Evaluation of Shared Walking Environment with Locomotion Interfaces

Hiroaki Yano, Kumiko Oonuki, Gensyun Tai, and Hiroo Iwata
University of Tsukuba
yano@iit.tsukuba.ac.jp

Abstract

This paper proposes a method of enabling users to share the sensation of walking with each other in a virtual environment. To achieve this shared sensation, it requires physical equipments with algorithms to control them. As an example of physical equipment, new footpad type of locomotion interfaces, named GaitMaster2 and GaitMaster3 have been developed. These locomotion interfaces were connected via network and constructed a master-slave walking environment. As an evaluation method of influences of this system to users, the electromyography was measured. As a result, we confirmed that visual and auditory aid is important as well as haptic feedback to the user's feet.

1. Introduction

Traveling on foot is an intuitive and natural practice in the real world. Most of us have experienced that a perception of distance traveled on foot is different from the perception of the same distance traveled by car. This implies that the sensation of walking affects our cognitive map. By contrast, a virtual environment (VE) is usually explored using a hand-held controller, even though walking is the most natural method of locomotion for human beings. Hence, moving around on foot in a VE is one of the major issues to be tackled in virtual reality research.

Locomotion interfaces (LIs) have been developed to allow a user to walk on foot in a VE. Using a LI, the user can experience space perception characteristics similar to those in real world (Iwata 1999). Although walking on foot in a VE could be achieved by the LIs, walking style in the real world takes many forms. There are many different types of walking situation, such as group walking, dancing with partners, jogging, etc. Of course, users of the VE can walk together side-by-side.

In virtual environment, many virtual objects may be placed at the same location simultaneously, unlike the real world. The users can be superimposed in the scene so that they can share the sensation of walking through it. This means that a new virtual environment can be constructed to permit the sharing of experiments with others. For example, in a tele-rehabilitation system, it will be possible for remote users to feel the partner's step-patterns directly and then move their own feet accordingly.

To achieve such various walking styles, it is essential that physical equipments are developed to move a user's feet according to the partner's movement, together with a controlling algorithm to enable the users to share the sense of walking.

The locomotion interfaces of the equipment should have the capability of moving a user's feet back-and-forth as well as up-and-down in sympathy with the remote user's movement. Two footpad-type LIs have been employed in this research. Each LI has two footpads that trace a virtual floor beneath each of the user's feet. This type of LI can be used, not only for displaying virtual terrain, but also for displaying the movement of the remote user's feet. The authors have already developed two footpad-type LIs named GaitMaster (GM1) [1] and GaitMaster2 (GM2) and connected them via network [2]. However the GM1 cannot operate in a sufficient working volume nor are the velocities of its footpads sufficient to trace a user's foot in natural walking. Accordingly, a new footpad type of LI, named GaitMaster3 (GM3), is now proposed to remove such drawbacks of the GM1.

Until now, researches have been mostly confined to the comparison of external aspects such as the trajectories of a user's foot in the real and virtual world. Evaluations using internal aspects, such as physiological indexes that can measure influences on users, have not been considered. The objective of this research is to measure influences on users in shared walking with LIs by using physiological indexes, electromyography.

In a prototype system, the GM2 and the GM3 were connected via the network to provide a bidirectional force feedback environment to the users. A master-slave walking environment was constructed with GM2 and GM3 to enable the sharing the sensation of walking. The influences to the users have been evaluated by several experiments using the prototype system.

2. Related Work

To achieve this shared sensation, it requires physical equipments. An exoskeleton type of manipulator could be used in the above-mentioned method for superimposing a remote and local user's feet in virtual environment,. However, this configuration is not suitable in this application, for several reasons, including mechanical inertia, safety of the user, and difficulties of putting-on and taking-off. As an alternative, LIs can be used to display the same floor simultaneously to both users, by restricting the users' feet to be acted on by their own moving floors.

Locomotion interfaces can be classified into the continuous-floor type or the footpad-type LI. The continuous-floor type of LI provides a floor, which has an area of a few square meters around a user. The floor consists of several belts such as in a treadmill for physical fitness. As a continuous-floor type of LI, the Omni-Directional Treadmill has been developed at Virtual Space Devices, Inc. This device employs two perpendicular treadmills, one inside the other. Each belt is made of approximately 3400 separate rollers, woven together into a mechanical fabric. The motion of the lower belt is transmitted by the rollers to a walker [3]. Iwata has developed the Torus Treadmill, employing twelve sets of treadmills. These treadmills are connected, side-by-side, and driven in a perpendicular direction [1]. The ATLAS has been developed at ATR, employing a treadmill platform with three degrees of freedom [4]. The TreadPort has been developed at the University of Utah, employing a large treadmill with a tilting mechanism [5]. The GSS has also been developed at ATR, employing several actuators inside the belt of a treadmill. The actuators push the belt and a user feels an uneven surface [6]. These LIs allow users to walk in an arbitrary style as long as they remain within the working area of the LIs. However, as it is difficult to restrict users' feet to the moving floors, this type of LI is inadequate for our purpose.

On the other hand, the footpad type of LI has two footpads that trace a virtual floor beneath each of a user's feet by using large manipulators attached to the feet. A footpad type of locomotion interface, named BiPort, has been developed at the University of Utah. Our team has developed the GaitMaster (GM1), employing two manipulators, each with three degrees of freedom. The GM2, which has been newly developed in this study, has improved the velocity and working volume characteristics of the GM1, even though the GM2 has only two degrees of freedom, i.e. back-and-forth and vertical movement.

As a group walking system using LIs, the NPSNET project has produced a battlefield simulator where many combatants can walk, using unicycle-like pedaling devices [7]. However, shared aspect of the sensation of walking that has been focused on in this study was not taken into account at all.

A virtual three-legged race system has been developed with the ATLAS and the GM1 [8]. However, the user of the ATLAS could not experience sufficient force feedback, because several different types of LI were used; the ATLAS, continuous-floor type LI, and the GM1, a footpad-type LI. If there was time lag between the steps of users on the ATLAS and the GM1, only the belt stopped on the ATLAS, even though the footpads of the GM1 had stopped the user's foot motion.

The innovations in this research are the connection of two footpad-type LIs via the network to provide a bidirectional force feedback environment to users, and the proposal of an evaluation method based on physiological characteristics, supplementing previously used evaluation methods, such as trajectories or force profiles on the floor.

3. System Configuration

3.1. Hardware configuration

In this system, the GM2 and the GM3 are used to provide a shared walking environment.

A pictorial overview of the GM2 is shown in the left hand side of Figure 1. The GM2 consists of two 2DOF motion-platforms, which are chain–drive jacks, equipped with an AC servomotor and an optical rotary encoder. Each motion-platform is surmounted by a footpad with dimensions 300mm (depth) x 270mm (width). The footpads have working distances of 670mm in the horizontal direction and 130mm in the vertical plane. The maximum velocity of the footpads is 1470mm/sec. The payload of each motion-platform is approximately 80 kg. The GM2 was also equipped with a safety frame around it. A user of GM2 wears a sandal. Wire length sensors measure the positions of the heel of each sandal. Since each sandal is also wired to each footpad with two 100mm length strings, the working volume of each sandal is limited to within 70mm of the center of the footpad. There is a possibility that a user stubs his/her toe when he/she walks faster than maximum speed of the GM2 because of the presence of the strings. However, the subjective impressions of most of the users are that they can usually walk without stubbing their toe. There is also a possibility that the distance between the sandal and the remote user's sandal is a maximum of 140mm. This problem is overcome if the sandal is fixed to the footpad. However, this results in an un-natural feel, as if he/she is wearing a very heavy sandal, because of the mechanical inertia of the footpad. This configuration is also very dangerous for the users if the GM2 runs out of control. The wired configuration was thus preferred.

In this study, we developed a new LI, GM3. A pictorial overview of the GM3 is shown in the right hand side of Figure 1. The GM3 consists of two 2DOF motion-platforms, which are four longitudinal motion actuators, equipped with an AC servomotor and an optical rotary encoder. Each motion-platform is surmounted by a footpad with dimensions 300mm (depth) x 270mm (width). The footpads have working distances of 800mm in the horizontal direction and 313mm in the vertical plane. The maximum velocity of the footpads is 750mm/sec. The payload of each motion-platform is approximately 80 kg. The GM3 was also equipped with a safety frame around it. The other condition is same as the GM2.

The GM2 and the GM3 were controlled by PCs (Pentium III 500 MHz and 800MHz with Windows 2000 OSs respectively). The position of the footpad could be easily controlled, just by changing the output data from the D/A converter on the PC.

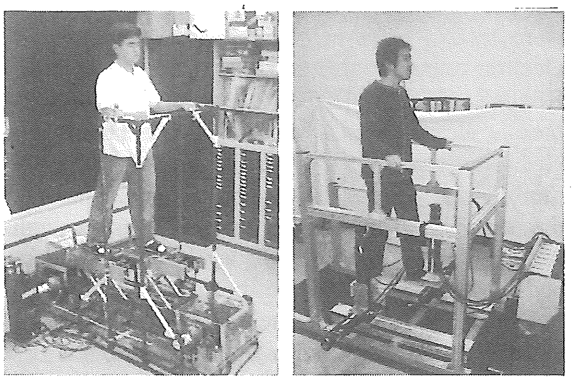

Figure 1. Overview of the GM2(left) and GM3(right)

3.2. Generation of a Sensation of Walking

In this study, two algorithms were developed for generating the sensation of walking on an infinitely flat terrain. One is "active walking", generating a sensation of ordinary walking. The other is "passive walking", which makes the user experience pre-programmed motions of the footpads.

In the active walking mode, when a user moves one of his/her feet forward (swing phase), the footpad under that foot follows it like a shadow over the virtual floor. At the same time, the other footpad (stance phase side) moves back by the same distance as the swing phase foot moves forward. By iterating this motion, the user can walk over an infinite virtual terrain while his/her position remains localized in the real world. In this system, when the height of the user's heel from the footpad is more than 15mm, the phase of walk changes to the swing phase. This threshold was defined for quick and stable detection above the sensor noise levels.

In the passive walking mode, the footpads follow a trajectory that was recorded from a healthy individual walking on a treadmill. The step length that defines the range of movement of the footpad was set to 330 mm, the same as the average of the active walking on the LIs. The height of footpads during a step, as defined by the height of a user's toe, was limited to 50 mm. The average maximum height of users' heel on the treadmill was 100 mm. It was then assumed that a user's toe was usually attached to the footpad and the height of the toe was approximately 50 mm below from the heel, so that a user's toe was usually 50 mm below the heel at top of the trajectory. The phases of the footpads were shifted by 180°.

4. Shared walking environment

The GM2 and the GM3 were connected via a 100BaseT LAN and a prototype system was constructed to share a sensation of walking, as shown in Figure 2. The LAN was used to exchange information on a user's foot position at each locomotion interface via UDP/IP. The exchanged data are 16 bytes consisting of the horizontal and vertical positions, 2 float-type data for each foot.

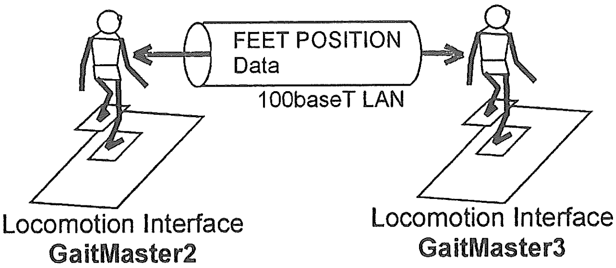

Figure 2. System configuration of a shared walking environment

The entire program was written in C language. The program was divided into the LI controlling thread and the asynchronous network communication thread. The communication data were updated at 100 Hz. The GM2 and the GM3 were controlled at 3 kHz and 4 kHz respectively. Consequently the update rate of the whole system was 100 Hz. When considering the mechanical inertia of the LIs, it is a reasonable configuration with stable control achieved by avoiding the setting of the feedback gain too high. In this study, these LIs lay side-by-side in a room. Users could share their walking experience with other people by watching and talking with each other and sharing the sensation of walking.

To investigate influences of the shared walking environment of the users, a master-slave walking system was implemented as an example of the shared walking environment. The walking style of the master site was set as active walking, while the walking style of the slave site was passive walking. The trajectory of the footpad motion in the slave side did not follow the recorded data but, in stead, followed the data of the foot position from the master site. Thus the footpads of the slave site traced the motion of footpads of the master site as shown in Figure 3.

The user at the slave site was constrained to move in response to the master's motion, and could experience the motion only by putting his/her feet on the footpads. On the other hand, the user at the master site could teach his/her feet motion directly to the remote user without fatigue. In addition, he/she can also adjust the motion of the slave site user by intuitive adjustments to his/her own motion.

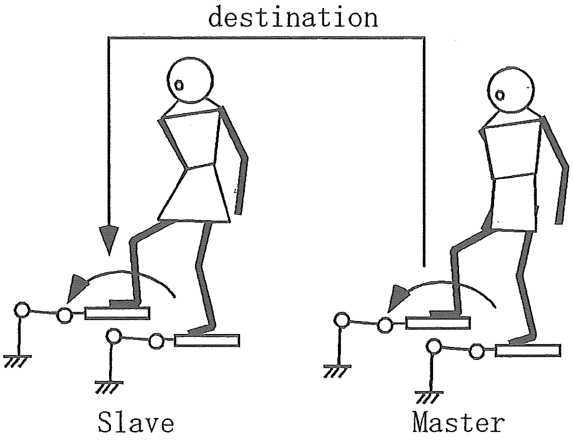

Figure 3. Master-slave configuration

5. Evaluation

5.1. Foot movement

To show the effectiveness of the master-slave walking environment, an experiment was conducted to measure trajectories of feet positions both at the master and slave sites with 5 pairs of healthy individuals. In this experiment, the subject at the master site walked actively and the subject at the slave site just stood on the footpads of the slave LI and walked by following the motion of the footpads.

Representative trajectories of right foot motion of the master site (GM2) and of the slave site (GM3) are shown in Figure 4.

As a result, the subject on the GM3, the slave site, could follow the motion of the foot on the GM2, the master site. The maximum time delay was 10 msec.

The mean distances between the master and the slave were 16.6 mm (2.0 mm standard deviation). Nonetheless, the result showed that the user of the master site could force the movement of the remote user's foot correctly using this technique.

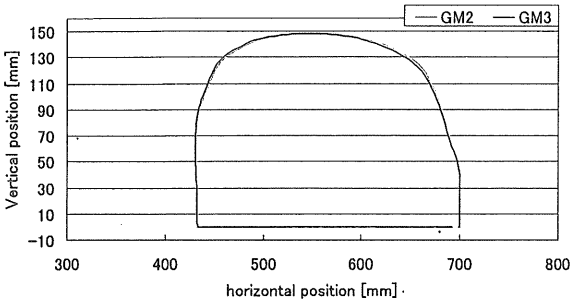

Figure 4. Trajectories of the User's Right Foot on the GM2 (master) and the GM3 (slave)

5.2 Electromyogram

Muscle function was measured using electromyograms to evaluate the influence of walking on the GM2 and the GM3 to each user. An experiment with 2 walking styles was conducted as in the previous section with 3 pairs of subjects who were 23-24 years of age healthy individual. An electromyograph, MEG-6108 made by Nihon Kohden, which has 8 EMG channels, was used for the measurements. We measured the electromyograms of 4 types of muscle. These were the bilateral gluteus medius muscle, the hamstrings, the medial vastus muscle and the gastrocnemius muscle. The muscles of right leg of both the master and slave subjects were measured.

The gluteus medius muscle is one of the muscles attached to the hip, which is in charge of rotation and flexion of the hip joint. It maintains the standing posture during walking. The hamstrings are the muscles at the back of the thigh, which are in charge of extension of the thigh and rotation of the lower thigh. They decelerate the lower limb of the swinging side when the gait switches from the swing phase to the stance phase. The medial vastus muscle is a knee muscle, which is in charge of absorbing the shock when the foot lands on the ground and extension of the knee joint. The gastrocnemius muscle is a sural muscle that is in charge of flexion of the lower thigh and the flinging-up motion used to obtain acceleration [9] [10].

In the experiment with master-slave environment, subjects conducted two conditions. One is "real-time mode" that a master user and a slave user walked together. Another is "playback mode" that only a slave user walked on the GM3 and the GM3 followed the master's trajectory recoded in the real-time mode experiment. The subjects could experience same walking sensation in the real-time mode. However, no visual and audio feedback was given to the subjects so that the effectiveness of visual and audio feedback was evaluated. The experiment conducted in the same day so that the condition of each capped electrode such as where to cling them was kept all the experiment.

Figure 5 shows representative electromyograms of the medial vastus muscle of a subject in the real-time mode. The muscle is in charge of shock absorbing and extension of knee joint in stance phase. Two peaks are observed in each stance phase. First peak is caused the shock absorbing action. The second peak is caused the extension of the knee joint. The first peaks of slave user are observed before each first peak of master user. This means the slave user prepares for landing. Also the second peaks of slave user are observed after each second peak of master user. This means the slave user follows leg movement of the master user.

Figure 6 shows representative electromyograms of the medial vastus muscle of a subject in the playback mode. Some peaks of the shock absorbing are observed 0.5-1.0 sec before master's landing action. This might be caused lack of visual and auditory aids. The playback trajectory of the master user included fluctuations that are caused adjustment by the master user according to the slave walking in the real-time mode and so on. Second peak of extension of the slave doesn't appear, since the slave user prepared for sudden movement.

Figure 7 shows representative electromyograms of the medial vastus muscle of the slave subject both in the playback mode and the real-time mode. Overall, the activations in the electromyograms of the playback mode were lower than those of the real-time mode. Since the subject in the playback mode needed to prepare fluctuations of movements, the subject should move their leg lower than in real-time mode.

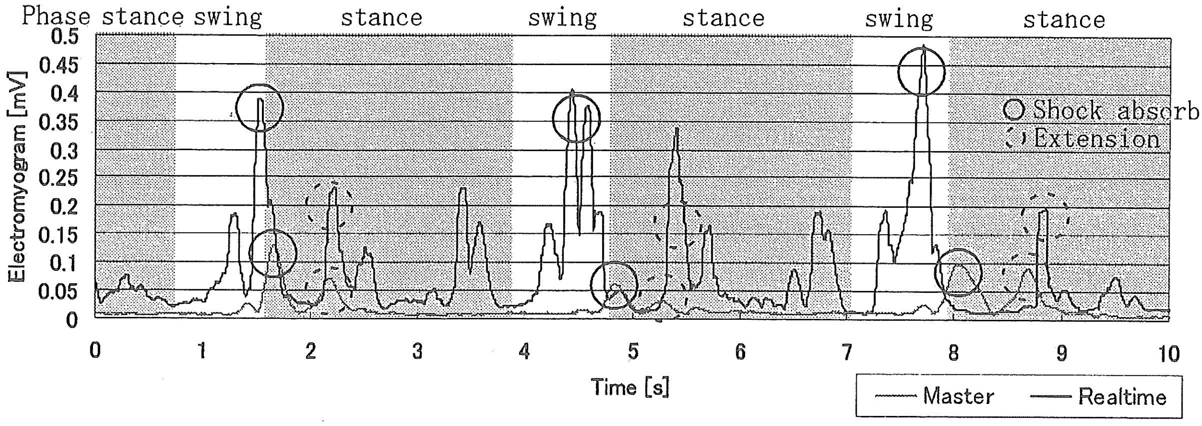

Figure 5. An electromyogram at medial vastus muscle of the master(GM2) and slave user in Real-time mode(GM3)

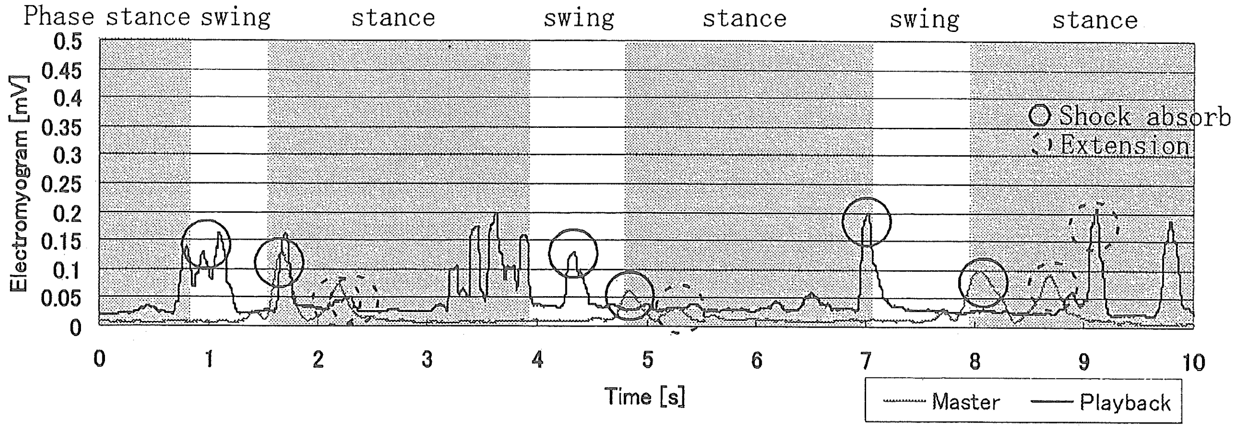

Figure 6. An electromyogram at medial vastus muscle of the master(GM2) and slave user in playback mode(GM3)

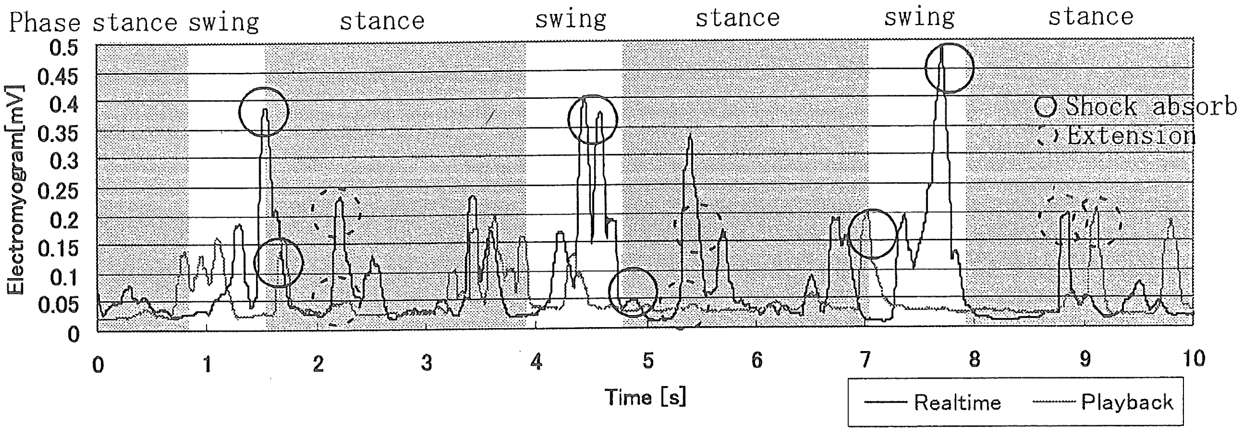

Figure 7. An electromyogram at medial vastus muscle of the slave user in Real-time and Playback mode

6. Discussion

We developed a master-slave environment that can share a sense of walking. We confirmed that the system can transfer the foot movement to remote users. In addition, the visual and audio aid is necessary to share sense of walking. This result could not have been obtained without using electromyogram. The subjects reported that they felt fatigue in the playback mode, since they had to prepare sudden change of the trajectory, even though they remembered the trajectory. This report supports the assertion. However, the quantitative evaluations of effectiveness of these information channels should be investigated.

As remote medical services, a networked locomotion interface would be particularly suitable. By connecting locomotion interfaces, one for the therapist and the other for the patient, the therapist could teach motion to the patient [6]. This system could send motion information from the therapist/trainer to the remote patient directly.

7. Conclusion

In this study, a shared walking environment that consists of two footpad-type locomotion interfaces has been developed. In a master-slave environment of this system, the user's electromyograms were measured and the influences of this system to the users were observed. As a result, visual and auditory aid is important as well as haptic feedback to the user's feet.

In future work, we plan to investigate the influence of this system such as entrainment of walking rhythms.

Reference

[1] Iwata, H., "Locomotion Interface for Virtual Environment." Proceedings of 9th International Symposium of Robotics Research, 220-226, 1999.

[2] Yano, H. et al, , "Shared Walking Environment Using Locomotion Interface"s, Journal of Human Interface Society, Vol.4 No.2, PP.119-126, 2002 (in Japanese)

[3] Darken, R.P., et.al , "The Omni-Directional Treadmill: A Locomotion Device for Virtual Worlds", Proceedings of UIST'97, pp. 213-221, 1997

[4] Noma, H., and Miyasato, T. , "Design for Locomotion Interface in a Large Scale Virtual Environment, ATLAS: ATR Locomotion Interface for Active Self Motion", Proc. of ASME-DSC-Vol.64, pp.111-118, 1998

[5] Christensen, R., Hollerbach, J.M., Xu, Y., and Meek, S., "Inertial force feedback for the Treadport locomotion interface", Presence: Teleoperators and Virtual Environments, 9, pp. 1-14, 2000

[6] Noma,H., Sugihara,T. and Miyasayo, T., "Development of Ground Surface Simulator for Tel-E-Merge System", Proc. of IEEE-Virtual Reality 2000 Conference, pp. 217-224, 2000

[7] Pratt,D. et.al., "Insertion of an Articulated Human into a Networked Virtual Environment", Proc. of the 1994 AI, Simulation, and Planning in High Autonomy Systems Conference, pp.7-9 ,1994

[8] Yano,H., Noma,H., Iwata,H. and Miyasato,T.:"Shared Walk Environment Using Locomotion Interfaces", Proc. of CSCW 2000, pp.163-170, 2000

[9] Whittle MW. "Gait analysis", 2nd ed, utterworth-Heinemann, 1996.

[10] Rose J, Gamble J eds. "Human walking", 2nd ed, Williams Wilkins, 1994