Haptic Effects Modulate Kinetics of Gait but not Experience of Realism in a Virtual Reality Walking Simulator

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Abstract— **Presence in virtual environments is achieved when the user is immersed and experiences a sense of realism. Multi-modal feedback is used to create this sense of realism. This study tested the contributions of visual stimuli and haptic effects to the users' sense of realism on a walking simulator. Haptic effects were modeled as an icy or a muddy road surface. To determine if the haptic effects modified gait we also measured the temporal spatial and kinetic characteristics of walking. Eleven healthy adults walked on a simulator to cross a virtual street. Twenty two walking trials were randomly presented in which either Visual, haptic (floor effects), or combined visual and haptic effects were presented. Realism, feeling and seeing were rated after each trial using a visual analogue scale (VAS). Kinetic data were extracted from the mobility simulator force transducer for initial contact and initial swing. Kinematic data were collected using reflective markers and six-camera system. Reports of realism were not enhanced with the addition of floor effects. Kinetics of gait were modulated by haptic effects with a shorter step length and decreased force in the z (downward) direction during initial contact for ice (haptics alone) and increased forces in the x (forward) and z (upward) direction during initial swing for mud. A shortened step length and decreased velocity relative to over-ground walking may have masked the perception of the floor effects, even though subjects changed their gait kinetics.**

I. INTRODUCTION

VIRTUAL environments (VE) involve real-time multi-modal interactions with simulated worlds [1]. Presence in the VE is achieved when the user is immersed and experiences a sense of realism, reinforced by this multi-modal (visual, auditory, haptic) real-time feedback. Vision and haptics have been shown to be integrated [2]. However, there is a dominance of visual stimuli relative to haptic stimuli for creating immersion [1]. We have designed a walking simulator in which the user experiences hardware driven haptic (road surface) effects linked to visual stimuli in a VE. Previously we characterized the walking behavior of healthy adults in the walking simulator relative to over-ground walking [3]. The purpose of this study was to determine if the haptic effects enhanced the experience of realism in the virtual environment and modified the kinematics and kinetics of gait. It was hypothesized that individuals would report a greater sense of realism when the haptic effects were coupled with the visual effects, followed by the visual effects presented alone and then by the haptic effects presented alone. It was hypothesized as well that gait characteristics would be modified by the surface conditions. For example in the presence of "virtual ice" individuals might shorten their step length and decrease their downward force at initial contact in order to prevent a slip.

II. METHODS

Testing was performed on the mobility simulator (Fig. 1a) with the active part consisting of two Rutgers Mega-Ankle (RMA) robot platforms (Fig. 1c) [4]. The robots allowed the system to change and measure 6 DOF positions and forces at the user's feet. The RMA features a 2 Hz mechanical bandwidth, and 100 Hz servo control loop. A haptic control interface operated the RMAs and was connected to a PC running a VR application. Haptic conditions (ice or mud) were rendered by the platforms, and audio and visual stimuli of a street crossing were presented as the users walked on the mobility simulator (Fig. 1b).

The RMA robot has a parallel-kinematics Stewart architecture implemented using six low-friction dual-acting pneumatic cylinders. On top of the robot and immediately under the user's foot, there is a force sensor that measures the three forces and three torques applied by the user to the platform. The RMA robot's position is calculated based on the length of the pneumatic cylinders measured directly by six co-axial linear potentiometers. For simulating walking, the RMA robot can function either in position control (during stance sustaining the user's foot) or in force control (during lift, attempting to minimize its own perceived weight) [5]

As visible in Fig. 1a, the subject stands with each foot attached to one of the RMA robots while supported by Biodex unweighting frame. The frame is used for safety as the subject is standing (and walking) approximately 45 cm higher than ground. The frame reduction in the subject's perceived weight helps the mechanical response from the RMA robots, by reducing their payloads.

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A. Modeling Haptic Effects

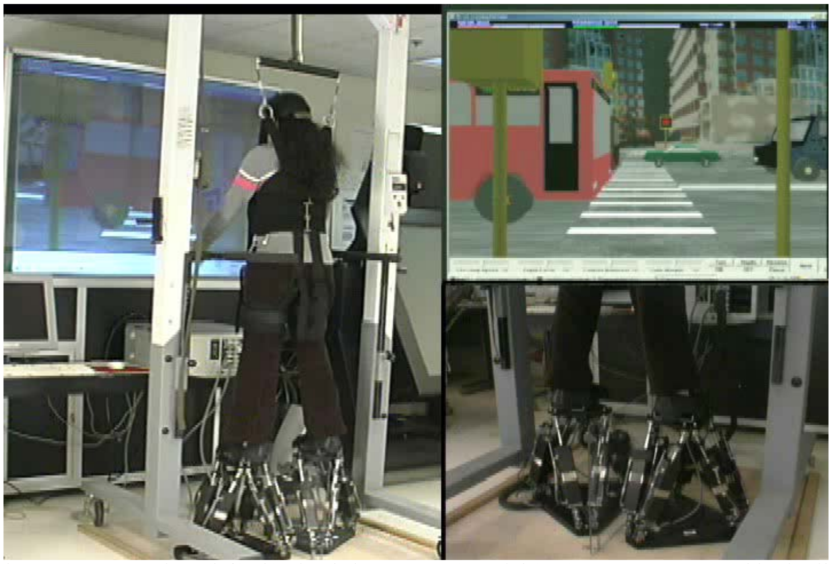

Fig. 1. The Mobility Simulator: a) system view (left); b) simulation screen (top right); c) Rutgers Mega Ankle detail (bottom right). © Rutgers University and UMDNJ. Reprinted by permission.

The haptic effects used for testing were “virtual mud” and “virtual ice.” Regions of the virtual walking surface are covered with such haptic materials, which are displayed visually as patches of color. The algorithm for calculating the haptic feedback specific to each haptic material is presented in detail in [6]. The virtual simulation calculates the forces and torques to be applied to the user’s feet based on the properties of each haptic material patch touched by the subject's foot avatar. The implementation used for these tests takes a simpler approach which yields more robust and stable feedback: the virtual simulation detects the haptic patches on which the user is stepping and notifies the servo controller which is responsible for rendering the required haptic feedback effects.

The mobility simulator models walking using a finite state machine [7]. To understand how the haptic effects were modeled it is sufficient to consider a subset of these states. During gait on the mobility simulator, each foot can be in one of the following four states:

- **FREE** – corresponding to the swing phase of gait;
- **LOCK** – corresponding to the moment when the foot starts making contact with the ground;
- **TRANSLATE** – corresponding to the support phase of gait, during which the RMA platform slides backwards bringing the supported foot in the position to take a new step;
- **RELEASE** – corresponding to the moment when the user starts lifting the foot off the ground.

The ice effect is applied during the TRANSLATE state. While the RMA corresponding to the support foot is sliding backward, it can apply sideway motions of amplitudes and velocities depending on the properties of the ice haptic patch. While the RMA can simulate slippage in any direction, sideways motions were chosen to make the haptic effect more evident during the TRANSLATE state which is in itself a backward motion. The controller applies the effect upon being notified by the VR simulation that the subject is stepping on an ice patch.

The mud effect is applied during the LOCK and RELEASE states, by increasing their duration and the forces the subject has to face. The LOCK state is the transition between the FREE and TANSLATE state. The RELEASE state is the opposite, being the transition between the TANSLATE and FREE states. During both LOCK and RELEASE states, the RMA robot must change its functioning from applying very high forces (that sustain the subjects' foot), to negative forces (that follow the subject's lifting foot). To avoid sudden jolts or instabilities, the transition between high and low forces is done by gradually changing the controller parameters in time. Through experiments, it was determined that the optimal transition is by following a sinusoid curve rather then a linear translation (see Fig. 2). The mud haptic effect is created during the RELEASE state by changing the transition curve such that forces are changing slower, thus creating the sensation of stickiness specific to mud. The same curve is used during the LOCK state. The flatter lower end of the curve applies to the foot high forces for a longer duration, thus creating the sensation of sinking into mud before reaching firm ground.

B. Participants

Eleven healthy individuals participated in the study. Six were female and 5 were male. They ranged in age from 20 to 50 years old. Individuals weighed no more than 150 lbs and were no taller than 5’7’’ These height and weight constraints were imposed by the capabilities of the system. They were free of any musculoskeletal pathology.

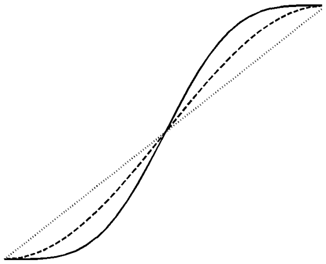

Fig. 2. Mobility simulator robot state transition just before foot lift: Dotted line: linear transition; Dashed line: sinusoid transition; Continuous line: mud haptic effect transition.

C. *Protocol*

Over-ground temporal spatial gait parameters were measured using self-selected walking speed on a GaitRite mat. Three trials were collected and the data were averaged. Subjects then stood on the platforms facing the display screen and were instrumented with markers, one on each fifth metatarsal, lateral malleolus, lateral knee, hip, and trunk. Subjects were unweighted (40% bodyweight) by a Biodex frame. They walked on the mobility simulator until they achieved a criterion gait pattern.

Subjects then performed 22 walking trials of street crossing simulation [8]. The first two trials and the last two trials were the same for all subjects. Pre-trial 1 and post-trial 1 consisted of the subject crossing the virtual street with the visual display on, while pre-trial 2 and post-trial 2 had the subjects crossing the street with the visual display off. The following 18 trials were randomly presented. The street they crossed was either visually displayed or not (Visual on or off). The virtual road surface was in one of three conditions (support surface of level ground, icy road, or muddy road) (See Figs. 3 and 4). The street crossing was always the same length. Objects, such as cars, presented in the street scene were standardized. The lighting was held constant. After each trial, subjects rated realism, visual, and surface experiences using a visual analogue scale (VAS). Specifically, subjects were asked how strongly they saw the environment, felt the environment and how realistic was their walking experience on the mobility simulator.

Fig. 3. Muddy road condition. Shown here in patches but presented continuously in the study. © Rutgers University and UMDNJ. Reprinted by permission.

D. *Data Analysis*

Force data at initial swing (IS), and initial contact (IC) were extracted from the RMA force transducers attached to the platforms. Temporal spatial parameters of gait were collected with and extracted from the 6-camera Peak System. Differences between conditions were analyzed using a RM ANOVA.

E. *Results*

1) *Realism and Sensory Experience*

Table I presents the ratings of realism, feeling and seeing for all conditions. As expected, all the visual (only) conditions had a rating for being seen and a low rating for being felt. As expected the sense of realism was significantly greater for the visual condition alone than the haptic condition alone. Unexpectedly, the combination of haptics and visual stimuli was not significantly greater than the visual stimuli alone. Overall the realism ratings were modest with an average score of 4 out of a possible 10.

Fig. 2. Icy road condition, shown here in patches but presented continuously in the study. © Rutgers University and UMDNJ. Reprinted by permission.

2) *Temporal Spatial Parameters of Gait*

Gait velocities are presented in the first row of Table II. The fastest walking velocity was on the virtual street crossing that was only presented visually and was free of perturbations (haptic effects). The slowest velocity was on the simulated icy road, when no visual feedback was provided (only the haptic effects were present). When both haptics and visual feedback were combined the gait velocities on simulated muddy and icy roads were essentially the same. Gait velocities for all conditions were significantly slower than average over-ground walking speeds (.18-.22 m/s). Step length was also reduced significantly (maximum 20 cm) relative to normal step length of 70 cm [8].

Gait Kinetics are presented in the 3rd- 5th rows of Table II. Forward force (x) during initial swing was significantly greater for the mud relative to the ice condition when the haptic effects were on. Upward force (z) during initial swing was significantly greater for the mud condition relative to the ice condition when the haptic effects were on.

Downward forces (z) during initial contact were significantly greater when haptics and vision feedback were combined. The least amount of downward force was generated during the ice conditions with the haptics alone (no visual feedback).

III. DISCUSSION

The purposes of this study were to determine if the haptic effects coupled with visual feedback increased the sense of realism in the VE (relative to each modality by itself) and to validate the haptic effects of walking on a mobility simulator by measuring the kinetics of walking. Modest immersion was reported for all conditions. We anticipated that reports of realism ratings would be greatest during concurrent haptics and visual stimuli presentations. However, reports of realism were more strongly influenced by the visual scene than haptic effects.

The haptic effects were validated with the kinetic results. Forces increased at appropriate gait events, IS to overcome mud and IC to restrain mud and ice effects. Kinematics and step length were unaffected by visual and haptic manipulations. Subjects reported that walking in a harness was not normal. They also felt that the platforms with their shortened step envelope interfered with the normal sensations of walking. Finally the mud condition created high forces that needed to be overcome in order to make the step, possibly creating a higher degree of exertion than what might be compared to the real situation.

TABLE I
REALISM, FEELING AND SEEING RATINGS*

	Street Crossing	Visual Ice	Haptic Ice	Both Ice	Visual Mud	Haptic Mud	Both Mud
Realism	4.2	4.0	2.8	3.9	4.4	2.7	4.7
Feel		2.6	1.5	3.0	3.7	3.0	3.9
Sight		9.5	0.2	9.8	9.6	0.7	9.5

*Rating scale of 1 to 10

TABLE II
VELOCITY AND KINETICS OF WALKING ON THE SIMULATOR

	Street Crossing	Visual Ice	Haptic Ice	Both Ice	Visual Mud	Haptic Mud	Both Mud
Velocity (m/s)	0.217	0.205	0.183	0.191	0.201	0.193	0.192
Force (N) @ IS X	33.91	40.95	34.95	34.90	36.94	49.11	49.56
Force (N) @ IS Z	17.42	16.50	17.67	17.71	17.38	41.20	40.20
Force (N) @ IC Z	-65.64	-68.94	-62.79	-74.36	-68.21	-66.81	-74.23

Therefore it appears that although the kinetics of walking behaved as one would have predicted, the effects this had on the realism of walking was masked by the shortened step length, decreased walking speed and potentially greater forces required to advance the limb (in the mud condition specifically). While the system hardware limitations adversely impacted the perceived interaction realism, it is important to mention that the Mobility Simulator was to our knowledge the first to simulate surface haptic effects in an walking activity. The system was designed for rehabilitation, with street crossing representing a task often encountered by individuals with walking disabilities

IV. CONCLUSIONS

It appears that while haptics modified the velocity and kinetics of gait the realism of the experience was not enhanced. We attribute this discrepancy to the shortened step length and decreased velocity of walking in simulator relative to over-ground walking. Modeling of the surface effects were validated by the kinetics of walking and the effects for ice may have more closely resembled real world conditions. Several mechanic challenges will need to be overcome in order to increase the step envelope and gait speed.

ACKNOWLEDGMENT

Research reported here was supported by NSF grant BES-0201687 and the Rivers Lab at the University of Medicine and Dentistry of NJ.

REFERENCES

[1] G. Burdea and P. Coiffet P *Virtual Reality Technology*, 2nd edition, Wiley, New Jersey, 2003

[2] M.O. Ernst, M.S. Banks, “Humans integrate visual and haptic information in a statistically optimal fashion.” *Nature* 415(6870):429-33, 2002.

[3] J. E. Deutsch, J.A. Lewis D. McCall, P. Lanin, P. Bowlby, R. Boian, G. Burdea. “Characterization and validation of virtual reality walking simulator. *JNPT* 30 (4) 198-199, 2006

[4] R. F. Boian RF, G.C. Burdea , J. E. Deutsch, JE, and S. H. Winter, SH. Street crossing using a virtual environment mobility simulator , *Proceedings of Third Int. Workshop on Virtual Rehabilitation*, pp. 27-33, Lausanne, Switzerland, September 2004

[5] R. F. Boian, M. Bouzit, G. Burdea, J.A. Lewis and J. E. Deutsch, “Dual Stewart Platform Mobility Simulator,” *International Conference on Rehabilitation Robotics (ICORR)*, pp. 550-555, Chicago, June 28-July 1, 2005.

[6] R. F. Boian, G. C. Burdea J.E. Deutsch Robotics and virtual reality applications in mobility rehabilitation, in *Rehabilitation Robotics,* Sashi S. Kommu Ed., I-Tech Education and Publishing, Austria, 2007

[7] R. Boian, M. Bouzit , G, Burdea and J.E. Deutsch JE. Dual Stewart Platform Mobility Simulator, *Proceedings of IEEE EMBS* , pp. 4848-4851, September, 2004

[8] Perry J. Gait Analysis: Normal and Pathological Function. SLACK 1992.