Shared Walk Environment Using Locomotion Interfaces

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ABSTRACT
By sharing data regarding the sensations experienced by individuals, as well as by sharing their knowledge, we are readily able to communicate with each other, and there are possibilities to further evolve this communication method. The different sensations experienced during voluntary walking and enforced walking give us different feelings. Also, the number of individuals involved can create a different feeling when walking. Networked computer-assisted walking can support and enhance these different experiences. In this paper, we introduce another walking style, the shared power-assisted voluntary walk, which is realized by a prototype networked locomotion system. This system can be used in tele-rehabilitation, which allows remote patients to share the sensation of walking. Also, it can be used to teach a group of patients rehabilitative walking. We developed two locomotion interfaces and connected them via a network. We developed enforced and semi-voluntary walking training systems using the shared walk environment and evaluated them with a series of experiments.

Keywords
shared environment, virtual reality, locomotion interface, rehabilitation

CSCW'00, December 2-6, 2000, Philadelphia, PA.

INTRODUCTION

Currently the importance of CSCW is increasing in the office environment. Many commercialized CSCW software packages are used in business. However, there are many other communicative and cooperative situations that can be encountered, such as those found in spatial communication, in the field of engineering, in medical applications and in amusements. CSCW is applicable not only to office work but also to these situations. By sharing the sensation data experienced by each user, such as visual, auditory and haptic sensations as well as their movements and by sharing their knowledge of the work allows the users to communicate easily with each other. By using multi sensory feedback, there is some scope to further evolve the communication method.

Now, traveling on foot is an intuitive and natural practice in the real world. However, the problem of moving around in the virtual environment (VE) on foot is one of the major obstacles to be tackled in virtual reality research. We usually explore a VE using a hand-held controller, even if walking is the most natural locomotion method for human beings. In order to realize natural navigation in the VE, we developed a networked walking system. It allows remotely located people to walk together. Also, a person at one side of the network can control the walking style of a person at the other end of the network.

In this paper, we introduce a method of classification of walking. We have developed two types of locomotion interface devices for walking, and we have created a shared virtual environment using those locomotion interfaces. We applied this networked walking system to tele-rehabilitation to evaluate the system.

The effectiveness of the shared walk environment is shown through the experiments.

RELATED WORK

Locomotion interfaces can be classified into the treadmill type, pedaling devices, the gesture recognition type and the large manipulator type. The treadmill type is a simple device, ordinarily used for physical fitness. A virtual building simulator was developed at UNC [1]. Their treadmill has a steering bar similar to that of a bicycle. An omni-directional treadmill has been developed at Virtual Space Devices, Inc. This device employs two perpendicular treadmills, one inside of 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 [2]. A unicycle-like pedaling device is used for the battlefield simulator of the NPSNET project [3]. A player on the system changes direction by twisting his/her waist. Slater et al [4] developed a gesture recognition system. They proposed locomotion in the virtual environment by "walks in place". The walking motion is recognized by a position sensor and a neural network. A large manipulator type locomotion interface named BiPort has been developed at the University of Utah. This device is driven by hydraulic actuators and is attached to the feet of a walker. Therefore, it is clear that many different types of locomotion interfaces have now been developed.

For the shared haptic environment, we developed the VECS system [5], which connected two haptic interfaces via the Internet and gave a shared haptic sensation for the fingertips. Also Brave and others have developed the inTouch system [6]. They connected force-feedback rollers on remote sites, and by this means shared same physical objects (the rollers) and the haptic sensation for the fingertips. However, there are no systems available that can share haptic sensation for feet. Our research is the first example of connecting locomotion interfaces via a network to build a shared walking environment.

As a rehabilitation system, Volpe-BT et. al used a robot to improve motor recovery of the upper limb [7]. Powered feeding devices have been developed at the University of Delaware [8]. Those devices help to assist the patient with feeding. However there aren't many rehabilitation systems that are specific to walking, though there is a specialized wheel chair to assist transfers [9]. Our system can support not only the patient but also the therapist. Using our system, a therapist can regulate the motion of the patient's foot and teach him/her how to move their legs directly, and with less fatigue.

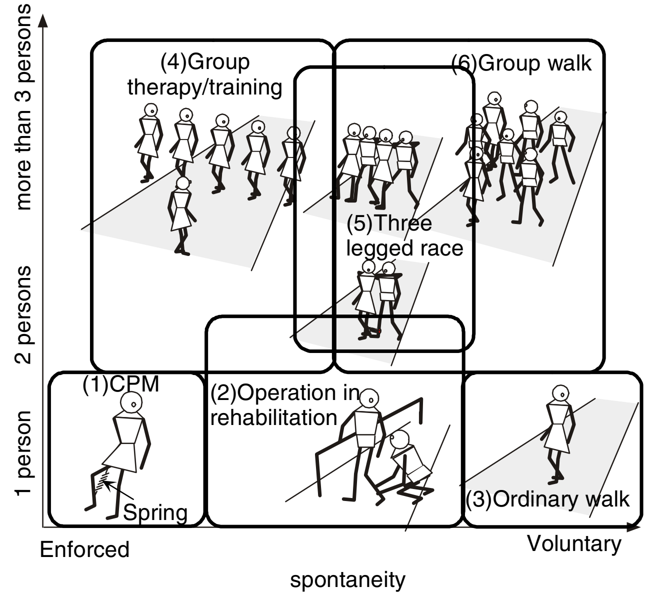

Figure 1. Classification of walking in the real world.

CONCEPT OF THE SHARED WALK ENVIRONMENT

Classification of Walking

There are many different types of walking situation, such as the 'ordinary' walk, the group walk and the training walk. Diagrammatically, walking can be categorized by spontaneity and the number of participants involved, as shown in Figure 1. The ordinary stroll is placed in a high voluntary position (Figure 1(3)). The group walk, such as a sight seeing tour, is placed above it (Figure 1(6)). This type of walk is less spontaneous than the ordinary walk, even if several different people lead the group. The group therapy/training walk is placed in the upper left area (Figure 1(4)). The patients/trainees follow the motion of the therapist/trainer. This is almost an enforced situation. If there are a large number of patients/trainees, it becomes very difficult for the therapist to train them. The three-legged race is placed in the middle of group training and group walks (Figure 1(5)). Synchronization of the participant's steps is necessary in order for them to walk together. CPM (Continuous Passive Motion) is placed near the origin (Figure 1(1)). In this situation the patient is forced to move their body using simple mechanical equipment such as a spring.

Shared walk environment

In this paper, we propose the concept of a shared walk environment, which supports and enhances all of these virtual walking situations. In this networked environment, users can share space by exchanging live video images, computer generated images, and data from sensors. Our locomotion interfaces can simulate uneven terrain surfaces.

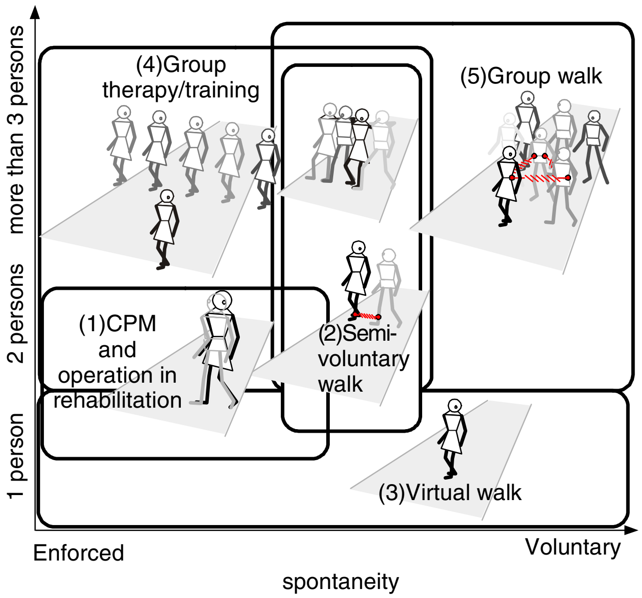

Figure 2. Classification of shared walk environment.

We can generate a haptic (force feedback) sensation to the user's foot. Since the locomotion interfaces are networked, it is not necessary for the users to be together in the same room. Furthermore, the image of each of the walkers can be virtually superimposed in the shared walk environment. Using our system with HMD and real time computer graphics images, we can superimpose the movements of one user's body onto the body of another user. This means that the users can feel each other's step-patterns directly with the aid of visual, audio and haptic sensations, and the users can then move their own feet accordingly. We can construct the environment for a group walk, a three-legged race, group therapy/training, CPM and rehabilitation, as shown in Figure 2. In this group walking environment, we can travel anywhere with other remote users. We can go sightseeing or even make a study tour.

In this paper, we apply the shared walk environment to rehabilitation, manipulation and semi-voluntary (spontaneous) walking. Due to perhaps a traffic accident or aging, people can need to undergo rehabilitation. In the rehabilitation of walking, the motion of the body all is important. Most rehabilitation sessions are conducted verbally or by handling the patient's body to teach them how to move correctly. However, the therapist often finds it difficult to explain the required motion to the patient using only these methods. Applying our system to these situations, the therapist can operate the patient's body easily and avoid fatigue. The patient can learn the motion required by having their foot moved directly, as well as by words. Furthermore, the patients and therapists can communicate while they are separated by hundreds of kilometers.

SYSTEM CONFIGURATION

To build the shared walking environment, we prepared an audio-visual data channel and locomotion interfaces for the haptic sensation required for the feet. The prototype tele-rehabilitation system consists of two locomotion interfaces, GaitMaster and ATLAS. There are many types of these locomotion interfaces, as described in the chapter referring to related work. The users do not always have the same locomotion interfaces. In any shared walking environment we should be able to support many configurations of locomotion interfaces. We choose two typical locomotion interfaces, a large manipulator type (GaitMaster) and a treadmill type (ATLAS). The GaitMaster [8] was developed at the University of Tsukuba, and ATLAS [9] was developed at ATR. They are 600km apart, and are connected by a 64Kbps network (ISDN). The details of the configuration of our system are shown below.

GaitMaster

A new locomotion interface that simulates an omni-directional uneven surface has been designed. The device is named "GaitMaster." The core elements of the device are two 6 DOF motion-bases mounted on a turntable. Figure 3 illustrates the basic configuration of the GaitMaster.

A walker stands on top of the plate on the motion-base. Each motion-base is controlled so that it can trace different positions of the foot, and the turntable traces the orientation of the walker.

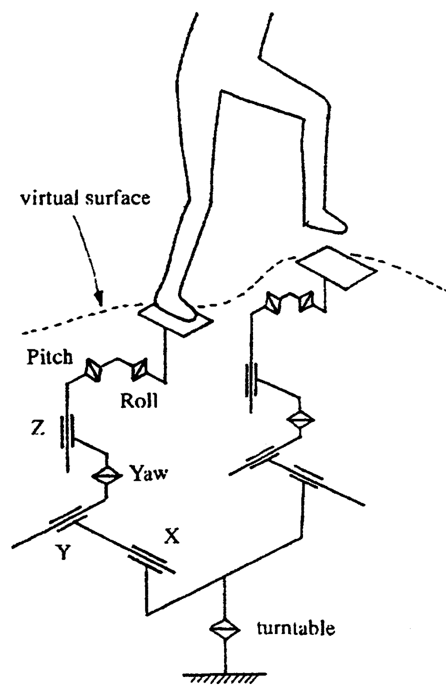

Figure 3. Basic concept of the GaitMaster.

Figure 4. Overview of the GaitMaster.

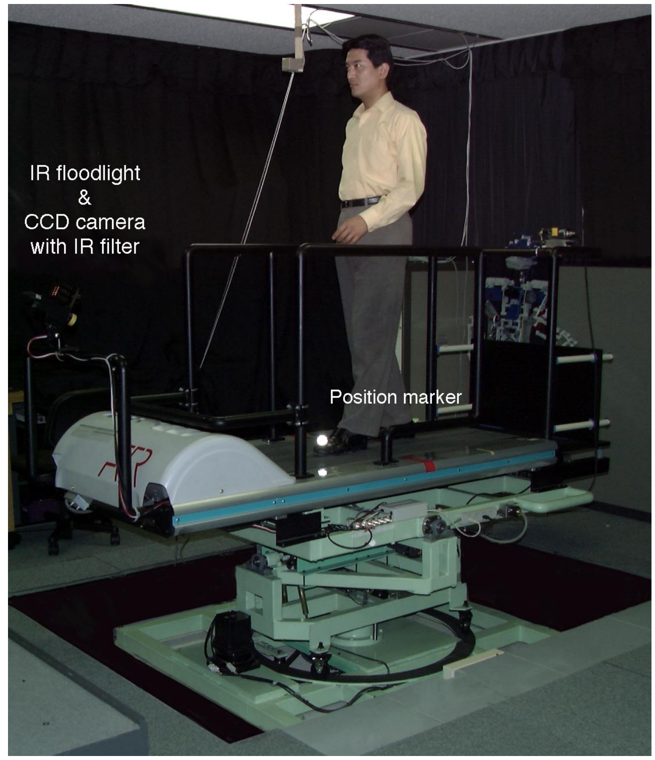

Figure 5. Overview of the ATLAS.

The motion of the turntable removes any interference between the two motion-bases.

The X and Y motion of the motion-base traces the horizontal position of the feet and cancels out the effects of their motion by moving in the opposite direction. The rotation around the yaw axis traces the horizontal orientation of the foot. The Z motion traces the vertical position of the foot and similarly cancels its motion. The rotation around the roll and pitch axis simulates inclination of a virtual surface.

The control algorithm of the GaitMaster keeps the position of the walker at the neutral position of the GaitMaster. In order to keep the walker at this fixed position, the motion-platforms have to cancel the motion of his/her feet. The algorithm of the cancellation mechanism is:

(1) Suppose a snapshot of a walking action, and the right foot is ahead of the left foot.

(2) When the walker moves the left foot forward, the weight of the walker is on the right foot.

(3) The motion-platform for the right foot goes backward in accordance with the displacement of the left foot, so that the center of gravity of the walker is maintained.

(4) The motion-platform for the left foot follows the position of the left foot.

When the walker finishes stepping forward, the motion-platform supports the left foot. When the walker climbs up or goes down stairs, a similar procedure is applied. The vertical motion of the foot is canceled in the same way. The vertical displacement of the forward foot is canceled in accordance with the motion of the backward foot, so that the central position of the walker is maintained at the neutral height.

We have developed a prototype GaitMaster system [8]. In order to simplify the mechanism of the motion-platform, we defined the surface of a virtual space as consisting of several sets of plain surfaces. Since most buildings and urban spaces can be simulated without inclination of the floor, we can neglect the roll and pitch axis of the motion-platforms. Each platform of the prototype GaitMaster is composed of three linear actuators on top of which a yaw joint is mounted. We made two XYZ stages. Three linear guides are applied to support the orientation of the top plate of the motion-platform. The payload of each motion-platform is approximately 150Kg. A rotational joint around the yaw axis is mounted on each motion platform. The joint is equipped with a spring that moves the feet towards the neutral direction.

Figure 4 shows an overall view of the prototype GaitMaster. We implemented the control algorithm mentioned above and succeeded in the successful presentation of various virtual staircases.

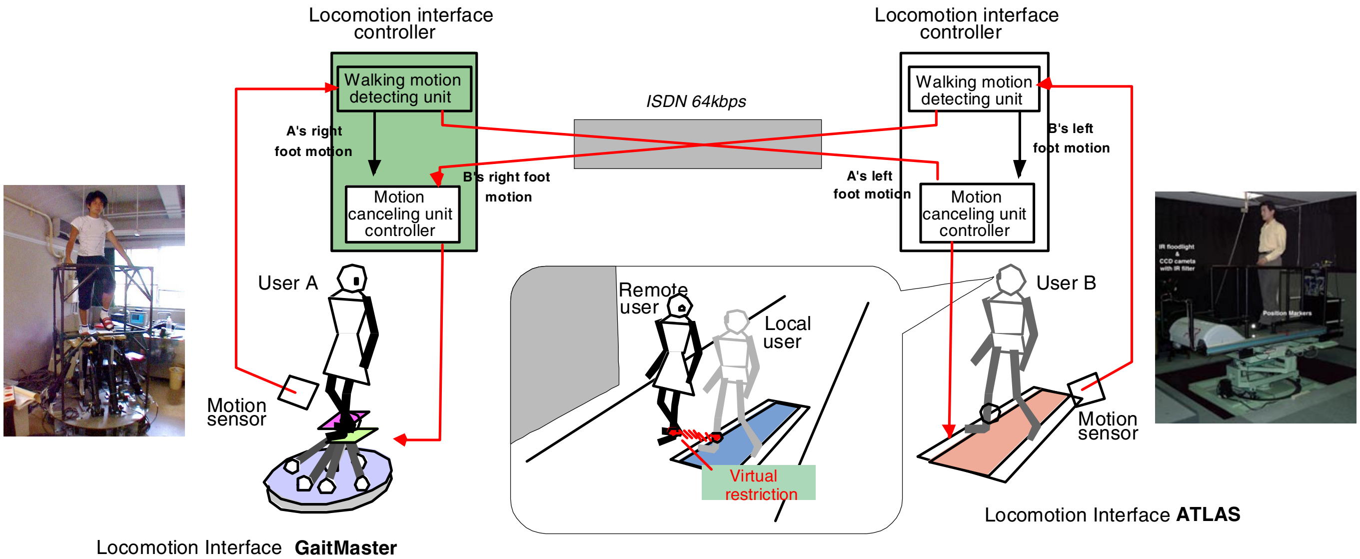

Figure 6. Overview of the shared walk environment.

ATLAS

ATLAS is a treadmill-like locomotion interface. The user can get the sensation of walking on flat ground or on a slope. The main advantage of the treadmill approach is that it gives the user a very natural feeling of walking without any bothersome equipment. We mounted a CCD camera with an infrared light filter and an infrared lamp in front of the treadmill. The relative positions of the small IR reflection markers fitted to each ankle of the walker can be measured by a video-tracking unit. The walking phase, stance and swing phases can be determined by the positions of these markers and the belt speed. By observing an ordinary walking motion on a flat floor, we could see that the duration of the stance phase is almost in inverse proportion to the walking speed. Using this relation, the system can estimate the walking speed while on the belt.

Figure 5 gives an overview of the ATLAS. It also employs a video tracking system, known as QuickMug™ manufactured by OKK. It can track bright markers at 60 Hz. It also uses magnetic position sensors to measure the walker's head direction to support a head-tracked visual display as an optional extension.

Our treadmill is a commercially available product. The walking area of the belt is 145 cm (D) x 55 cm (W). The belt speed can be continuously controlled by a PC from 0 to 4 m/s, with a time delay of 0.09s, and the time constant of 0.10s, within the walking speed. The treadmill is mounted on a custom made three-axis motion platform. It can tilt and rotate the walking surface in any direction. The maximum rotational speed is 1.0 rad/s.

Two computers, a PC and an SGI ONYX control these devices. The PC acts as an interface I/O for the video tracker, the magnetic sensors, the treadmill, and the motion platform. All the data is exchanged via Ethernet. The motion analysis sub-system and belt speed controller reside on the ONYX. These sub-systems operate at 60 Hz. The virtual world simulator sub-system is also implemented on the ONYX. A visual image feedback sub-system generates images of the world on a projector screen in front of the walker.

Configuration of the Shared Walk Environment

The prototype system consists of the two locomotion interfaces that are directly connected via a digital network (ISDN). This system has two digital network lines. One is used to exchange information on the user's foot position on each locomotion interface via UDP/IP. If we use another network line, such as an ATM or analog phone line using a modem, we can switch the data line easily. Another digital line is used to exchange NTSC live video and audio data for a TV phone. The users can share their walking experience with other people by watching the same live image, talking with each other and sharing the sense of locomotion.

Both digital network lines have 64kbytes bandwidth. The data is updated at 30Hz. The frame rate of the video images is 15Hz with a time delay of a few frames. The voice channel has no time delay.

TELE- REHABILITATION: LEG OPERATION

As a first example of the shared walk environment, we implement a leg operation system. Usually, a therapist explains the motion of walking to the patient with words or by physically handling the patient's body. However, using the shared walk environment, the therapist and the patient can be superimposed virtually, as shown in Figure 7. In this system, the ATLAS is used by a therapist/trainer and the

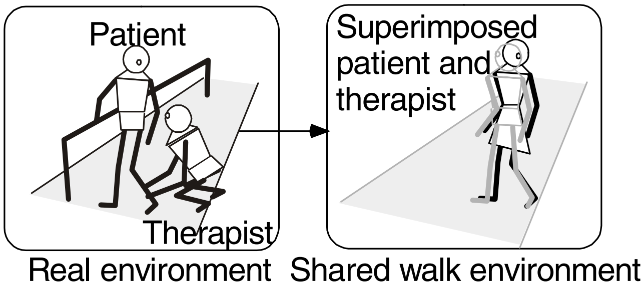

Figure 7. Basic concept of the leg operating system.

GaitMaster is used by a patient/trainee. When the therapist/trainer moves his/her left foot, the top plate of the GaitMaster traces the motion. As a result, the patient/trainee's foot is forced to move along with the therapist/trainer's motion. This is particularly effective for use in rehabilitation (Figure 1-(2)). Using the system the therapist/trainer can teach the motion easily to his/her patients without fatigue, and can also adjust the applied force to the patient/trainee.

Three-dimensional positional data of the therapist/trainer's left ankle is sent to the GaitMaster. The GaitMaster traces it in real time. Therefore the trainer on the ATLAS can operate the left foot of the trainee on the GaitMaster. Furthermore the therapist/trainer can tell what has occurred at the remote site with the aid of the live video image and sound. By using this technique the therapist can adjust his/her patient's motion. On the other hand, the patient/trainee can learn how to move his/her body not only from video and sound, but also from force feedback to their foot. Of course, they can also talk to each other with the TV phone. However, because of the differences in the working volumes of each of the locomotion interfaces, the position data from the ATLAS (therapist/trainer's site) are scaled down by 50 %.

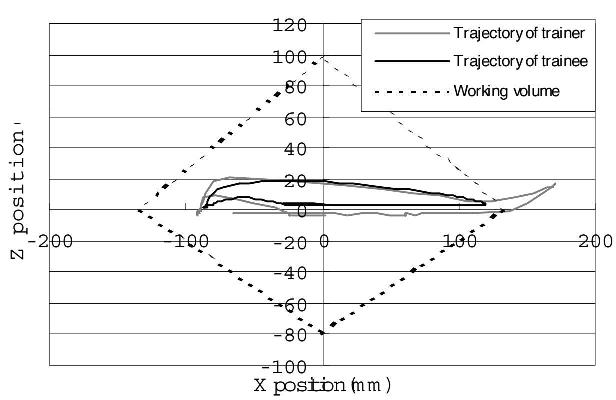

Figure 8. Trajectory of each motion of locomotion interfaces

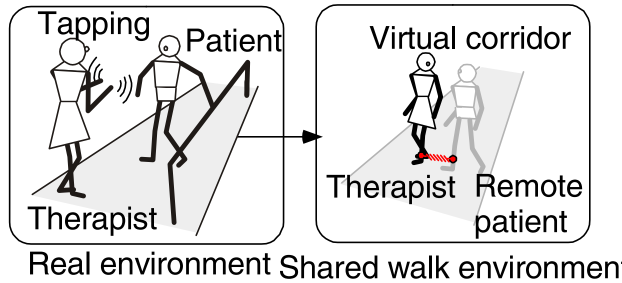

Figure 9. Basic concepts of semi voluntary walk system.

Experiment with Leg Operating System

We conducted an experiment to examine a leg operating system. We measured the trajectories of a user's left foot on the ATLAS and on the top plate of the GaitMaster for a user who is 60kg in weight. As shown in Figure 8, the GaitMaster can follow the user's left foot on the ATLAS. According to the subject, who is a specialist in rehabilitation, the GaitMaster has sufficient working volume and renders sufficient 'feel' of walking to be used as a primary rehabilitation stage. The other advantage of this system is that a trainer who isn't strong enough to manipulate the body of patient can operate them via the equipment.

TELE- REHABILITATION: SEMI VOLUNTARY WALK

As a second example of the shared walk environment, we implemented a semi-voluntary walking environment for use in rehabilitation. Usually the therapist explains the timing of each step during the walk to the patient by using words and tapping out a rhythm. Using the shared walk environment, the therapist and the patient can share their leg motion naturally, as shown in Figure 9. This environment is like the three-legged race, and is the next stage of the CPM. The patient can learn the timing of the step. To generate force feedback there is a simultaneous exchange of motion data between the users. As shown in Figure 6, the left foot motion data of the user of the GaitMaster and the right foot motion data of the user of the ATLAS were exchanged between the two sub-systems. Therefore, the locomotion interfaces restricted the foot motion of each user as if they were actually tied. Accordingly, the users had to synchronize their walking steps. The patient also learns the timing from visual and audio feedback.

Experiment with Semi Voluntary Walk System

We conducted an experiment to examine the degree of synchronization of the user's walking motion with this system. Four pairs of subjects were asked to walk together as fast as they could. To estimate the degree of synchronization, we measured two time lags in the motion of their bound feet for each step. t1 was the time lag in starting the swing phase, and t2 was the time lag in finishing the swing phase. We asked the subjects to walk for 15 minutes and recorded the time lags of the entire step. They were defined by basing them on the motion of the ATLAS user; in short, when the subject on the GaitMaster started his/her motion later than the subject on the ATLAS, the time lag was given a positive value. All the subjects were novice users. The subject on the ATLAS was allowed to call out to his/her partner on GaitMaster to synchronize their steps through the TV-phone.

Figure 10 shows the results of the user testing. We divided each trial into three periods, i.e., the first, middle, and final periods. One period lasted five minutes. One column in the figure represents the average time lag for one period and the error bar represents the standard errors.

In the first period, t1 and t2 vary widely, but they converge as the trial goes on. The converged value t1, i.e., the time lag in starting the swing phase, depends on the particular pair. On the other hand, t2, i.e., the time lag in finishing the swing phase, converges to about 0.4s for all pairs. From these results, we focused on the standard errors of t1 and t2, which represented the degree of convergence of the time lags. As a result of statistical analysis, there was a significant difference in the standard errors for the measured periods (P(F=9.50)=0.01) and between the time lags (P(F=6.14)=0.048). There was no difference in the standard errors between the subjects (P(F=0.98)=0.46).

The user testing showed that the subjects could synchronize their motion step by step, but it seemed that the way in which the walking motions were harmonized depended on each pair's strategy. Furthermore, it was more difficult to synchronize the motion finishing the swing phase than it was the motion starting the swing phase. In fact, observing the trials, the subjects failed to synchronize their motion at this first period, even if they confirmed their steps by calling out to each other. In the final period, however, they could synchronize their steps successfully even if some subjects didn't call out to each other. These results lead to the conclusion that the subjects could become aware of their partner's motions through the locomotion interfaces and adjust their motion by referring to their partner's motion.

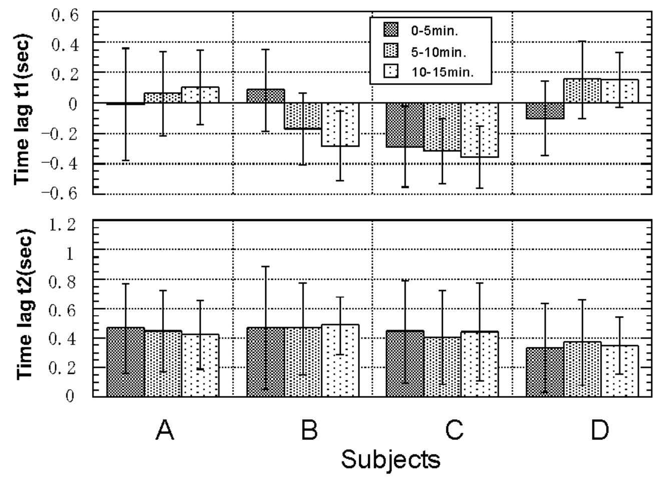

Figure 10. Time lag of starting and finishing swing phase between bound feet

DISCUSSION

We classified various ways of walking from the viewpoint of spontaneity and number of people taking part.

The shared walk environment can support and enhance the process of learning to walk among remote users. In particular, we expect to be able to use the shared walk environment system for rehabilitation and group walk therapy.

This system can improve current training methods, such as those that use only verbal commands and the operation of simple training machines. This system can send motion information from the therapist/trainer to the patient directly, and their motion can also be digitized. The therapist can check the progress of the training quantitatively and plan the next training schedule. Also this system can be applied to a situation where one person needs to communicate with many others, such as group therapy. The precise motion data of the therapist can be sent to the patients simultaneously without fatigue. This is very efficient for under-populated areas where the therapist cannot go easily. The therapist can take care of many patients simultaneously. Needless to say, care should be taken to ensure the user's own safety.

Additionally, the shared walk environment can support and enhance the presence of walking through systems for environmental simulators, architectural simulators and travel simulators. We can share experiences, not only in a visual and auditory sense, but also with a heightened sense of actually walking within those applications. Our system can also be applied to city planning. In any city planning system, we should consider the needs of aging persons [13]. The aging person's sight and hearing ability can become diminished and their muscular strength can become weak. We can simulate those situations using our system.

For future work, we need to develop an algorithm that can connect more than three locomotion interfaces. We should consider how to transmit positional data and how to share live video images among them. We should also consider the symmetry of the locomotion interfaces. There are many different types of locomotion interfaces and associated control algorithms. This system also consists of two different types of locomotion interfaces. A mechanism to merge the differences, such as a scaling factor needs to be developed.

To generate a sense of presence in a remote location, we are planning to combine a special visual display such as an immersive projection display like CAVE [14][15].

CONCLUSION

In this paper, we proposed the shared walk environment as one of new 'shared environments' concerned with using body motion. We classified different types of walking in the real and virtual worlds. We developed a shared walk environment using two networked locomotion interfaces. Two trial applications for the rehabilitation of patients have been implemented using the system. The experimental results showed that the subjects could operate and synchronize their walking motion step by step, as expected.

As the next step of this study, we need to investigate the way in which subjects recognize and react to their partner's motion through a motion synchronizing process using our system. We also plan to develop a group walking environment and a group therapy environment by connecting the locomotion interfaces through the Internet.

ACKNOWLEDGMENTS

The authors would like to thank Hideyuki Saito, who is a physical therapist, and Yuichiro Nara, a graduate school student of the University of Tsukuba, for their many useful suggestions and their cooperation.

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