Virtual Reality in Gait Rehabilitation

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Abstract

This paper describes an innovative approach to gait rehabilitation via a system that combines the use of traditional and advanced rehabilitation techniques with a virtual reality (VR) training environment. The VR-Gait system that has been developed consists of VR software that generates and displays a dynamic urban environment on a large high definition television mounted in front of a treadmill. The treadmill is paired with an overhead suspension device that can provide a patient with partial weight support. Inertial tracking is used to actively monitor a patient's posture during a training session and prompt auditory cues that encourage a patient to maintain correct walking posture. This project aims to demonstrate that improved gait rehabilitation can be accomplished using a VR environment composed of widely available, relatively inexpensive, and unobtrusive hardware components. This project will also have the capability to improve medical decision-making by providing objective guidelines for patient progress and projected functional outcome. A validation study with stroke patients is currently ongoing.

1. INTRODUCTION

Gait disabilities are a serious problem that affect millions of people and are accompanied by exorbitant costs. A multitude of causes lead to gait disability including stroke, limb amputation, traumatic brain injury, spinal cord injury, cerebral palsy, and progressive neurological disorders. This paper describes an innovative approach to gait rehabilitation via a system that combines the use of traditional and advanced rehabilitation techniques with a virtual reality (VR) training environment. The goal of this approach is to help patients achieve their maximum functional capacity as efficiently as possible. The first population targeted by this work is stroke patients; however, the results of this project could be applicable to the wider group of individuals with gait disabilities from other causes.

According to the American Stroke Association (ASA), approximately 700,000 individuals each year are diagnosed with a stroke. Of the individuals who survive up to 90% of them report one or more disabilities [6]. Also according to the ASA, the direct cost of strokes in the United States is estimated at 37.3 billion dollars, due to many contributing factors including the loss of ability to work and direct patient care.

As seen in Figure 1, during stroke rehabilitation it is common for patients to practice motor skills and compensatory strategies for daily living activities, including ambulation, within a clinical setting. The hope is that skills gained in a clinical environment will generalize to the patients' home environments.

Figure 1: Current clinical gait rehabilitation for a post stroke patient

The traditional approach to rehabilitation is labor intensive limited in intensity and duration of repetitions and its carryover outside of the rehabilitation setting is uncertain.

Virtual reality technology can help address these limitations by allowing the development of low-cost training environments consistent with a client's home environment. Furthermore, virtual environments are adaptable and can afford patients the opportunity to practice under a variety of simulated circumstances.

The difficulty level of the training scenarios can be adjusted by varying the speed and slope of the treadmill, the complexity of tasks, and the amount of body weight support. A VR system can also give the patient immediate feedback on performance, which is an important component of learning [16]. While skilled therapy will always be a part of rehabilitation, the use of VR-enhanced treadmill training may be a cost-effective way to increase patient motivation to practice walking under different simulated conditions. To study these issues, a new VR-enhanced treadmill system with partial body weight suspension has been developed.

The remainder of this paper is organized as follows. Section 2 reviews previous work related to VR-enhanced rehabilitation and training. Section 3 describes the methods employed to create the VR-Gait system, and section 4 outlines the ongoing validation study. Conclusions and future work are discussed in section 5.

2. PREVIOUS WORK

Extensive research has been conducted to examine the efficacy of VR-enhanced training and rehabilitation. In particular, virtual training environments have been successfully used in teaching both decision-making skills and physical skills [9],[11],[14],[15]. More specific to stroke rehabilitation, a previous study has shown that a stroke patient's use of a paretic arm can be improved through the use of a virtual training environment that delivers visual and auditory cues [6].

Yeh, et al., also performed insightful research on upper extremity motor training for post-stroke rehabilitation using a VR-enhanced environment [18]. The system implemented a "Static Reaching Task" environment in which the subject would reach for virtual 3D objects. This system used shutter glasses to display a 3D environment, and used a tracking device attached to a subject's hand to support interaction with the environment. Although not in the area of gait rehabilitation, this research indicated that VR could be useful in stroke rehabilitation.

Wellner, et al., performed studies on gait rehabilitation by pairing the use of a rehabilitation gait robot "Lokomat" with a virtual environment, to study obstacle crossing improvement [17]. The "Lokomat" system is designed to help subjects with spinal cord injuries; however, the system that was developed could also be used for post-stroke gait rehabilitation. "Lokomat" has a haptic (active touch) interface which can simulate obstacles within the VR environment. In this system the VR environment also contains an avatar that provides event-driven, auditory and visual cues. Testing on spinal cord injury or stroke victims had yet to be completed at the time of publication, but positive feedback was provided by healthy test subjects regarding the visual and audio feedback and the obstacle force feedback.

Closely related to our work is a previous project on gait training that tested two post-stroke patients using a combined treadmill and VR system. This study found that the subjects' abilities to increase their speed and to walk on a slight slope were greatly improved by the VR-enhanced training [5]. However, this research did not incorporate partial weight support or examine the efficacy of the system for patients who were unable to walk completely independently.

Fung, et al., performed studies on gait training for stroke patients by using a treadmill mounted on a 6-degree-of-freedom motion platform with a motion-coupled VR environment [7]. The 6-degree-of-freedom system provided the unique feature of simulated turning within the environment. This system contained an overhead harness, but it was not used in the study. This system also provided auditory and visual cues as positive/negative feedback. Subjects were required to wear 3D stereo glasses to visualize the virtual environment. Test results from this project demonstrated improved gait speed with training.

The VR-Gait system presented in this paper builds on these earlier results and aims to demonstrate improved gait rehabilitation using a VR environment constructed of widely available, relatively inexpensive, and unobtrusive hardware components. If this system provides demonstrable benefits for gait rehabilitation, it could be easily replicated and deployed in a variety of clinical settings.

3. METHODS

The VR-Gait system consists of VR software that generates and displays a dynamic urban environment on a large high definition television mounted in front of a treadmill. The treadmill is paired with an overhead suspension device that can provide a patient with partial weight support. Research has shown that the use of partial weight support in gait training not only acts as a safety device to protect a patient from falling, but it also enables subjects to practice walking with a more normal pattern and at a higher speed [2]. The VR program includes an interactive graphical user interface (GUI) that allows the physical therapist to configure the virtual environment and record information about each training session. In addition to moving cars and pedestrians, the VR environment includes an avatar that acts as a virtual walking partner during the training session. During a session the avatar offers auditory encouragement and advice to improve the subject's morale and to deliver feedback on proper posture. Walking posture is monitored via a small inertial tracking device mounted on a hat worn by a patient during training.

The multidisciplinary team responsible for creating this system has a wide range of expertise. Computer science, engineering, modeling, and simulation capabilities were required to develop the VR environment, interactive GUI, and the data recording and analysis tools. Physical therapists contributed to the design and evaluation of the system, and are conducting the evaluation study with stroke patients. Physician collaborators have assisted with patient recruitment.

3.1 Hardware

The hardware components which are involved in creating the VR-Gait system are an inertial orientation tracking device, a high definition TV, a computer terminal, a programmable treadmill, and an overhead suspension device. The inertial orientation tracking device is an Intersense InertiaCube2, with 3-degree of freedom tracking and a 180Hz update rate. The InertiaCube2 is placed on a cap that a subject wears on his or her head. The tracking system determines whether a subject is maintaining correct posture, looking down, or leaning to one side; leaning is a common problem for stroke patients. The 51 inch Sharp Aquos high definition television is mounted on a stand in front of the treadmill and acts as the display for the VR environment. The computer running the VR software and GUI is a Windows™ Vista PC, containing an Intel® Core™ 2 Duo Processor E6700 (4MB L2 Cache, 2.66GHz, 1066 FSB), 2GB of 667MHz memory, and a 256MB nVidida GeForce 7900 GS video card. The programmable treadmill is a Biodex Gait Trainer 2. The overhead suspension device, Biodex Unweighing System, provides weight support for the patient and has a patient weight capacity of 360lb (163kg).

3.2 Interactive GUI & Data Collection

The GUI provides the entry point into the VR program environment. As seen in Figure 2, the GUI accepts as input the user's personal information, the base speed at which to run the program and a selection of simulation scenarios which vary in speed and length. The GUI acts as a data collection tool as it stores the information of each session for each individual patient in a Microsoft® Excel™ spreadsheet. The GUI can also be used to trigger early termination of the

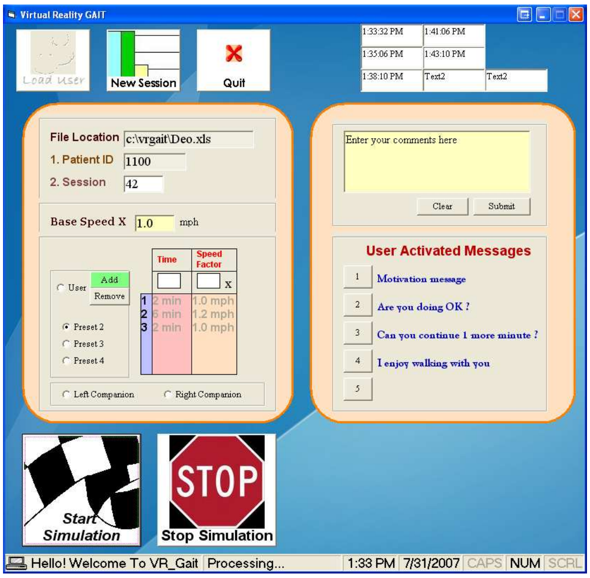

Figure 2: Interactive GUI to enter into simulation containing input boxes for data storage on the right & environment variables settings on the left

simulation. The GUI was developed using Visual Basic.

3.3 The VR Walkthrough Environment

The VR walkthrough environment is a 3 dimensional (3D), interactive linear milieu that subjects walk through. It simulates a cityscape created using the high performance graphics toolkit OpenSceneGraph, the 3D character animation library Cal3D, the character animation toolkit ReplicantBody, and 3D modeling program Autodesk's 3D Studio Max.

As seen in Figure 3, the cityscape is made up of a series of blocks. Four blocks are rendered on each side of the road at any given time. As a block passes behind the subject's viewpoint, that block is deleted, and a new block is created at the end of the remaining three blocks. This ensures that the rendered scene is four blocks deep at all times; however, it results in a pop-up effect. The pop-up effect is controlled through the use of simulated fog that hides objects in the distance and eases them into the visible scene gradually and realistically.

Each block contains a straight road with an array of 3D car models driving up and down the road. The order of buildings and car models is randomly generated each time the simulation is run, thus guaranteeing a different visual experience for each training session.

Located at each side of the virtual road is a series of 3D city buildings and other miscellaneous 3D items such as trees and signs that are randomly selected from a list of 3D models. A footpath is located on each side of the road. The scene camera moves down the left footpath, simulating

Figure 3: Screenshot of the block walkthrough with the avatar located on the left

the subject's walking motion. Also located on and near the footpaths is a selection of 3D character models that are walking, waiting at corners, and interacting with other characters.

The city blocks continue to appear through the fog while the simulation runs; however, when the time for the simulation ends or the GUI is used to initiate the early termination, a call will be made for a final block to appear. The final block contains a selection of tree models, signifying the end of the urban environment, and a model of the "Arc de Triomphe," signifying the "triumphant" completion of the simulation. The display of the final block acts as a positive and encouraging method informing the subject that he or she has successfully completed a session.

3.4 Avatar & Inertial Tracker

Embedded within the VR environment is a virtual friend/avatar that provides support and feedback for the subject within the system. A series of recorded auditory cues are triggered upon the performance of certain events. These include congratulatory messages when certain milestones are achieved and warning messages when the subject is looking down or leaning. Some of these auditory cues are triggered by the inertial tracker.

3.5 System Integration

The VR-Gait system combines many successful features that have been shown to be associated with motor learning and successful gait training. These include progressive decrease in body weight support using the overhead suspension device and repetitive practice and positive feedback on performance using the VR environment and inertial tracker. As seen in Figure 4, all the equipment has been successfully put in place for the system.

Figure 4: A subject on a treadmill connected to the overhead suspension device, wearing a baseball hat with the inertial tracker attached, and looking at the VR environment on the monitor

4. VALIDATION STUDY

The investigation into the success of this system is currently underway. It involves the testing of up to 20 patients who have had a stroke. The Eastern Virginia Medical School (EVMS)

Institutional Review Board (IRB) has granted approval to perform testing on human subjects, allowing recruitment of the patients to begin. The validation study is designed to determine whether there are significant changes in objective measures of gait and functional gait performance.

Each patient must meet a certain set of criteria to be included in the study. These criteria are:

- Be 18 years of age or older
- Have had a stroke within the previous year
- Be able to ambulate independently with or without an assistive device for at least 20ft, but still deem that there is room for improvement
- Have adequate cognitive ability to participate in the study (a mini-mental state examination score of 24 or above)
- Be safe to exercise at low to moderate levels

- Adequate ability to hear VR audio, see VR images, and follow physician commands

Table 1: Sample Progression of Training Speed and Duration

Week/Time	Warm-Up	Training	Cool-Down
Week 1 10 min	1.0 X 3 min	1.0 X+0.5 3 min	1.0 X 4 min
Week 2 12 min	1.2 X 2 min	1.4 X 8 min	1.2 X 2 min
Week 3 15 min	1.4 X 2 min	1.6 X 11 min	1.4 X 2 min
Week 4 20 min	1.6 X 2 min	2 X 14 min	1.6 X 4 min

Each patient will follow a testing storyline that simulates the patient walking through a cityscape, where they are greeted and accompanied by an avatar acting as the patients' "friend." The table of program times and speeds can be seen in Table 1. Where the maximum time is 20 minutes (min), and 'X' is the speed at which a patient walks 20 feet without assistance during the functional gait assessment (FGA). The overhead suspension device starts with 40% body weight supported. The length of time spent walking and the speed of walking gradually increase across sessions, and then the percent of body weight supported decreases by 10% each week. Each subject will progress according to this protocol unless he or she shows signs of exercise intolerance. If there are signs of exercise intolerance, the subject will move to a lower level of exercise for the next training session. If the signs of intolerance indicate that the subject has become medically unstable, the subject will discontinue the intervention and be referred for medical treatment.

Each patient will undergo a functional gait evaluation prior to testing, and parameters of performance will be recorded during training sessions to track progress. Training will be conducted over 12 sessions or until a subject can walk for 30 minutes at 3mph with 0% weight support assistance, whichever comes first. A subject may also discontinue the training session by requesting that the session be discontinued. When either the 12 training sessions have been completed or the patient can walk for 30 minutes at 3mph with 0% weight support assistance, the patient will be re-tested using the functional gait assessment tool. Patients will also be asked for their subjective comments on training with the VR system. All testing and interventions are being performed at the Old Dominion University School of Physical Therapy Research Laboratory.

5. CONCLUSIONS & FUTURE WORK

Although the initial research is being conducted on stroke patients, the VR-Gait system could be used to treat any of the multiple gait disability causing ailments mentioned in Section 1 above. Even though each area of gait rehabilitation may require some specific fine tuning of the system, the overall functionality of this system could be useful for all areas of gait disability.

Application with the amputee population is a strong possibility. Increased motivation and participation might be achieved by adding the gaming element of a scoring system, which would be particularly appealing to younger patients, such as young soldiers coming back from war.

The loss of vision on one side is a common symptom of stroke patients. This motivates future implementation of interactive events and distractions in the VR environment in the hemisphere with diminished vision to stimulate development of a compensatory head-turning habit.

The implementation of visual obstacles within the VR environment along with sensors to track the leg motion is another avenue of possible future extension. While the use of a simulated environment in rehabilitation is mainly a treatment tool, it also will aid in medical decision making in patient progress and prognosis. When the system is fully developed it can be made intelligent, taking into account the patient's abilities in terms of distance, speed, weight bearing, and movement responses so that the decision of when and how much to advance the program's difficulty is automatic and based on patient performance parameters. Once a database of patient use parameters and endpoints has been established, the system could track a patient's starting point and the trajectory of progress in the first few treatments and predict the probable endpoint. Predicting a patient's functional abilities and limitations will help the patient, family and healthcare providers make decisions about the future. This information may also be used to predict who will not benefit from continued treatment so that resources are used most wisely.

6. ACKNOWLEDGEMENTS

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