
Virtual Reality-Based Approaches to Enable Walking for People Poststroke

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Several approaches have been developed and implemented to use virtual reality for rehabilitation of walking for people poststroke. The purpose of this article is to compare and contrast these approaches by describing the virtual reality technology and evaluating the evidence to support its use. Early findings are encouraging but await verification, refinement, and extension. **Key words:** *ambulation, hemiplegia, locomotion, stroke, virtual reality*

The standard of care in physical therapy for improving gait of people poststroke is largely described in a nonspecific qualitative manner and includes preambulation strength, range of motion, coordination training, and developing postural stability and standing tolerance.^{1,2} Pregait activities are followed by gait training with variable degrees of assistance provided manually or with technology such as gait trainers and body weight-supported treadmill training.^{3,4} The benefit of pregait training is simplicity; the limitation, however, is that it often demands considerable assistance from the therapist, the intensity of treatment is suboptimal, and the actual activity of walking is often delayed limiting the functional gains.⁵

The demand for early active, intensive, and repetitive training has facilitated the development of new technology for gait training. The scientific rationale behind the use of robotics and virtual reality (VR) devices in rehabilitation is that it enables the creation of interventions in which the duration, intensity, and feedback can be manipulated and enhanced to create the most appropriate exercise program for the individual. With the use of VR, the participant can achieve multiple repetitions that are linked to a task or a goal, thus creating a motivating, motor learning experience.^{6,7}

The promise of VR as a tool for rehabilitation of people poststroke has been explored for over 10 years. Many investigators have designed and tested VR-based systems for rehabilitation of the arm⁸⁻¹³ and hand¹⁴ of individuals in the chronic phase poststroke. Upper extremity rehabilitation has been done on site as well as remotely.^{13,15} The

literature evaluating the arm rehabilitation was recently reviewed and found to be promising.¹⁶

Although not as extensive as the upper extremity work, there have also been efforts to design and test VR systems to improve walking ability of people poststroke. Biomechanical and safety challenges for adapting VR to walking have motivated approximately four groups¹⁷⁻²¹ to create VR-based systems to improve walking for people poststroke. There are also groups working on improving walking for people poststroke who have neglect.^{22,23} The purpose of this article is to describe the technologies used to improve walking for people poststroke and evaluate the evidence supporting their use.

VR Systems

VR or the use of a virtual environment (VE) is a simulation of the real world generated by computer software and experienced by the user through a human-machine interface.²⁴ The goal of the VR system is to create a sense of presence,

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Table 1. Description of VR systems and simulations

Citation	Design	Hardware	Simulation	Feedback
Jaffe ¹⁷	Randomized clinical trial With follow-up	HMD, TM with harness	Obstacle clearance	Visual, auditory, vibrotactile
You ¹⁸	RCT	Video capture	Stepping, "Sharkbait," snowboarding	Visual, proprioceptive, faded KP and KR
Deutsch ^{19,20}	Double-baseline, pretest/posttest, blinded, single group With follow-up	Desktop display with haptic robot as input device	Navigation of plane and boat through air or seascape	Visual, auditory, haptic, KR, and KR summary feedback
Fung ²¹	Two cases	Stewart platform, TM with harness	Corridor walking street crossing, park stroll	Visual, auditory, KR

Note: HMD = head-mounted device; KP = knowledge of performance; KR = knowledge of results; RCT = randomized controlled trial; TM = treadmill.

whereby the user is engaged and immersed in a VE. Application of VR as an adjunct to rehabilitation has been termed *VR-augmented rehabilitation*; when provided alone, it is called *VR-based rehabilitation*.²⁵ The fundamental components of a VR system are a computer, software that renders the VE, an input device into the virtual world, and software that coordinates all the elements. As the visual system is most strongly engaged in VR, the simulations need to be rendered with high velocity graphics cards.²⁴

The systems developed to improve walking of people poststroke are all different. Each of the systems will be described in terms of their hardware and software, with emphasis on the simulations and how they have been designed to stimulate specific motor behaviors. The work will be presented by weight of evidence and in mostly chronological order. The research design and elements of each system are summarized in **Table 1**. Selected subject characteristics and elements of the training protocol are summarized in **Table 2**.

Jaffe and colleagues¹⁷ designed a system in which a head-mounted device (HMD) worn like a hat displays virtual objects. Users wore the HMD while walking at their self-selected speed on a treadmill secured with a harness. The user and the therapist saw a side view of the user's leg as it approached an object (see **Figure 1**). The goal of the simulation was to promote lower extremity movements by negotiating the virtual objects

whose height and length changed. If the foot was not lifted high enough or if the step was not long enough, there was a collision with the object and the user experienced vibro-tactile feedback (produced by pager vibrator units) at the heel or toe of the foot.

The application of the VR technology used visual (the presentation of foot as it approached the object), auditory, and vibrotactile (error detection) stimuli as feedback. Although not characterized by the authors in this manner, the vibrotactile feedback could be considered a form of knowledge of results (KR), specifically bandwidth feedback. Namely the user was signaled when the movement was outside (or in this case inside) of an accepted movement trajectory. Bandwidth KR's powerful effect on learning occurs because the error KR decreases as the person improves.²⁶ Users walked at their self-selected speed, which was increased as they became more comfortable with the training. Repetitions were held constant throughout training (120/session), which was administered over 2 weeks for a total time between 6 and 12 hours.

To determine the efficacy of using the VR system, 20 individuals in the chronic phase poststroke were randomized to either the VR group or the real-world obstacle training group. Outcomes were assessed for balance, gait speed, and endurance as well as obstacle course navigation. Two weeks of training yielded improvements for both groups. Notably, the VR group improved

Table 2. Subject characteristics, outcomes, and intervention dosing

Citation	Sample size and acuity	Initial gait speed	Outcome measures	Dose
Jaffe ¹⁷	N = 20	VR Group x = .52m/s SD .22m/s	<ul style="list-style-type: none"> • Balance • Gait speed • Endurance 	1–2 hrs, 3x/wk, for 2 weeks
	X = 3.7 y VR	Range .26–.82 m/s	Obstacle course	120 steps/session
You ¹⁸	N = 10	Not provided	FAC MMAS fMRI	1 hr, 5x/wk, for 4 weeks
	X = VR 2.2 y Control 4.7 y			
Deutsch ^{19,20}	N = 6	x = .64 m/s Range	Gait speed, elevations, endurance, coordination	1 hr, 3x/wk, for 4 weeks
	X = 4.3 years	.14–.84 m/s		200–500 ft movement/session
Fung ²¹	n = 2		Success or failure of habituation & adaptation to VE	10- to 15-min session 39-m walks (3) trials each simulation and increased complexity
	4.5 months 2 years	1.32 m/s 0.74 m/s		

Note: FAC = Functional Ambulation Category; MMAS = Modified Motor Assessment Scale.

significantly more on the percent of the gait speed increase and step length when tested at faster walking speeds. The greatest difference in performance between the real-world and the VR groups was on the percent improvement of the obstacle course test (37% for the VR group in contrast with 7% for the real-world group). At follow-up testing, there was 95% retention for all gait parameters tested. Although encouraged by the findings, the authors appropriately identified several factors that could account for the observed changes, such as a placebo effect because of the novelty of the technology.

You and colleagues¹⁸ used a commercially available video capture system (Gesturetek/ IREX; Sunnyvale, CA) to compare training gait-related activities in VR to a no-treatment control group (see **Figure 2**). Users wore gloves that were detected by a camera and embedded the user in a two-dimensional flat space environment where they interacted with graphical objects.²⁷ The virtual environment was projected onto a large screen in front of the user. Three tasks were selected from

the software's repertoire to stimulate lower extremity movements involving flexion and extension by going up and down a step, balance reactions by capturing stars while avoiding shark and eel attacks, and weight-shifting by "skiing" down a hill and taking as many ramp jumps as possible. None of the simulations involved forward walking, but users did multiple stepping forward and sideways. Users saw themselves in the VEs and interacted with the objects.

Visual (location of the person relative to the objects) and auditory (water sounds in the Sharkabit) feedback were provided by the VR system. The researchers also used weights to increase the difficulty of the movements, and, although not stated explicitly, to augment sensory input. KR was provided by the system for accuracy (number of jumps while ski boarding versus misses) and error rates (number of times the user was contacted by an eel or a shark) as well as by the experimenter about the amount of weight lifted. The experimenter provided knowledge of performance (KP) about the kinematic features of the

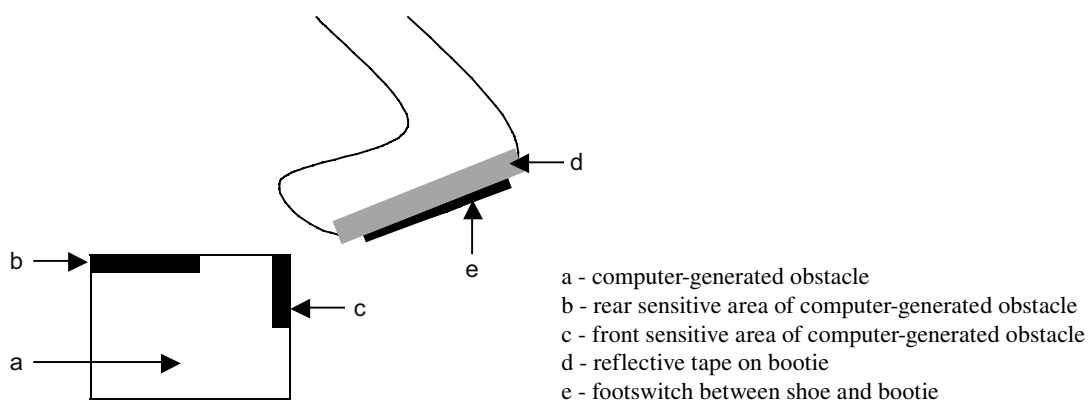


Figure 1. Schematic drawing of subject's view in the head-mounted display. If the foot-sensitive area collided with the front-sensitive area of the object (c), then a toe collision was registered. If the foot-sensitive area collided with the rear-sensitive area of the object (b), then a heel collision was registered. Reprinted with permission from Jaffe DL, Brown DA, Peirson-Carey C, Buckley E, Lew HL. Stepping over obstacles to improve walking in individuals with poststroke hemiplegia. *J Rehabil Res Dev.* 2004;3A:283–292.

movements at the end of the tasks. Exercise progression was not clearly described by the authors. Each of the simulations was performed five times, and the level of the simulation could be adjusted for difficulty based on movement rate. This resulted in a high number of repetitions between 1,320 and 1,965 per session. It should be noted, however, that repetitions and how they were de-

finied were not clearly described by the authors, so this number is difficult to interpret. Training took place over 4 weeks for 1 hour each day for a total of 20 hours.

The VR training group was compared to a nontreatment control group. Outcomes were walking categories and motor ability. Neural plasticity was measured using an fMRI laterality index of sensorimotor-related areas activated during the execution of a knee flexion–extension movement. All individuals in the VR group increased one level in their walking capacity compared to only two individuals achieving this gain in the control group. Four out of five individuals in the VR group improved their motor function compared to none in the control group. Using nonparametric *t* tests, the investigators reported these to be significant differences, although group severity was not comparable. The laterality index shifted from being primarily ipsilateral to contralateral for the sensorimotor cortex and the supplementary motor area. The brain imaging findings were interpreted as a sign of activity dependent plasticity.

Our research group developed a VR rehabilitation system that consists of a desktop display, a controller, and robot as an input device.²⁸ The robot is a pneumatic Stewart platform with 6 degrees of freedom that allows the users to move their foot in all physiologic ankle positions (see

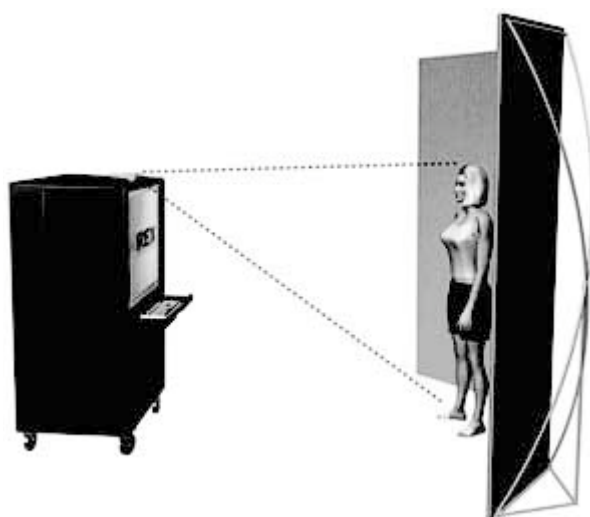


Figure 2. Video capture system used by You et al. Reprinted with permission from Gesturetek.



Figure 3. Rutgers Ankle Rehabilitation System. Six degrees of freedom robot on the left serves as input device for the simulation displayed on the desktop on the right. Reprinted with permission from UMDNJ and Rutgers.

Figure 3). Foot movements executed in sitting are mapped to an object (plane or a boat) in a virtual air- or seascape. Using inverse kinematics, the motions of the foot on the robot are read into the simulation. The user navigates the plane or boat through a series of targets without contacting them. Kinematic and kinetic data are collected for every foot movement with linear potentiometers and a force transducer, respectively. Parameters within the VE (such as target speed and location) are modified to create warm-up, strength, coordination, speed, and endurance exercises for the affected ankle. The VE can be manipulated to change visibility and to add inclement weather (thunder, lightning). The user receives sensory input to the foot (haptics) when they contact a target (by being pushed back) or they experience turbulence in the environment (by oscillations of the robot). The theoretical rationale for the system development is described in detail elsewhere.¹⁹

Visual feedback was provided using three-dimensional graphics on the desktop computer. Vision was further manipulated by changing visibility of the targets (this was as high as 16 targets ahead to the complete absence of the target until it was presented to the user) and the lighting in the simulation, which decreased as the storm in-

creased. Auditory information was provided as an error signal when a user missed the target or contacted it. Haptic (touch) information was provided by the robot's movements: jolts when a target was contacted (the foot was pushed back) and medial lateral oscillations when there was turbulence in the environment.²⁹ KP was provided using color-coded bars that referenced the participants' torques and range of motion to their baseline performance, as well as with the haptic feedback for target contact. KR was provided as summary feedback for accuracy, distance, and repetitions.

In a series of cases, we examined the feasibility of implementing the system in a clinic setting.^{30,31} Based on findings of a case for a person poststroke, we designed a double baseline, pretest/posttest clinical pilot study to confirm that training lower extremity movements in VR transferred to increased gait and elevation speeds and walking endurance in the real world. Training was performed for 1 hour, three times a week, for 4 weeks. The total training time was 12 hours with repetitions increasing from 200 in the first week to 500 in the last week. We found improvements in gait speed (11%), elevations (14%), and endurance (11%). Elevation speed changes were statistically significant, and walking endurance reached the minimal

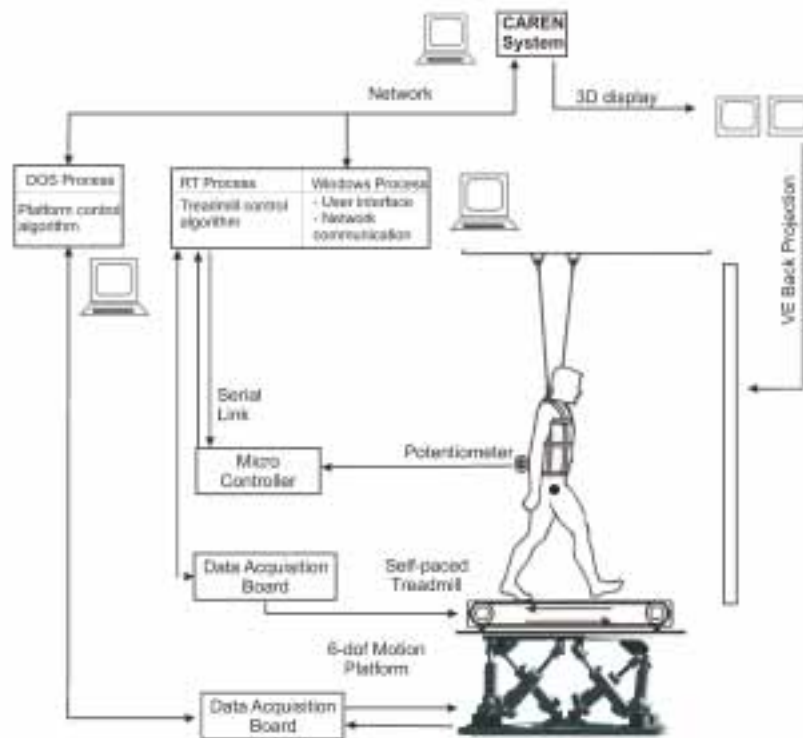


Figure 4. Diagram of the system used by Fung and colleagues. The person walks on a self-paced treadmill that is mounted on a 6 degrees of freedom platform. Velocity is read into the virtual world displayed by a rear projector onto a large screen in which different walking scenes are displayed. Individuals have a harness for safety. Reprinted with permission from Fung J, Malouin F, McFadyen BJ, Comeau F, et al. Locomotor rehabilitation in a complex visual environment. In: Proceedings of the 26th Annual International Conference of the IEEE EMBS; 2004; San Francisco; p. 4860. Copyright © 2004 IEEE.

clinical detectable difference.²⁰ There were also findings of improved intralimb coordination. Controlled studies to determine the relative contribution of the robot and VE are underway. Preliminary findings show a greater effect size for the integrated robot-VR group compared to the robot alone.³²

Fung and colleagues' VR system used a treadmill mounted on a Stewart platform that was interfaced with a rear projector to display the walking environment (see **Figure 4**). The platform allowed for movement into pitch and roll directions. Individuals poststroke walked on the treadmill (at 75% of their self-selected speed) while wearing harness and using an instrumented rail for hand support. Commercially available CAREN (Computer Assisted Rehabilitation Environments, Motek BV, Amsterdam) software was used to control the sys-

tem by synchronizing the instantaneous treadmill speed and scene progressions as well as the motions of the platform. The body and lower limb motions were tracked by an electromagnetic system that allowed the CAREN system to detect collisions with virtual objects.²¹ Three virtual environments were provided: street crossing, corridor walking, and a park stroll. The users' task was to walk through the environment in a predetermined time without contacting any obstacles.

Visual, auditory, and sensory feedback were provided to the users. KR (the successful navigation of the VE) was provided with a visual and auditory cue. Sensory information was provided as the Stewart platform changed orientation. Exposure to the VE was presented in a systematic fashion. Progression to the next level occurred after three successes. First, individuals walked a fixed

distance of 39 m on level ground within a time constraint. Second, they were asked to maintain their gait speed as the terrain moved up and down in the forward direction and from side to side. In the third level, users had to avoid collisions as well as maneuver uneven surfaces and complete the walk in a predetermined time. Training occurred in one session.

To determine if people poststroke could adapt to the walking simulations, the investigators studied two individuals poststroke and compared them to a healthy control. Adaptation to the environment was measured as successful or unsuccessful. Both users adapted to the VE in about 10–15 minutes. As expected, their walking speed initially decreased as they transitioned to level 2. They were not able to complete level 3.

Discussion

The solution to the problem of creating a VR-based system to improve walking for people poststroke has been attempted in four different ways. There are striking differences in the technology used to deliver the VE. One group used a commercially available system with the existing exercises that were designed for balance and lower extremity strength and applied them to gait training.¹⁸ Two groups developed a hybrid system using commercially available technology (HMDs¹⁷ and the CAREN system)²¹ and customized them with their own hardware and software. The fourth group created a complete system.²⁸

In addition to the differences in the technology, the approach to gait training differs among the four groups. Two groups^{18,19} used training that they argue contained relevant components of gait. You and colleagues used balance and weight-shifting activities as well as lower extremity control tasks in standing to transfer to gait; whereas Deutsch and colleagues selected relevant kinematic features of walking (ankle control and coordination) trained in the context of navigation tasks to transfer to gait. In contrast, both Jaffe and Fung trained walking in what would be considered a more ecologically valid approach, namely by having users walk.³³

All the VR walking systems used multisensory

feedback. While somato-sensory input was incorporated into three systems (vibrotactile,¹⁷ haptic,²⁹ and proprioceptive²¹), the fourth application added proprioceptive input manually.¹⁸ Principles of motor learning were incorporated in all systems. The sophistication and extent of these varied. In the future, studies will need to determine how to provide feedback most efficiently and effectively. This process will be informed by the motor learning literature for people poststroke in tandem with VR literature.

It is interesting to note how the dosing for the training studies varied (see **Table 2**). The lowest dose in terms of frequency of treatment (6 sessions) as well as intensity (120 repetitions) produced robust effects, particularly for the obstacle course.¹⁷ The other two training studies^{18,19} had doses that were more consistent with our current understanding of repetitive task practice³⁴ and of high dose practice to improve walking speed.³⁵ The studies with the higher doses, however, were not as task specific in their training approach. We speculate that it is likely that the task specificity will interact with the training intensity. This is a potential research question for dosing in VR.

Subject selection for the implementation of the VR-based walking systems is also of interest. On the important variable of walking speed, there was great variation of subjects enrolled. The slowest walker ambulated at .14 m/s while the fastest ambulated at 1.3 m/s. This broad range is worth noting as individuals' poststroke initial gait speed and balance capabilities may qualify them for one VR training system over another. In addition, visual spatial processing, balance control, and cognitive ability are variables that still remain to be elucidated when one is selecting patients to train in VR.

The four systems presented differ substantially in terms of costs and ease of implementation. To our knowledge, only one¹⁸ of the systems is commercially available; the other three are either prototypes²⁸ or one-of-a-kind systems that have commercial components.^{17,21} The appeal of having a complete system available for use is high as one could purchase it and install it in a clinic. The drawback, however, is that it may lack the customization in terms of tasks and data collection that the other three systems offer.

It is likely that there will be other VR-based systems to improve walking. Several robotic exoskeletal systems (such as dynamic gait orthoses) that operate in conjunction with a treadmill could incorporate VEs to enhance the capability of their systems.^{36–38} Similarly, VR-based walking systems that have been used with healthy people might also be applied to individuals poststroke.³⁹ Also, of the four groups that were described in this article, at least three continue to refine and test their systems. The technology therefore is continuing to develop, and the extent of the application to individuals poststroke remains to be explored.

Summary

Four VR-based systems to improve walking for people poststroke were described. The evidence to support their use was evaluated. Although the

findings are preliminary, they are encouraging. The longevity and specific use of VR-based walking systems is to be determined. However, this technology holds some promise for augmenting existing approaches to rehabilitation of gait for people poststroke.

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