Journal of Diabetes Science and Technology
Volume 5, Issue 2, March 2011

SYMPOSIUM

Using Virtual Reality to Improve Walking Post-Stroke: Translation to Individuals with Diabetes

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Abstract

Use of virtual reality (VR) technology to improve walking for people post-stroke has been studied for its clinical application since 2004. The hardware and software used to create these systems has varied but has predominantly been constituted by projected environments with users walking on treadmills. Transfer of training from the virtual environment to real-world walking has modest but positive research support. Translation of the research findings to clinical practice has been hampered by commercial availability and costs of the VR systems. Suggestions for how the work for individuals post-stroke might be applied and adapted for individuals with diabetes and other impaired ambulatory conditions include involvement of the target user groups (both practitioners and clients) early in the design and integration of activity and education into the systems.

J Diabetes Sci Technol 2011;5(2):309-314

The Challenge of Improving Walking Post-Stroke

Recovery of walking post-stroke is an important rehabilitation goal.[1,2] Independence with ambulation is associated with participation in meaningful social roles and decreased burden of care.[3] Individuals post-stroke walk up to 50% more slowly than their healthy counterparts.[4] They also experience decreased community ambulation activity,[5,6] with the reported mean daily number of steps taken by individuals post-stroke being 2837 compared to 5000–6000 taken by a comparable group of sedentary adults.[6] Barriers to achieving full recovery of walking in the community include disturbed motor control, fitness challenges, and low self-efficacy. Basic and preclinical science research has shown that certain ingredients are critical for mobility rehabilitation to produce both behavioral and neural changes. These include enriched environments,[7] salient tasks,[8] and repetitive intense training.[9]

Task-specific training, body-weight-supported treadmill training, and resistive exercise are among the rehabilitation techniques that have been used to improve walking for people post-stroke.[10] Challenges in gait rehabilitation post-stroke include creating the biomechanical and environmental conditions to improve walking. The development of robotic devices has sought to address some of the biomechanical challenges with training walking.[11]

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Abbreviations: (PAD) peripheral artery disease, (VE) virtual environment, (VR) virtual reality

Keywords: fitness, interactive video gaming, mobility, motor control, stroke, virtual reality

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Virtual reality (VR) systems have been proposed as an approach to simulate the environmental conditions of walking and to motivate people to practice.

Since 2004, approximately six different groups have developed and tested VR technology to improve walking for people post-stroke.[12–18] Some of the details of this development were highlighted in a paper that focused on the state of the art in 2007.[19] In the time since that publication, there have been new advances in this area. The purpose of this article is to provide an updated overview in this area of research. First, the technology (hardware and software) used to create VR systems will be presented, followed by an evaluation of the research on training methods to improve walking, with an emphasis on the software used to create the virtual environments (VEs) and the walking outcomes. Finally, insights from observing and working in the field will be provided with specific suggestions for application to individuals with diabetes and other impaired ambulatory conditions.

Virtual Reality Technology: Hardware and Software

Virtual reality systems for rehabilitation typically consist of hardware, software, and a method to connect the user with the VE. Descriptions of such systems for motor rehabilitation[20,21] and integrated motor and cognitive rehabilitation can be found in the literature.[22] In general, the user needs to see the VE displayed or projected in a head-mounted display, a desktop computer, a television, or a screen. Sound and the sense of touch augment the realism of the VE. The interaction of the user with the VE occurs through devices such as gloves, joysticks, treadmills, or sensors, all of which read the user's movements and link them to the behavior of an object or character in the VE. The software renders the VE that may be viewed from either a first-person (seeing the action as if you were in the environment) or third-person (seeing the action from a bird's-eye view, namely, watching the object or person moving in the environment) perspective. The following paragraphs describe how the VR systems for walking rehabilitation have been designed and tested.

The technology used to present the VE and how the person who is walking interfaces with the VE has varied. Virtual environments have been presented using head-mounted displays—in which the user wears a goggle-like device that projects the environment in front of their eyes[12]—as well as computer desktops,[13,17] large rear-projected screens,[14–16,18] and televisions.[18] The primary mode of interacting with the environment is by walking on a treadmill and having the head,[18] foot,[12] or treadmill[15,16] movement read into the environment. The exception to these are the motion-capture systems that read body position and enter the user into the virtual world using their mirror image[14] and a lower extremity robotic interface.[13,17]

The sophistication of the hardware allows the delivery of in some instances of haptic feedback (physical sensation about the movement).[23] Examples include vibration in the shoe when an object is contacted in the virtual obstacle that needed to be cleared by stepping,[12] the sensation of the foot being pushed back when it contacts a target or jostled with turbulence when navigating through a stormy environment,[24] and the sensation of whole body movement congruent with going up or down a ramp.[15]

While the hardware serves as the interface into the virtual worlds, it is the software that animates these systems by providing interactive VEs for people post-stroke. The six research groups working on VR and walking have created task-based software consisting of VEs that primarily require walking in different settings such as parks, street crossings, and indoor environments. The exception to this were the two groups that used either gait-related activities such as side stepping and weight shifting[14] or navigation tasks that did not involve walking, such as boating and flying a plane.[13,17] All VEs provide users with feedback about their performance, whether clearing an obstacle[12,15] or the time to walk on a path. In some instances, the simulations have been game based, where players received feedback in the form of a score.[13,14,17] The feedback provided was designed to motivate the users as well as improve features of their movement. The task, system elements, and outcomes of stroke rehabilitation studies are summarized in **Table 1**.

Virtual Reality to Improve Walking: Lessons from Research

The results of research to determine if training on the VR systems transferred to improved walking in the real world has generally been positive. All investigators have studied people in the chronic phase post-stroke to reduce the chances that the changes observed were a result of natural recovery. These individuals walked at what is considered to be either household ambulation or limited community ambulation speeds (not to exceed 0.8 m/s).[25] For most studies, the goal has been to increase walking speed as well as other mobility and participation goals. One group reported neural plasticity as a result of VR training.[14] Two groups reported increased community mobility.[16,17] Specific outcomes of each study are presented in the outcomes column of **Table 1**.

Feedback provided, dosing of the interventions, and whether the walking simulations were task specific (based on walking) or task based (used tasks other than walking) are presented in **Table 2**. A review of the dosing and task-training columns indicates that a relatively small duration of training of task-specific simulations produced positive walking outcomes, while the task-based therapies required a higher degree of repetition and duration. These findings are consistent with principles of task specificity. Regardless, the dosing of these VR interventions is lower than many other walking therapies (such as body-weight-supported treadmill training), pointing to the promise of VR to improve walking. Although early in the game, the literature is generally positive with Oxford levels of evidence[26] (level of evidence column **Table 2**), ranging from developmental studies to small randomized controlled trials.

Table 1.
Summary of Task, System Elements, and Outcomes of Stroke Walking Rehabilitation Studies

Study (first author)	Task	System	Outcomes
Jaffe[12]	Walking over virtual obstacles	Used head-mounted displays to show a sagittal view of stepping, a treadmill and harness for support, a vibrotactile shoe insert, and a foot with a reflective marker tracked using a camera	Improved speed of walking and obstacle course navigation compared to a group that performed the task in real world
Deutsch[13] Mirelman[17]	Navigation through targets by a virtual plane or boat, using the foot as a controller	Subjects sat with their affected foot in a haptic six-degree-of-freedom robotic lower extremity device interfaced into a VE displayed on a desktop computer	Training with the robotic device interfaced with the VE resulted in improved walking speed, distance, and ankle kinetics compared to training with the robot alone
You[14] Kim[19]	Skiing, avoiding sharks, and stepping games	Motion-capture system tracked the users' movement	Walking category improved relative to a no-treatment control group, and functional brain imaging changes consistent with plasticity
Fung[15]	Walking in a corridor and avoiding obstacles	VE displayed on a rear-projected screen while subjects walked on a self-paced treadmill mounted on a six-degree-of-freedom actuated platform with electromagnetic tracking	Feasible for two persons post-stroke to walk in the VE and avoid obstacles
Yang[16]	Walking in park, lane, and street crossing and over obstacles	VE displayed on three large screens while subjects walked on treadmill and had their feet tracked	Walking speeds improved compared to a control group that walked on the treadmill without the VE
Walker[18]	Walking in a street scene	VE displayed on a television while subjects walked on treadmill with an unweighted harness and had their head motion tracked	Walking speed improved compared to baseline

Table 2.
Summary of Training Elements and Application of Virtual Walking Studies

Study (first author)	Dosing	Walking task specific	Level of evidence[a]	Commercially available
Jaffe[12]	6–12 hours, 120 reps[b]	yes	2	no
Deutsch[13] Mirelman[17]	12 hours, 200–500 reps	no	3, 2	no
You[14]	20 hours, 1320–1965 reps	no	2	yes
Fung[15]	10–15 minutes	yes	4	yes
Yang[16]	3 hours	yes	2	no
Walker[18]	4 hours	yes	3	no
Kim[19]	8 hours VR + 10.5 PT[b]	no	2	yes

[a] Oxford levels of evidence: 1 is the highest level of evidence (individual randomized controlled trial with a narrow confidence interval or systematic review with homogeneity of randomized controlled trial), and 5 is the lowest (expert opinion) level of evidence.
[b] Reps, repetition. PT, physical therapy

Review of the commercial availability column in **Table 2** reveals the biggest challenge in translating the knowledge gained from VR studies from the laboratory into clinical practice. Most of the systems have been developed in laboratories without industry partners. Only two systems are currently commercially available. The cost to purchase them would make it difficult for many sites to afford. Therefore, the promising evidence to support the use of VR in practice is not easily transferred into the clinic. This, in part, explains the enthusiasm for off-the-shelf gaming systems that, at a much lower cost, provide some of the features on these specialized VR systems. The application of such systems in rehabilitation of mobility and balance for individuals post-stroke is being trialed.[27,28]

My opinion about the state of VR rehabilitation of walking post-stroke is based on observations of the field as well the work of my group as described earlier.[13,17,24] The findings of improved walking are encouraging and consistent with the promise that VR could deliver training systems that motivated individuals to practice relevant mobility tasks. It is clear that there has been an optimization and miniaturization of the technology. One group used a system with only a treadmill, markers on a hat, and a television display.[18] These features, found in many clinical settings, make it likely to transfer the technology to practice. The limitation in the field is that systems have not been developed with the intention of using them in the clinic. Possibly partnering with industry early in the development of the VR systems may improve the chances of bringing VR systems to the clinic.

From previous work, we found that the active ingredient in training is the VE rather than the robotic interface.[17,29] Our environments and the theoretical rationale for how they were constructed are described elsewhere,[30] but briefly, important elements of the environment are the carefully selected feedback based on motor learning concepts, flexibility of system based on principles of exercise, and the game-like nature of the simulations. An important feature of the sensor-based haptic systems we have built is the database where all movement performance from the sensors and game performance from the simulation are stored. This rich source of data can be used for feedback during training as well as ongoing monitoring of therapy and reporting of outcomes. The elements of clinical practice that allow the clinician to make decisions about exercise and training parameters were incorporated into to the system, making it acceptable both to clinicians and patients.[31] It took almost 9 years to go from a proof-of-concept study[32,33] to the clinical application at the level of a case report[34] and finally a single-blind randomized trial.[17] This timeframe can clearly be compressed based on previous experience and adjustments in our study methods. It is essential to begin any of these studies with the end user, both the clinician and the patient.[35] In addition, collaboration with a multidisciplinary team of clinician scientists, engineers, human–computer interface and usability experts, and game specialists may expedite development of user-friendly system. Partnering with industry will aid in bringing a product that is vetted by the research to the clinic.

Virtual Reality Applications for People with Diabetes and Other Conditions Affecting Ambulation

The VR systems developed to improve walking for people post-stroke may also be used to encourage mobility for people with diabetes. Management of diabetes to obtain and maintain optimal glycemic control is multifaceted and requires lifestyle changes.[36] Moderate exercise has been shown to have many benefits for individuals with type 2 diabetes, such as decreased cardiovascular risk factors,[37] improved quality of life,[38] and improved blood glucose control by decreasing hemoglobin A1c.[39] Indeed, physical activity has been recommended for individuals with type 2 diabetes.[40] Yet exercise adherence is one of the most difficult behaviors to control, with physical inactivity prevalence between 60% and 70%.[41] Virtual reality walking systems may promote exercise adherence and increase walking and exercise capacity for individuals with diabetes.

Management of diabetes is multifaceted with a heavy emphasis on self-care. Virtual environments for this population may, in addition to promoting physical activity, embed in a game format patient education about medication, nutrition, and lifestyle management. Thus, both cognitive elements of rehabilitation as well as movement elements might be integrated. This approach is consistent with findings that the combination of exercise and diet has better outcomes than either alone for prevention of diabetes.[42,43]

An approach to combining diet, education, and exercise may be easier with VR systems that do not necessarily require walking but instead use biking and monitor heart rate as an input.[44] Work with a VR-augmented cycling kit that was developed for people post-stroke could have their simulations adapted for a cycling task that focuses on the needs of people with diabetes.

In the VRACK system, both motor control and fitness are monitored using the person's pedaling ability as well as the heart rate response to exercise as inputs into the VE. While riding the bike, the person could engage in a game that requires knowledge either about disease management or nutrition.

Further, one might speculate on the application of VR walking systems for individuals with other walking deficits such peripheral artery disease (PAD) and peripheral neuropathy. The design of the VE might be different for each condition by targeting specific movement limitations. For example, individuals with peripheral neuropathies lack flexibility and have foot pain. Creating walking simulations to promote pain distraction while increasing mobility would be of benefit. In addition, such simulations might emphasize balance requirements because balance is known to be affected in persons with peripheral neuropathies.[45] For individuals with PAD who experience ischemic muscle pain, exercising on a virtual biking system might be the first step in increasing exercise tolerance. Progressing to a VR treadmill walking simulation would be consistent with the improved walking performance over ground and the improved quality of life associated with treadmill walking.[46] Alternatively, adapting a VR biking simulation for an upper body ergometer could be used to promote walking capacity. This approach has been shown to improve pain-free walking in individuals with PAD-induced claudication.[47] It is possible that the distraction and or motivation elements of VEs that are based on the evidence for improving physical activity for individuals with PAD and peripheral neuropathy may augment existing interventions.

Thus adapting existing simulations designed to improve mobility for individuals post-stroke to new populations such as individuals with diabetes or PAD may be a way to save on development costs and time to produce VR systems for a patient population that currently does not have them. Viewed from an optimistic perspective, the transfer of knowledge from rehabilitation of walking using VR for individuals post-stroke to other populations may augment existing therapies.

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