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Street Crossing Using a Virtual Environment Mobility Simulator

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Abstract

There is a need to manipulate and enrich the gait rehabilitation environment for individuals post-stroke. The virtual environment mobility simulator described in this paper uses two Rutgers Mega Ankle robot prototypes, a PC rendering the simulation exercise, a large display showing the virtual scene, and an unweighing frame. The simulator is designed for training while standing, in a realistic setting of a street-crossing environment. Therapists can change the difficulty of the task in the simulated environment by manipulating a set of variables such as street width, the duration of pedestrian green light, the level of environmental distractions (visual and auditory), as well as the road surface and visibility conditions. The system is currently under development, with pilot trials planned.

Keywords

virtual environments, robotics, gait rehabilitation, Stewart platform, force feedback, post-stroke patients

INTRODUCTION

Most individuals post-stroke do not fully recover their walking ability. Although at 11 weeks most individuals post-stroke may be able to walk [7], they do so at reduced speeds [15][8]. Often, they are not able to achieve the attributes for successful community ambulation, which include a critical gait speed as well as the ability to negotiate uneven terrains (such as street curbs), avoid obstacles and handle manual loads [14].

Remediation of gait speed deficits has been accomplished through the use of task specific training [1] as well as body weight supported treadmill training [18][17]. While both of these interventions were designed by applying theories of motor control and learning to practice and offer individuals post-stroke a mechanism for improving gait, neither provides a rich environmental context for practice. The need for environmental context has been identified as a missing ingredient in rehabilitation of gait [12]. The ability to create meaningful environments is a potential contribution of rehabilitation using VR [16].

This paper describes a mobility simulator consisting of an unweighing frame that supports the individuals as they stand on two Stewart platforms interfaced with a virtual street-crossing environment. The mobility simulator combines haptic feedback and a flexible virtual environment and may be used to complement existing forms of rehabilitation of gait for individuals post-stroke. It is based on the Rutgers Ankle Rehabilitation System (RARS) developed by our group [6][5]. The RARS consists of a single Stewart platform used to train subjects in sitting to reduce lower extremity impairments that interfere with gait [3][2]. The mobility simulator described here can be used to provide repetitive and controlled walking practice while manipulating surface and environmental conditions to set the complexity of the training environment.

HARDWARE SETUP

The hardware components of the Mobility Simulator (shown in Figure 1*a*) are two Rutgers Mega-Ankle (RMA) force feedback robotic devices, one large back-projection screen and an Unweighing System (Biodex Co., Shirley, NY). The patient stands with each foot secured to the top of one RMA robot, facing the screen displaying the

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virtual environment. A dual-processor PC (not shown) performs the graphics rendering and communicates with the RMA electro-pneumatic controller (not shown).

a) **b)**

Figure 1. The -VE Mobility Simulator: a) general view; b) Rutgers Mega-Ankle (RMA) haptic device. © 2004 Rutgers University and UMDNJ. Reprinted by permission.

The Rutgers Mega-Ankle Robot

The RMA (Figure 1*b*) is a compact size Stewart platform robot actuated by compressed air. It is a larger version of the original Rutgers Ankle force feedback device used for training in sitting. It consists of a fixed platform and a moving platform actuated by six pistons. Each piston has two air chambers, so its shaft can either push or pull. A linear potentiometer is mounted on each piston, in order to measure the piston displacement, while a force sensor mounted on the mobile platform measures the forces directly under the foot. The RMA was designed to sustain the larger loads necessary for simulating walking, which the original Rutgers Ankle could not handle. Thus, its actuators output four times the force of the RARS system. The actuators are controlled by a dedicated electro-pneumatic box, which receives data from the PC running the simulation exercise. Force and position data are sampled by the box and used in the RMA position and force control loops.

The Stewart platform architecture used for the RMA robot was chosen because of its good power-to-volume ratio and the flexibility of its six degrees of freedom (DOF). The displacement range of the RMA robot is reduced in comparison to normal walking. The 20 cm forward-backward range only allows the patient to walk with small steps. This hardware constraint is the result of a design trade-off between robot size and workspace dimensions. The goal was to have a robot that could provide a reasonable workspace while being compact enough to be easily deployed. Although short, the step length is long enough to simulate slow walking.

Walking on a treadmill, patients can train at full speeds but the walking surface is always flat and smooth. The RMA robot has an angular workspace large enough to cover human ankle angular range in the center of the workspace (Table 1). By changing the haptic device angles at the point of contact with the virtual walking surface, the system can simulate more challenging ground shapes and slopes, which are more likely to be faced by the patient in the real world than infinite flat and smooth surfaces associated with treadmill training.

Table 1. Rutgers-Mega Ankle workspace limits

Displacement	20 cm sideways	20 cm forward-backward	13 cm up-down
Orientation	45 deg pitch	45 degrees roll	80 degrees yaw

Unweighing Frame

Another hardware component of the Mobility Simulator is the Unweighing System (Biodex Co.). The Rutgers Mega-Ankle robots are strong enough to lift a 300 kg load each. In order to simulate a walking surface, the robots must not only sustain the user but also keep the feet in fixed orientations. The capacity to maintain the orientation of the load is determined by the RMA device's torque output capability. Based on the size of the foot binding mounted on top of the RMA, it was determined that one platform can balance a maximum dynamic load of 50 kg. During walking, a person's weight is fully shifted from one foot to another; hence, each RMA robot must be able to handle, by itself, the full weight of the user. The role of the Unweighing System is to overcome the 50 kg maximum load limitation and make the simulator usable by the majority of patients. Due to the frame's capacity to unload up to 60% of a user's weight, patients weighing up to 120 kg may use the system successfully.

Besides reducing the patient's weight, the unweighing frame also improves safety and comfort for the patient. A side effect of having the patient suspended in the frame is a tendency to spin sideways while using the simulator. This is mitigated by the frame handles, which the patient holds during the exercise, thus reducing body lateral spin.

Back-Projection Screen

The RARS system used a 21" monitor to display the virtual environment that was part of the exercise. Although not large, the monitor was sufficient - to produce immersion, as demonstrated during studies in which the training took place in a busy clinical environment [3][2]. The role of vision in scanning the environment and preparing for movement is a well-demonstrated requirement for gait [13][11][9]. It was considered essential to produce an immersive environment whose complexity could be systematically manipulated based on task hierarchies [4]. Important aspects of gait related to ambient conditions, attentional demands and traffic level can be delivered with the proper visual surround. Thus, it was deemed necessary to scale the visual scene up for the mobility simulator system. A large back-projection screen (74" diagonal, viewable area) was constructed for displaying the virtual environment, in order to increase the patient's "immersion".

Simulating Walking

When the system starts up, both RMA platforms lift at the middle of their vertical workspace and slide all the way backward, where they hold the position. Patients then step onto the platforms and have their feet secured to the foot bindings. In this position, patients experience the feel of a solid surface under each foot. As one foot is lifted to make the first step, the corresponding platform switches from holding the position to following the moving foot. During this phase, the RMA robots compensate for their own weight and inertia so that the patient's foot feels like it is moving freely in air. When the active foot touches the "ground" again, a full step is completed. To take the next step, the patient lifts the backward foot and simultaneously, the front foot starts sliding backwards toward the initial position.

This process is very similar to walking on a treadmill with the major difference that the points of contact with the walking surface can have various orientations and elevations. This features allows for simulating walking on uneven surfaces or climbing stairs. In addition, during the surface contact phase, (touch down, sliding backwards and lift up), the corresponding RMA robot can be programmed to apply haptic effects simulating various surface conditions.

VIRTUAL ENVIRONMENT SIMULATION

Crossing a virtual street is the first VE exercise developed for the mobility simulator described here. The patient's task is to cross the street while the pedestrian light is green. This VE was designed to combine important requirements of community ambulation, which include gait speed and the negotiation of uneven surfaces.

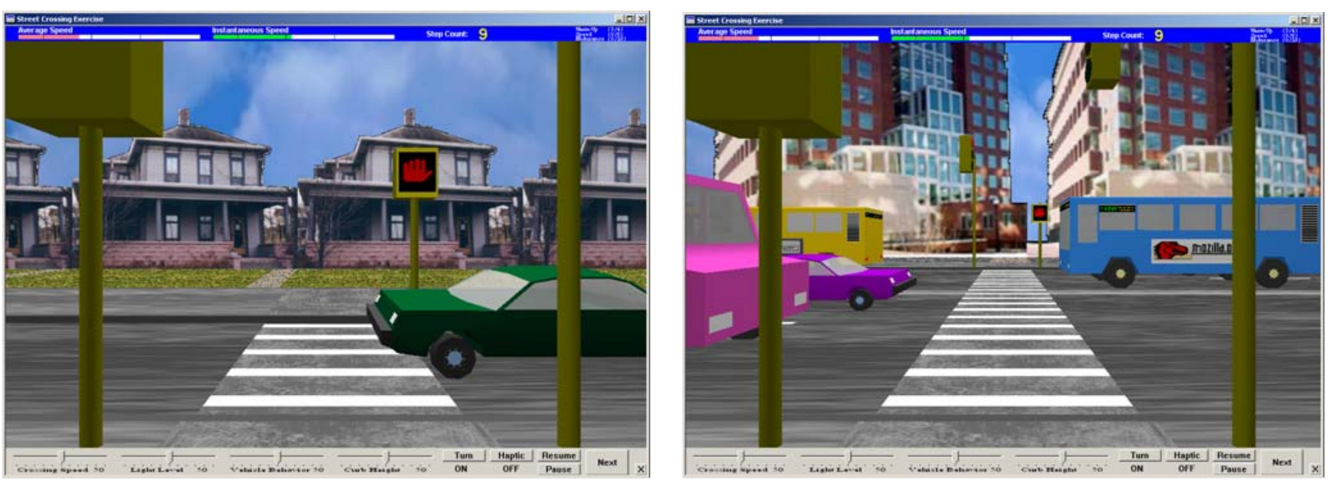
Attributes required for ambulation in complex environments were modeled on the framework presented by Patla [10] and the task taxonomy presented by Gentile [4]. For example, perturbations in this environment can be added to increase the attentional demands of the patient, such as introducing vehicles that encroach on the crosswalk. Ambient conditions can be altered by changing the seasons. Traffic level is increased by adding vehicles or pedestrians. Task complexity is adjusted to patients' abilities to maintain engagement and reduce frustration.

The application window (Figure 2) is divided in three areas: the 3D virtual environment, the control panel and the 2D therapist feedback panel. The virtual environment consists of a dynamic street model containing two sidewalks, driving lanes, stoplights, pedestrian lights and intelligent vehicles. The difficulty of the exercise can be adjusted through a number of configuration parameters that define it. These parameters have been chosen to allow setting the distance and speed at which the patient has to walk as well as changing the virtual world's appearance by season, time of day, or type of community. All the parameters are set by the therapist prior to the session and a subset of them can be modified while the patient is exercising as well.

Simulation Configuration Parameters

The main parameter of the simulation, based on which the success of each tasks is decided, is the patient's average speed required to cross the street. The speed parameter is a percentage between the normal and maximum walking speed the patient can achieve on the simulator. A baseline of these values is obtained daily at the beginning of the therapy session.

The width of the street is defined prior to the exercise start by specifying the number of lanes the street should have. While this affects the distance the patient has to walk to reach the other side of the street, it also triggers a change in the street's appearance. One or two lane streets cause the building textures populating the back of the scene to show houses resembling a suburban setting (Figure 2*a*). Streets with more than two lanes make the environment have an urban look by displaying city buildings (Figure 2*b*). This parameter cannot be changed at run-time. From the speed parameter and the width of the street, the simulation automatically calculates the duration of the pedestrian green light. A flashing red light signals to patients that they are running out of time to cross. In case pedestrians are caught still in the street by the red light, the cars in the same lane will wait for them to cross while the vehicles in the other lanes will continue driving until pedestrians step into their lane.



a) b)

Figure 2. The Street Crossing VR Simulation: a) rural setting; b) urban setting.

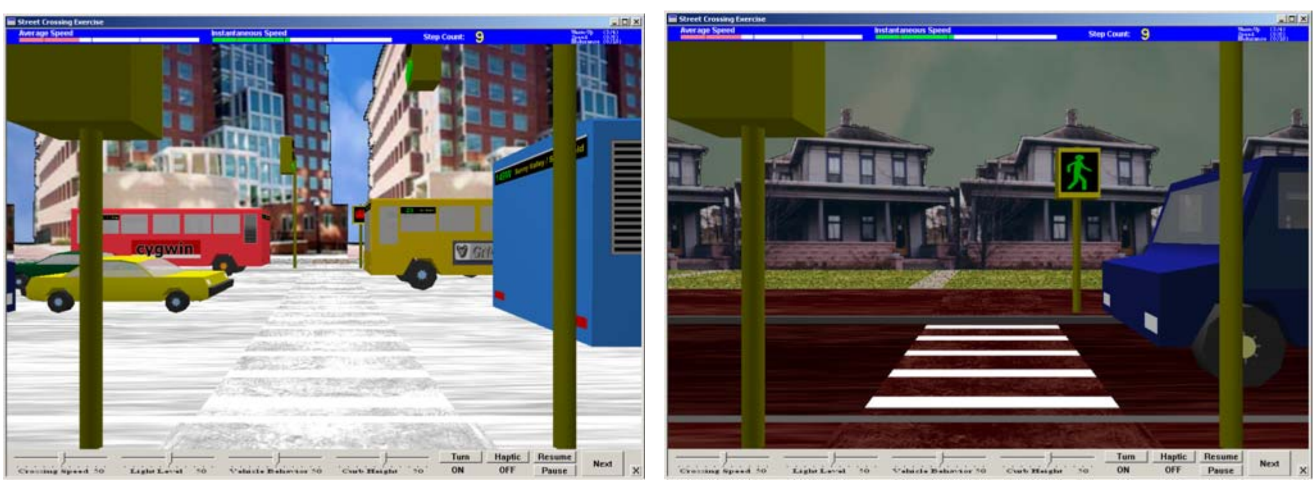
The behavior of the vehicles can be set as a percentage between "well behaved" and "aggressive." Aggressive vehicles will accelerate faster, drive at higher speeds and brake later. They will also behave impatiently when forced to stop; when stopped at the red light, they will slowly inch on the pedestrian crossing. Vehicles will sounds their horns when pedestrians are caught in the middle of the street, during a pedestrian red light. It is anticipated that only individuals who live in settings where these driving behaviors are common (such as large cities) will be exposed to the extreme behaviors of aggressive drivers.

The sidewalk curb height and shape are also configurable. In real settings, the shape of the sidewalk edge can be either a curb or it can be sloped to accommodate wheelchairs. The same situations are supported by the simulation both visually and hapticly. By adjusting these two parameters, the therapist controls the difficulty of the transition from the sidewalk to the road surface. A higher sidewalk can mean either a higher curb or a steeper slope. The curb height is defined as a percentage of the maximum height that can be rendered by the Rutgers Mega-Ankle robots. This feature can be changed at run-time from its current value if the patient is unable to climb the opposite sidewalk, unlike real environments.

Changing the lighting of the virtual world makes elements of the street more or less obvious, thus adjusting the difficulty of the task. The parameter controlling this aspect is a percentage between a minimum and maximum lighting level. Changes in the lighting level also require changes in the building and sky textures. Because the images used as textures were created during a certain time of the day, they may not match the world's lighting level, by showing a sun lit house in a dark environment. To solve this problem, multiple copies of each texture have been created by manipulating the luminosity. The value of the lighting level causes the building and texture images to be switched to lighter or darker versions.

The surface condition parameter is used mainly to define the haptic feedback applied to the patient's feet. Possible settings are ice, mud, gravel, or normal. Since the surface conditions are mostly determined by the weather, this parameter also triggers changes in the visual aspect of the scene. An icy surface will cause the scene to switch to a winter look by applying different house and walking surface texture images (Figure 3*a*). The gravel and normal surfaces will trigger a summer scene setup. The muddy surface will darken the scene as to simulate a rainy day (Figure 3*b*).

Finally, the appearance of the pedestrian crossing can also be selected to be either a zebra or just two lines bordering the path. The zebra crossing provides a greater degree of visual contrast, which may make crossing easier.



a) b)

Figure 3. Selected simulation environment configurations: a) icy road surface in winter; b) muddy crossing at night.
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Off-line Session Configuration

The number of parameters defining an exercise is large, and the duration of one exercise (one street crossing) is less than a minute. Anticipating that the amount of practice and repetition on this task may need to be considerably longer, the simulation can run a series of street configurations set by the therapist prior to the rehabilitation session. Each configuration can be named and the therapist can specify the number of trials (i.e. street crossings) to be used. At the end of each trial, the patient is provided with knowledge of results about the success of crossing, and if necessary, the street is reconfigured to match the next settings. After that, the patient's viewpoint is repositioned on the starting side of the street and the next trial is ready to begin. Using this mechanism, the therapist can plan a complete intervention session with a sequence of simulations and then monitor the patient's performance and adjust the parameters as required.

Run-time Control

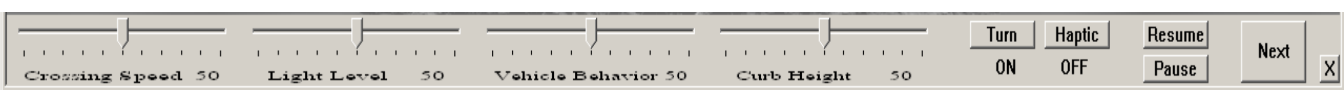
Certain configuration parameters can be adjusted while the patient is exercising through the GUI control panel at the bottom of the application window (shown in Figure 4*a*). Percentage parameters such as patient speed level, ambient lighting level, vehicle behavior and curb height are changed using sliders. Buttons are provided for changing on/off parameters such as ignoring the patient's change in walking direction, or disabling the ground surface haptic effects. Such settings are useful in the early phases of training on the simulator, when the patient and the therapist may need to adjust several parameters to achieve the best frequency, duration and intensity of training.

Four more buttons are provided to allow the therapist to change the flow of the session. The EXIT button ends the session, while the PAUSE/RESUME button can be used for giving the patient a resting break. The NEXT button is used to skip to the next preconfigured trial. This can be used to shorten the current therapy session if the patient shows signs of fatigue.

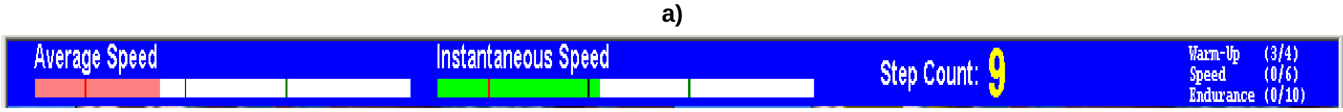
Performance Feedback

The third area of the application window is a GUI 2D panel displaying session and patient information intended for the therapist (see Figure 4*b*). The patient's instantaneous and average speeds are displayed in relation to the trial's target street crossing speed and the baselined normal and maximum speeds. The instantaneous speed is measured over the short time intervals between two sensor readings. The average speed is calculated dividing the distance walked by the patient by the time elapsed since the light turned green. The patient's measured speed is displayed as a scaled bar graph on which the three reference values (trial's target street crossing speed, baseline normal speed, baseline maximum speed) are marked with thin vertical bars. The bar graphs switch color from red to green as the their value exceeds the corresponding set target. Adjacent to the speed bar graphs is displayed the number of steps taken by the patient during the current street crossing simulation.

The session's progress versus the preconfigured setup is displayed by showing a list of configuration names followed by the number of trials completed and the number of trials that have to be executed for that particular configuration.



a)



b)

Figure 4. Simulation GUI: a) control panel. © Rutgers University 2004; Therapist 2D feedback panel. © Rutgers University and UMDNJ. Reprinted by permission.

CONCLUSIONS AND FUTURE WORK

The system is currently in a development phase, in an effort to refine the platforms control and their coupling with the visual feedback from the exercise simulation. This will be followed by validation studies with healthy - subjects and individuals post-stroke. Subsequently, pilot trials with individuals post-stroke will be conducted to determine the effect of the VR-based street crossing training on impairment and functional measures. It is anticipated that training using this system will transfer to improvements in over ground walking in different environments. The feedback from these first trials will be used to improve the technology and address some of its current limitations. This will target increases in platform force output and mechanical bandwidth, as well as reduction in overall system complexity.

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REFERENCES

[1] Dean CM. Richards CL. Malouin F. Task-related circuit training improves performance of locomotor tasks in chronic stroke: a randomized, controlled pilot trial. *Archives of Physical Medicine & Rehabilitation*,. Vol. 81, pp.409-417, 2000.

[2] Deutsch JE, Latonio J, Burdea G, Boian R. Post-Stroke Rehabilitation with the Rutgers Ankle System – A case study. *Presence*, MIT Press, Vol. 10, pp. 416-430, 2001.

[3] Deutsch JE, Latonio J, Burdea G, Boian R., Rehabilitation of Musculoskeletal Injuries Using the Rutgers Ankle Haptic Interface: Three Case Reports. *Proceedings of Eurohaptics Conference*, pp. 11-16, 2001.

[4] Gentile AM. Skill Acquisition in Carr J and Shepherd (Eds) Movement Science Foundations for Physical Therapy in Rehabilitation, pp. 93-154, 1987.

[5] Girone M., Burdea, G., M. Bouzit, V.G. Popescu, and J. Deutsch, "A Stewart Platform-based System for Ankle Telerehabilitation," invited article, Special Issue on Personal Robotics, *Autonomous Robots*, Vol. 10, pp. 203-212, Kluwer, March 2001.

[6] Girone, M., G. Burdea, M. Bouzit, V.G. Popescu and J. Deutsch, "Orthopedic Rehabilitation using the `Rutgers Ankle' Interface," *Proceedings of Medicine Meets Virtual Reality* 2000, IOS Press, pp. 89-95, January 2000.

[7] Jorgensen HS, Nakayama H, Raaschou HO, Olsen TS. Recovery of walking function in stroke patients: The Copenhagen stroke study. *Archives of Physical Medicine and Rehabilitation*, Vol. 76, pp. 27-32, 1995.

[8] Olney SJ, Richards CL. Hemiparetic gait following stroke: Part I: Characteristics. Gait & Posture. Vol. 4, pp.136-148, 1996.

[9] Patla AE, Adaptive Locomotion the eyes have it In Duyens J et al., (Eds.) *Control of Posture and Gait*, pp589-593.2001

[10] Patla AE, Shumway Cook A., Dimensions of Mobility: Defining the complexity and difficulty, *Journal Aging Physical Activity*, Vol. 7, pp. 7-10, 1999.

[11] Patla AE, How human gait is controlled by vision?, *Ecological Psychology* , Vol. 10, pp.287-302, 1998.

[12] Patla AE, Mobility in Complex Environments: Implications for Clinical Assessment and Rehabilitation, *Neurology Report* Vol. 25 (3), pp. 82-90, 2001.

[13] Patla AE, Understanding the role of vision in the control of human locomotion (Invited Review Paper) *Gait and Posture*, Vol. 5, pp. 54-69, 1997.

[14] Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population,. *Stroke*. Vol. 26(2), pp. 982-989, 1995.

[15] Richards CL, Olney SJ. Hemiparetic gait following stroke: Part II: Recovery and physical therapy. *Gait and Posture*,. Vol. 4, pp. 149-162, 1996.

[16] Rizzo A., A SWOT Analysis of the Field of Virtual Reality, Keynote Address, *Proceedings of the Second International Workshop on Virtual Rehabilitation*, pp. 1-2, 2003.

[17] Sullivan KJ. Knowlton BJ. Dobkin BH. Step training with body weight support: effect of treadmill speed and practice paradigms on poststroke locomotor recovery. *Archives of Physical Medicine & Rehabilitation*, Vol. 83(5), pp. 683-691, May 2002.

[18] Visintin M, Barbeau H, Korner-Bitensky N, Mayo NE.A new approach to retrain gait in stroke patients through body weight support and treadmill stimulation. Stroke, Vol. 29, pp. 1122-1128, 1998.