issues could be augmented with innovations such as virtual reality gaming based technologies. The chapter provides an overview of virtual reality gaming based technologies currently being developed and tested to improve motor and cognitive elements required for ambulation and mobility in different patient populations. Included as well is a detailed description of a single VR system, consisting of the rationale for development and iterative refinement of the system based on clinical science. These concepts include: neural plasticity, part-task training, whole task training, task specific training, principles of exercise and motor learning, sensorimotor integration, and visual spatial processing.

Keywords. Virtual reality, gaming, stroke, gait, multiple sclerosis, Parkinson Disease, cerebral palsy, balance training, motor control, motor learning.

Introduction

Rehabilitation of walking for individuals with musculoskeletal and neuromuscular conditions remains a challenge in rehabilitation. The application of new technologies such as virtual reality, gaming and robotics has stimulated many approaches to enable walking for individuals with disabilities. The purpose of this chapter is two-fold, first to provide a brief overview on technology that incorporates virtual reality (VR) to promote walking or mobility for individuals with disability; second to describe in some detail the development and testing of one such system used for individuals with both musculoskeletal and neurological impairments that interfered with functional mobility.

1. Overview of VR and Gaming Systems to Improve Mobility and Walking

Virtual Reality based systems used to rehabilitate walking or mobility for individuals with disabilities, generally, are composed of hardware used as an input into a virtual environment that is generated by software delivered to the user with an interface. The hardware appliances vary from simple cameras for motion capture to elaborate
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Advanced Technology in Rehabilitation
Empowering Cognitive, Physical, Social and Communicative Skills through Virtual Reality, Robots, Wearable Systems and Brain-Computer Interfaces
Volume 145 Studies in Health Technology and Informatics
June 2009, approx. 310 pp., hardcover
ISBN: 978-1-60750-018-6 NEW
Price: US$167 / €115 / £81

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Price: US$161 / €115 / £81

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Edited by: G. Riva and F. Davide
2001, 292 pp., hardcover
Price: US$161 / €115 / £81
instrumented robots. The software renders a variety of environments (VE) in which some form of navigation or movement takes place. The display of the environments can be through a head mounted display (HMD), desktop computer, television screen or a large rear projected screen. Gaming systems typically have a console that is connected to a display device and has a controller that the user manipulates to enter the game. The user can train on these systems by physically executing movements or by practicing navigation skills. The following sections will review VR systems and applications based on patient populations.

1.1. Individuals Post-Stroke with Walking and Mobility Deficits

Six different VR-based approaches were identified in the literature that were designed to improve walking or mobility for individuals post-stroke. All of these approaches involved the physical practice of either gait or gait-related activities. Four of these are summarized in more detail elsewhere. [2] The earliest work, was presented by Jaffee and Brown who used a HMD to display virtual obstacles as a stimulus for stepping. [3] Individuals post-stroke had their foot movements tracked by a camera as they walked, with the support of a harness, on a treadmill. They trained for 12 hours over two weeks for a total of 120 steps. Visual and tactile inputs were provided users when their foot contacted the virtual objects. They reported that training in the VE had some benefits relative to improved gait speed and navigation of obstacles in the real world compared to a group of patients that trained on an over-ground obstacle course. You and colleagues used the commercially available IREX system by GestureTek to train gait related activities. [4] The motion capture system displayed the user avoiding sharks and eels in a seascape, practicing stepping, and practicing balance and weight shifting as they skied down a course. Visual and auditory feedback and performance scores were provided to the users. Compared to a no treatment control group the VR group improved walking category and displayed laterality shifts on fMRI consistent with plasticity. Deutsch and colleagues used a robot-vr system that will be described in more detail in the second section of the paper. Fung and colleagues used the CAREN system consisting of a treadmill mounted on a Stewardt platform interfaced with a virtual hallway displayed by rear projector on a large screen. For two individuals post-stroke with fast-walking speeds they reported adaptation to walking in the virtual environments. [5] Using the Sony Playstation II with the Eye Toy, Flynn and colleagues [6] reported a case of individual post-stroke that used this system as a home based exercise. The PlayStation II with Eye Toy uses similar motion capture technology as the IREX. [7] After 20 sessions of training with this low cost motion capture system the individual increased her speed in the timed up and go test (TUG).

Improvement on the TUG removed the subject from the risk for falls category. Yang and colleagues [8] used a treadmill interfaced with a three rear projectors to display walking environments on a three-sided large screen display which afforded a 154 degree horizontal and 37 degree vertical field of view. Subjects’ leg motions were tracked with an electromagnetic system to detect collisions. They reported increased speed of walking and greater distance with community ambulation for the group that trained (for only nine twenty minute sessions) with the VR-treadmill set up compared to the group that trained with the treadmill alone.

In contrast to physical practice of a mobility task, way finding and navigation through virtual environments has also been used as a way to train skills that are required for mobility. [9] Individuals post-stroke navigated a two-dimensional virtual
environment (VE) was navigated using a joystick. When compared to a video-based psycho-educational modeling program superior performance, was reported, on a scale developed to rate community mobility skills such as road crossing and station navigation.

These approaches to improve walking all have in common the delivery of task-based therapy with augmented, multisensory feedback. The initial findings are encouraging but require further study to answer a variety of questions that are relevant to rehabilitation. Several of the groups are continuing to refine their technology and test it further to identify what is the best VR system to use for which type of individual post-stroke. What are the dosing requirements for optimum outcomes and in the end most importantly which system will be widely adopted in a clinical setting? While the majority of the studies reviewed involve physical practice of walking or walking related motor skills, the way finding study indicates that aspects of mobility such as basic navigation skills can be trained in the absence of physical practice. It is likely that to attain complex skills like community ambulation it will be important to train both motor and cognitive skills in combination.

The VR systems currently available to rehabilitate walking for people in the chronic phase post-stroke can be categorized as direct and indirect walking interventions. Direct walking systems involve the task of walking; this would include the work by Jaffee, Fung and Yang. Indirect interventions by Deutsch, Flynn and You, use gait related activities, but none that involve translation. In reviewing the literature it was notable that the indirect interventions had a higher dosing. For example the number of repetitions in work by You et al., ranged from 1320-1965 for gait related activities, while the work by Jaffee et al., had a 120 repetitions of stepping over objects while walking. All groups are incorporating principles of motor learning into their simulations providing multisensory and cognitive feedback to the users. Outcomes have focused on motor performance and motor control. Cognitive self-efficacy, which was explored in the VR way finding study, may be appropriate to incorporate into gait rehabilitation studies. Finally the active ingredients in each system have not been fully explored.

The important question of transferring the technology to practice remains to be addressed. The early findings show transfer of training from walking in virtual environments and or physically training gait related activities to improved walking in the real world. [2, 8] There are however practical considerations such as system cost and their commercial availability. Specifically, the challenge with implementing these technologies in the clinic is that several are not commercially available and those that are, in some cases, are cost prohibitive for most institutions. Another consideration is whether systems that were specifically designed for rehabilitation like the IREX, and the CAREN system will be superior to off the shelf gaming consoles. The off the shelf gaming software has only been tested for feasibility and not efficacy. Further research with gaming technology may demonstrate efficacy and therefore justify its use in practice. Comparison between highly specialized virtual reality applications relative to the commercially available systems is warranted.

1.2. Individuals Post-Stroke with Neglect

Virtual environments have been developed to train Individuals with neglect to safely cross the street. [10, 12] Using a desktop computer and a joystick, healthy individuals were compared to a group of right-hemisphere damage patients post-stroke.
in a street-crossing task. The emphasis was on safe crossing. [11] The same system with refinements was further tested on a larger group of patients who all had unilateral spatial neglect and used wheelchairs as their primary source of mobility. The authors reported that the individuals with unilateral spatial neglect looked left more often and had fewer accidents than the group that trained on computer visual scanning tasks. [10]

Transfer to real life crossing was not significantly different between the groups. These studies illustrate the use of a navigation task for individuals who have mobility deficits that are heavily influenced by their visual spatial processing abilities.

1.3. Virtual Reality Applications for Individuals with Multiple Sclerosis and Parkinson Disease who have mobility challenges

Although not as extensive as the research on virtual reality enabled walking and mobility for people post-stroke, the literature on VR to improve mobility for people with multiple sclerosis (MS) and Parkinson Disease (PD) is emerging. As with the research on stroke there are various methods used to deliver the virtual environments and train the patients.

For people with MS two contrasting approaches were found in the literature. Baram and colleagues used VR as a cueing strategy to improve stepping for people with MS who presented with an ataxic gait. [13] A checkered board tiled floor was displayed through a visor worn over the subjects’ head. The VR was used as an orthotic to stabilize the stepping pattern. They demonstrated improvements in walking speed that had short term carry over. Fulk and colleagues reported on a single case in which they combined bodyweight supported treadmill training with virtual reality based balance training using the IREX-GestureTek motion capture system described in the section on mobility and stroke. The combined treatment resulted in improved walking and balance outcomes. [14] The case report format allowed the formulation of a treatment plan that reflected a combined therapeutic approach to meet the patient’s mobility needs. This is in contrast with research studies that require a reductionistic approach to testing interventions in order to guarantee the internal validity of the study. It is likely that clinicians would use VR technologies in combination with other therapeutic modalities to achieve patient goals.

Research on use of virtual environments for individuals with PD has focused on motor control aspects related to action and navigation as well as performing activities of daily living, rather than training walking. [15, 16] This more basic research, however, has implications for practice. Individuals with mild to moderate PD were compared to healthy controls during a virtual supermarket navigation task. The task involved navigation and specific actions that occurred using a first person perspective as if pushing a shopping cart. The individuals with PD achieved similar outcomes in the virtual environment tasks but required greater distances and more time to complete the tasks relative to healthy controls. These differences were attributed to planning deficits that may be amenable to training. [15] Using a HMD and joystick two individuals with PD (Hoehn and Yahr Stage 2) and 10 healthy controls navigated through environments and performed activities of daily living. The goal was to determine, if in the absence of deficits on paper and pencil neuropsychological tests, the VR tasks could identify deficits in planning for the individuals with PD. Evaluated on orientation, speed, hesitation and memory tasks, individuals with PD were found to have the most notable deficits on speed of execution. This was pronounced when they had to navigate through a narrow doorway. [16] Both studies suggest that virtual environments can be used for
examination of cognitive deficits that may interfere with mobility. It will be interesting to see if they can be applied to rehabilitation.

1.4. Gaming and VR to Improve Mobility for Individuals with Cerebral Palsy

Use of virtual reality and gaming has been used to improve selective lower extremity motor control and improve mobility and balance in adolescents with cerebral palsy (CP). Bryanton and colleagues demonstrated that individuals with CP were more motivated and exercised at a greater intensity when working with a Kung Fu Game on the IREX system compared to standard of care exercises. [17] Deutsch and colleagues, incorporated gaming with the Nintendo Wii sport software, into an adolescent with CP’s summer program. The individual trained in sitting and standing over 11 sessions using boxing, baseball, bowling and golfing games designed to improve postural control, spatial abilities and mobility. They reported gains in standing symmetry and control, scores on the Test of Visual Perceptual Skills III (a measure of spatial ability) and walking distance. [18] They had hypothesized the direct changes in visual spatial ability and balance but were uncertain if they would see the transfer to walking. Finally there has also been a case report in which neural plasticity was demonstrated after virtual reality training with an individual with cerebral palsy. [19]

The evidence for use of virtual reality to improve mobility across a variety of rehabilitation populations is modest. Of interest is the variety of approaches in terms of the technology used for similar applications. The greatest number of studies and labs that are integrating virtual reality or gaming technology for mobility rehabilitation has focused on individuals post stroke. Important questions about transfer of training, what is the right amount of technology will need to be addressed before these approaches are widely adopted in the clinic. Such efforts are underway in applying virtual reality to upper extremity [20] as well as walking rehabilitation in individual post-stroke. [2]

2. Description of Development and Testing of One VR-Based System to Improve Mobility and Walking

2.1. Introduction

The inclusion of a more detailed description of a specific VR-based system to improve mobility and walking for people with neuromuscular and musculoskeletal conditions is presented here. The main objective of this section is to describe a process that is multi-disciplinary, and requires technical, clinical and patient expertise for development and refinement of a system. It is also to describe a progression of studies that range from proof of concept and validation to efficacy trials.

2.2. The system and rationale for development

A robot-virtual environment lower extremity system was developed through a collaboration of clinician-scientists, engineers and eventually users. The engineering team included mechanical (Mourad Bouzit), electrical (Greg Burdea), computer (Rares Boian, Jeffrey Lewis) and human interface engineers (Marilyn Tremaine). The clinician-scientists’ background was in applied neuroscience and physical therapy. The
users were individuals with lower extremity musculoskeletal injuries, individuals post-stroke and physical therapists. Over the course of six years the system was conceptualized, developed, refined and tested in feasibility, pilot and user studies culminating in randomized single blind clinical trial.

The system consists of a six-degree of freedom parallel kinematics robot (Stewardt platform) interfaced with a controller and a desktop computer, which displays the virtual environments. The Stewardt platform is instrumented with a force transducer and linear potentiometers that read forces and displacements of the platform, which are referenced to the foot movements. Using inverse dynamics the ankle orientation and position relative to the floor can be read into the simulation. The robots pneumatic actuators also provide forces and torques to the patient’s foot and ankle. This force feedback system allows for the delivery of haptic effects to the foot. The haptic effects were modeled at a low and a high level. High-level effects allow for manipulation of augmented sensory input to the user’s foot. Thus the robot serves as input into the virtual environment as well as a recorder of all the movements. Details on the hardware and haptic modeling can be found elsewhere. [21, 22] [23, 24]

The software evolved from a basic representation of a foot moving on a checkerboard pattern to an airplane navigating through a series of simple targets into an airscape and a seascape complete with visual, auditory and haptic effects to increase realism, challenge mobility and augment sensory input. It was designed using principles of exercise and motor learning. [25] We have described the theoretical rationale for the construction of a robot coupled with a virtual environment elsewhere [25]. Briefly it was based on evidence from pre-clinical and basic science studies of the effects of training animals in enriched environments that produced superior task performance than those trained in impoverished environments, on the identification of the important role of the distal effector namely the ankle in walking and the integration of principles of motor learning and principles of exercise. Animals (primarily rats) trained in enriched environments perform better on functional tasks and in solving problems when compared to animals trained in impoverished environments. [26] This difference is accentuated when the complexity of the problem increases. [27] It has been suggested that the use of virtual environments for rehabilitation may provide the stimulation to extend the existing benefits of rehabilitation and promote functional recovery. [28]

The initial goal of developing the system was to create a tool for rehabilitation of the lower extremity to remediate impairments such as weakness, lack of flexibility, incoordination, decreased endurance and sensory loss. The patient population initially identified that would benefit from such a device were individuals with musculoskeletal conditions that primarily affected the ankle. These included but were not limited to individuals with ankle sprains and fractures. These individuals were selected because we hypothesized that the training provided by the robot-vr system would target all of the relevant impairments that may interfere with their recovery of mobility. Training at the impairment level was a frequently employed therapeutic approach with this population. Training relevant kinematic features of a movement is also believed to transfer to whole tasks. [29] For our particular application there was some speculation about whether training ankle impairments as well relevant kinematic features of walking, namely the kinetics of ankle push-off, would transfer to improved walking.
2.3. The Experiments, Iterations and Refinements

The first set of experiments was designed to validate the system and its capabilities. These validation and proof of concepts studies were executed with individuals with ankle sprains or ankle fractures. [23, 30] A simple simulation of a foot was used as a stimulus for basic ankle motions. Using their non-affected side as a control we demonstrated that individuals with ankle sprains had lower force production and ankle excursions with their affected ankles compared to their non-affected ankles. These measurements derived by the robotic system were comparable to clinical gold standards thus establishing the diagnostic validity of the system. [23]

To determine if the system might be transferred to the clinic we placed it in an outpatient orthopedic physical therapy practice. By this time we had created a gaming simulation where a virtual plane navigated through targets and the user received feedback about their navigation. To run the study we required a clinician scientist, an engineering student (and many cold packs to cool the compressor that often overheated). In the clinic six patients with different diagnoses that involved the lower extremity agreed to discontinue their physical therapy and substitute the virtual reality training. Three of patients had ankle sprains and or fractures. They demonstrated ease in using the system and clinical improvements in range of motion and strength. [30]

One of them worked at such high intensity that her sessions ended with application of ice to cool the joint. We realized that we would need to enhance the simulation to assist with engagement and immersion by adding to the task complexity, as one of the participants (a 14 year old adolescent) reached the maximum settings for range of motion and resistance for the navigation tasks.

One of the clinic participants was an individual in the chronic stage post-stroke. The findings from his participation in the proof of concept or feasibility trial altered the direction of our research. He benefitted from the virtual reality robotic training in unexpected ways, showing a transfer to walking and stair climbing. [31]

This launched a series of studies to confirm that this transfer of training while seated and moving your ankle in a virtual environment was a finding that could be replicated. It was. [32] In parallel the simulation was enhanced adding haptic effects that were coordinated with the virtual environment. [24]

In addition we conducted usability studies. The purpose of these studies was to involve the end-user in the design of the system, in our case both the clinician and the patient. Typically these should occur in the design phase and be repeated with system modifications. We had informally solicited input in our earlier studies but learned much more once we formalized the approach. We learned that our system could be used by clinicians and was liked by the patients. [33, 34]. There were however aspects to change and enhance consistent with the iterative process of developing technology.

These included changes to solve command structure problems, by changing the labels and order of the action buttons; as well as simplifying terminology to make it more accessible to the clinician. [34] A series of studies were also performed in which the system was interfaced for tele-rehabilitation. [35, 36] These will not be elaborated on here.

The most recent work related the robotic-virtual reality system was to determine whether it was the robot or the combination of the robot with the virtual environment that produced the transfer of training to the real world. We hypothesized that the combined system in which the learner has to solve the task of navigating in the virtual environment would produce the transfer of training, whereas training with the robot
alone might produce some impairment level changes but not a transfer to function. In a single blind, randomized clinical trial we demonstrated that individuals who trained with the robot-virtual reality system had gait speed and distance increases that were measured both in the clinic and the real world, that were significantly greater than those who trained with the robot alone. [37, 38] Other interesting findings from a fully instrumented gait analysis was the dramatic change in ankle push off kinetics of the robot-vr group compared to the robot alone. The specificity of training the ankle kinetics as well as transfer of relevant part-task training is one of several explanations for the positive outcome of the vr-system coupled with the robot. A complex system like the one that we have just described has many features that remain to be explored.

Probably the most relevant finding of single blind randomized trial is the transfer of training from the lab setting to the community. Using an activity monitor subjects’ gait was measured for a week in advance of training and a week after training concluded. Significant improvements in walking distance and velocity were measured in real world situations for the robot-vr but not the robot alone group. [38] These findings are important as transfer for the real world from virtual reality training is a central goal of this rehabilitation approach.

3. Summary

Virtual reality and gaming based approaches to rehabilitation of individuals with neuromuscular and musculoskeletal conditions has been reviewed and evaluated. Approaches in terms of technology (hardware and software) have been quite variable. In common, the systems developed, use rich augmented multi-sensory feedback, as well as information about performance and results. Whether it is the hardware that interfaces into the (VE), or the stimulus for goal directed movement that the VE offers that promotes the changes in the motor behavior remains to be elucidated. Most of the work has used custom built, primarily lab-based systems. These offer the advantages of customization and rich data collection. However, off the shelf commercially available systems are also being trialed. Their reduced cost and ease of availability relative to the lab-based systems makes them appealing. Which of these systems will be adopted in practice remains to be determined. It is likely that exploration of off-the-shelf gaming systems will continue in parallel with the development of lab-based systems. Each will serve an important role in understand the usefulness of virtual reality and gaming technology in the rehabilitation of walking and mobility.

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