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Sharing Sense of Walking With Locomotion Interfaces

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This article proposes a method of enabling users to share the sensation of walking with each other in a virtual environment (VE). Achieving this shared sensation requires physical equipment, with algorithms to control it. As an example of such physical equipment, a new footpad type of locomotion interface (LI), named *GaitMaster2,* has been developed and physiologically evaluated. An algorithm for the positional control of users' feet has been proposed, enabling the users to share various aspects of the sensation of walking. As an evaluation, two footpad type LIs were connected via a network. Using the proposed control algorithm, there followed the construction of a master–slave walking environment and a synchronized walking environment. These experiments demonstrated that this method is effective for sharing the sensation of walking in a VE.

1. INTRODUCTION

Traveling on foot is an intuitive and natural practice in the real world. Most people 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 people's cognitive map. By contrast, a virtual environment (VE) is usually explored using a handheld controller, even though walk-

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ing 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 an LI, the user can experience space perception characteristics similar to those in the 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 situations such as group walking, dancing with partners, jogging, and so forth. The objective of this research was to achieve a shared sense of walking related to various walking types and situations in a VE. Of course, users of the VE can walk together side by side, and 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 VE can be constructed to permit the sharing of experiments with others. In a telerehabilitation system, for example, 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 equipment is 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 LIs of the equipment should have the capability of moving a user's feet back and forth as well as up and down in synch with the remote user's movement. In this research, we used a footpad type of LI. It 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. Iwata (1999) has already developed a footpad-type LI named *GaitMaster* (GM1). 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, we now propose a new footpad type of LI named *GaitMaster2* (GM2) to remove such drawbacks. Physiological indexes are now newly introduced to assist the evaluation of the LIs. 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. In this research, we have considered the walking behavior on the GM2 by using physiological characteristics that provide an addition to ordinary evaluation methods such as trajectories or force profiles on the floor.

To control LIs for sharing the sensation of walking, we propose an algorithm that carries out some operations on foot position data of the LIs' users. In a prototype system, two footpad-type LIs, GM1 and GM2, were connected via a network to provide a bidirectional force feedback environment to the users. Using this algorithm, a master–slave walking environment and a synchronized walking environment were constructed with GM1 and GM2 to enable the sharing of the sensation of walking. The effectiveness of the proposed method has been verified by several experiments using the prototype system.

2. RELATED WORK

An exoskeleton type of manipulator could be used in the method mentioned in section 1 for superimposing a remote and local user's feet in a VE. However, this configuration is not suitable in this application for several reasons including mechanical inertia, safety of the user, and difficulties of putting it on and taking it 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.

LIs can be classified into the continuous-floor type or the footpad-type LI. The continuous-floor type of LI provides a floor, which occupies an area of a few square meters around a user. The floor consists of several belts such as in a treadmill for physical fitness. Virtual Space Devices, Inc. (partnered with MTS Systems Corp, USA) has developed the Omni-Directional Treadmill as a continuous-floor type of LI. This device employs two perpendicular treadmills, one inside the other. Each belt is made of approximately 3,400 separate rollers woven together into a mechanical fabric. The rollers transmit the motion of the lower belt to a walker (Darken, Cockayne, & Carmein, 1997). Iwata developed the Torus Treadmill employing 12 sets of treadmills. These treadmills are connected side by side and driven in a perpendicular direction (Iwata, 1999). ATR developed the ATLAS employing a treadmill platform with 3 *df* (Noma & Miyasato, 1998). The University of Utah has developed the TreadPort employing a large treadmill with a tilting mechanism (Christensen, Hollerbach, Xu, & Meek, 2000). ATR has also developed the Ground Surface Simulator employing several actuators inside the belt of a treadmill. The actuators push the belt and a user feels an uneven surface (Noma, Sugihara, & Miyasayo, 2000). 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. The University of Utah has developed a footpad type of LI named BiPort. The authors' team has developed the GM1 employing two manipulators, each with 3 *df.* 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 2 *df*—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 (Pratt et al., 1994). However, the shared aspect of the sensation of walking that we 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 (Yano, Noma, Iwata, & Miyasato, 2000). However, the user of the ATLAS could not experience sufficient force feedback because several different types of LIs were used; the ATLAS; a continuous-floor type LI; and the GM1, a footpad-type LI. If there was a 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 a 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. FOOTPAD TYPE LI: GM2

3.1. System Configuration of GM2

Because the GM1 employs six longitudinal motion actuators, the working volume (see Figure 1) and the velocity (300 mm/sec max) are not sufficient for natural movements. Thus, a new LI named the GM2 has been developed employing chain-drive jacks instead of the longitudinal motion actuators.

A pictorial overview of the GM2 is shown on the right side of Figure 2. Figure 3 shows the system configuration of the GM2. The GM2 consists of two 2 *df* 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

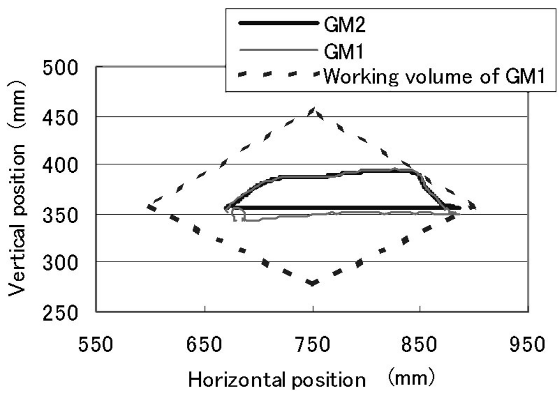

FIGURE 1 Trajectories of the user's right foot on the GaitMaster1 (GM1; the master) and the GaitMaster2 (GM2; the slave) in the GM1 coordinate.

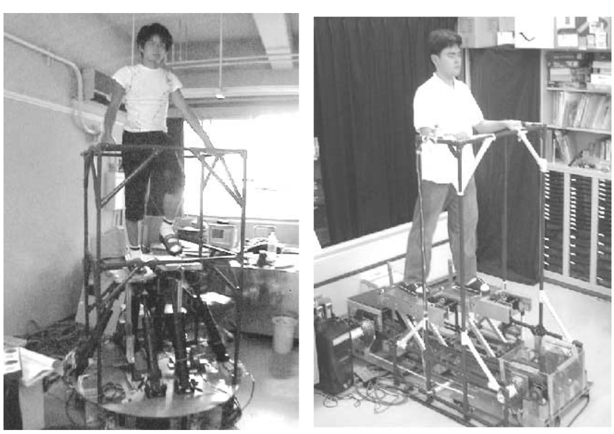

FIGURE 2 Overview of the GaitMaster1 and the GaitMaster2.

dimensions 300 mm (depth) × 270 mm (width). The footpads have working distances of 670 mm in the horizontal direction and 130 mm in the vertical plane. The maximum velocity of the footpads is 1,470 mm/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 the GM2 wears a sandal. Wire length sensors measure the positions of the heel of each sandal. Because each sandal is also wired to each footpad with two 100 mm length strings, the working volume of each sandal is limited to within 70 mm of the center of the footpad.

There is a possibility that a user can stub a toe when walking faster than the 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 requirement that the distance between the sandal and the remote user's sandal is a maximum of 140 mm. In fact, this distance might be larger in the synchronized walking described later. This problem is overcome if the sandal is fixed to the footpad. However, this results in an unnatural feel as if the user is wearing a very heavy sandal because of the mechanical inertia of the footpad. This configuration is also very dangerous for the user if the GM2 runs out of control. The wired configuration was thus preferred.

The position of the footpads was measured using an optical rotary encoder on the AC servomotors (Panasonic MSMA 0.4kW, 1/30 reduction ratio; Japan). The GM2 was controlled by a PC (Pentium® III 500 MHz with a Windows® 2000 operating system). The position of the footpad can be easily controlled by changing the output data from the D/A converter on the PC.

3.2. Generating 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," simulating ordinary walk-

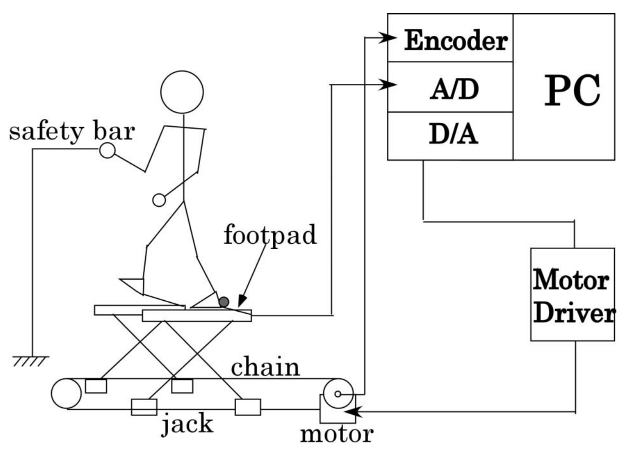

FIGURE 3 System configuration of the GaitMaster2.

ing. The other is "passive walking," which makes the user experience preprogrammed motions of the footpads.

In the active walking mode, when a user moves one foot 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 remaining localized in the real world (see Figure 4). In this system, when the height of the user's heel from the footpad is more than 10 mm, 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. The height of the footpads during a step as defined by the height of a user's toe was limited to 50 mm. The average maximum height of the 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 the top of the trajectory. The phases of the footpads were shifted by 180°.

3.3. Evaluation of GM2

Previously, evaluations of LI have been carried out mainly by comparison with external properties such as the trajectories of the foot and the lumbar or barycentric coordinates of a user on an LI and those in the real world. Walking on LIs is at an elementary level compared to real walking. To achieve a more natural sense of walking with an LI, internal properties such as physiological characteristics must be used for the evaluation with feedback to the development process of the LI. In this study, we addressed energy consumption of walking and the activity of the mus-

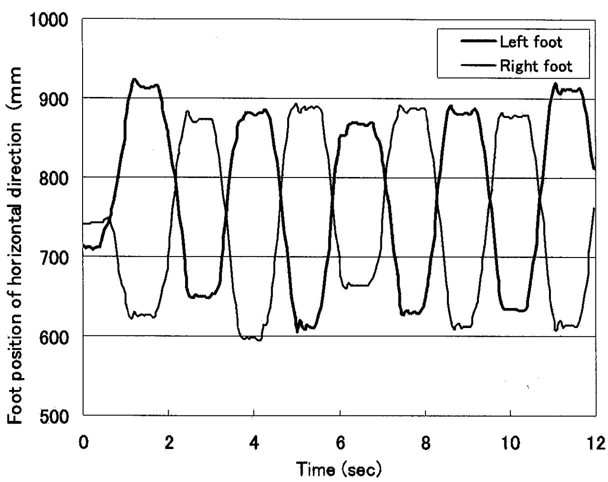

FIGURE 4 Trajectories of user's foot on the GaitMaster2 in the active walking mode.

cles of the users. In practice, the GM2 was evaluated by measuring the physiological cost index (PCI; MacGregor, 1979) and electromyography.

3.4. Evaluation of GM2 Using PCI

The energy consumption of a human being during manual work can be estimated from the oxygen consumption and the heart rate is also proportional to the oxygen consumption. The so-called PCI (MacGregor, 1979) is calculated as follows: PCI = (heart rate after 3 min walking – heart rate before walking)/(walking velocity) [beats/m]. The PCI depends on the walking velocity and has values between 0.2 and 0.4 beats/m at a comfortable walking velocity (Steven, Capell, Sturrock, & MacGregor, 1983).

PCI values were measured for three walking styles: walking in the real world, passive walking on the GM2, and active walking on the GM2. The participants consisted of 8 male and 1 female healthy individuals who were 21 to 31 years old, with an average of 24.1 years. The walking velocity was 26.3 m/min with a 1.32 Hz step cycle. However, the walking velocities in the active walking mode were 25.35 ± 2.01 m/min dependent on the participants' ability to walk on the GM2. The heart rates were measured while the participants sat on a chair placed near the GM2.

Figure 5 shows the average values and standard deviations of the PCI in each mode. The average values are 0.20 beats/m in real walking, 0.23 beats/m in passive walking, and 0.67 beats/m in active walking. From dispersion analysis, there was no significant difference between passive walking and real walking. However, there was a difference, with a 1% significance level, between active walking and the others. Thus, active walking requires more energy than the others, whereas passive walking requires about as much energy as real walking. A significant deference with 5% significance level was observed between one participant and the rest.

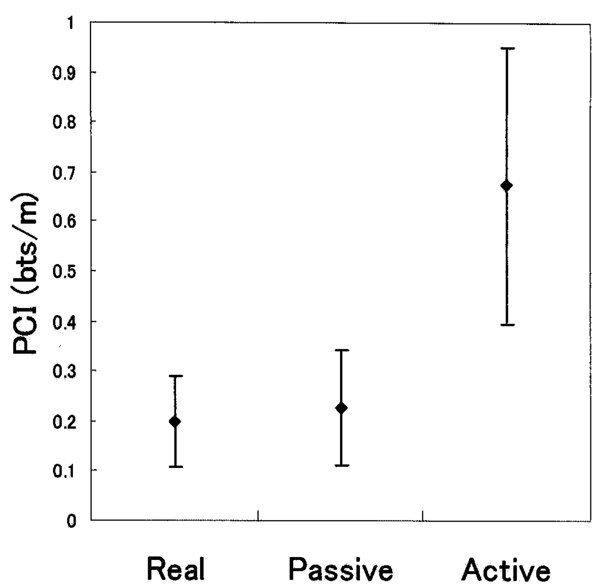

FIGURE 5 Averages of the Physiological Cost Index (PCI) in three walking styles.

In passive walking, the participants might not consume the energy compared with real walking because they did not actively move on the GM2 but were forced to walk with the support of the GM2. However, to keep their balance on the GM2, they tended to lift up their heels involuntarily while their toes were on the footpads when the gait switched from the stance phase to the swing phase. This tendency might be the cause of energy loss in passive walking.

In the active walking, the participants' walking styles differed from each other. Some participants would lift up their heels higher than in real walking. This caused a stilted walking gait that consumed more energy. In addition, the footpad on the side in the stance phase moved backward while the participants kept their weight on the footpad. To maintain balance on the GM2, they also held tightly on to the safety frame around the GM2. Thus, the PCI appeared to be larger than for real walking.

3.5. Evaluation of GM2 Using Electromyography

Muscle function was measured using electromyograms to evaluate the effect to a user of walking on the GM2. An experiment with three walking styles was conducted as described in the previous section with five participants who were 22 to 34 years of age, with an average of 27.4 years. An electromyograph, MYOSYSTEM MR4, EM–103, made by NORAXON (USA), was used for the measurements. We measured the electromyograms of three types of muscles. These were the medial vastus muscle, the gastrocnemius muscle, and the anterior tibial muscle. The medial vastus muscle is a knee muscle, which absorbs the shock when the foot lands on the ground. The gastrocnemius muscle is a sural muscle that controls the flexion of the lower thigh and the forward motion used to obtain acceleration. The anterior tibial muscle is a lower thigh muscle, which is responsible for elevating the toe (Rose & Gamble, 1994; Whittle, 1996).

Figure 6 shows representative electromyograms of the three walking styles of the participants. Overall, the magnitudes of the electromyograms were ordered in this sequence: passive walking, real walking, and active walking. The activations in the electromyograms of real walking were lower than those of a healthy individual walking normally in the real world because the length of the probes of the electromyograph was 3 m, which was too short to permit the attainment of the steady walking state, with the velocity of the real walking also being lower than normal walking. However, the overall characteristics of real walking corresponded to those of normal walking. Therefore, this data can be used as a standard for comparison with the other walking styles.

In passive walking, the electromyograms of the gastrocnemius muscle and the anterior tibial muscle were less active than those of real walking. It seems that those muscles were not actively exercised in the passive walking because those muscles are activated when the participants moved their legs up and down. On the other hand, the medial vastus muscle was more active than in the case of real walking. Because the maximum height of the users toes is set to 50 mm, which is higher than that of real walking, the medial vastus muscle actively absorbed the shock when the foot landed on the footpad.

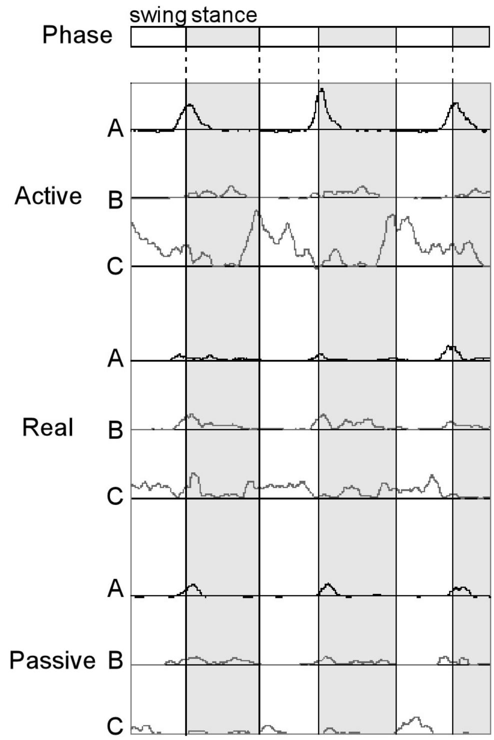

FIGURE 6 Electromyogram of the muscles of the leg in three walking styles. A = Medial vastus muscle; B = Gastrocnemius muscle; C = Anterior tibial muscle.

In active walking, the electromyograms of the medial vastus muscle and the anterior tibial muscle were more active than in real walking. The reason was that the participants needed to move their leg higher than in real walking because the threshold of height of heel to shift the swing phase was set to 10 mm above the footpad, and the participants were consciously forced to move their legs higher, increasing the shock when the foot landed on the footpad. Hence, the medial vastus muscle was activated more than in real walking. The anterior tibial muscle was also activated because the participants had to pull their toes up to avoid removing the sandal. The gastrocnemius muscle was less activated than in real walking because the participants learned that even if they flung their feet up to obtain acceleration, the walking velocity did not increase because the velocity in the VE on the GM2 was determined not by the acceleration of the foot but by the velocity of the foot in the swing phase side.

The results are summarized as follows. The muscle actions of the measured muscles in passive walking and active walking occurred with the same timing as in real walking. However, the GM2 still requires refinement in some respects, which were overlooked by not considering internal aspects as well as external aspects.

4. A METHOD OF SHARING THE SENSATION OF WALKING

There are many different types of walking situations with a number of participants such as ordinary walking, group walking, dancing with partners, and jogging.

In a VE, many objects can be placed simultaneously at the same location, which would be impossible in the real world. Hence, users can walk together side by side and can also be superimposed virtually in the same VE. Therefore, we can share the sensation of walking together with users with a feeling of oneness. The sensation of walking on an LI is determined by haptic feedback to the user's foot. In all footpad types of LI, the position of the footpads controls the haptic feedback. These are determined from the user's foot positional data. It is believed that the sense of walking among remote users can be shared by gathering and manipulating foot positional data of all the users. For example, when a local LI is connected with a remote LI as a master–slave system, the movement of feet of the remote user can be experienced by overwriting feet positional data of the local LI with that of the remote LI. A synchronized walking system can also be constructed, such as a three-legged race, by exchanging the feet positional data.

In this shared walking environment, the LIs are controlled with foot motion at the swing phase side. Any walking mode can be created by using the foot motions at the swing phase side calculated from the local and remote feet motion data.

The foot position at the swing phase side is calculated using the following equation:

$$P_{in,i} = C_{local,i} \times P_{local,i} + C_{remote,i} \times P_{remote,j} \quad (1)$$

where $P_{in,i}$ is the foot position at the swing phase side, $P_{local,i}$ is the foot position of the local user, and $P_{remote,j}$ is the foot position of the remote user. $C_{local,i}$ is a coefficient of the local user's contribution to the walking, and $C_{remote,i}$ is a coefficient of contribution of the remote user. The *i* and *j* refer to the side of the leg and could take the left foot or the right foot.

A shared walking mode can be changed by changing these coefficients of contribution. In the following sections, to verify this idea, two LIs were connected via a network and a prototype system was constructed for sharing the sensation of walking.

5. SYSTEM CONFIGURATION OF SHARED WALKING ENVIRONMENT

The GM1 and the GM2 were connected 50 m apart from each other via a wireless LAN (Icom WaveMaster, 11Mbps; Japan), and a prototype system was constructed to share the sensation of walking as shown in Figure 7. The wireless LAN was used to exchange information on a user's foot position at each LI via TCP/IP. The exchanged data are 20 bytes consisting of the horizontal and vertical positions, two float-type data for each foot (16 bytes total), and the body distance from the origin of the VE (4 bytes; not used in this study).

The entire program was written in C. Researchers divided the program into the LI controlling thread and the asynchronous network communication thread. The communication data were updated at 180 Hz. The GM1 and the GM2 were controlled at 30 Hz and 250 Hz, respectively. Consequently, the update rate of the whole system was 30 Hz. However, the GM1 compensates the data with 1 kHz update rate. 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

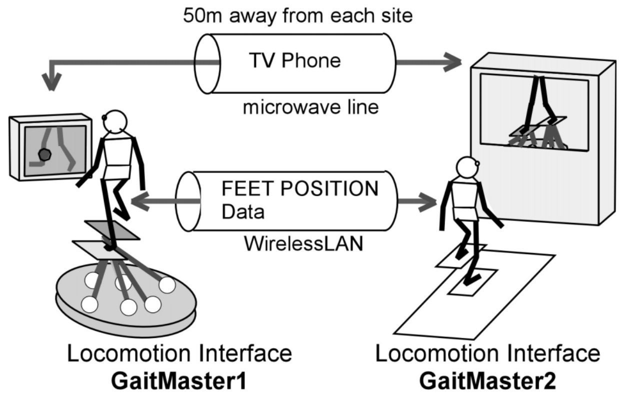

FIGURE 7 System configuration of the shared walking environment.

too high. A microwave line (RF SYSTEMlab, BS–550GT, BS–120GRH; Japan) was also used for exchanging NTSC live video and audio data in real time. Users could share their walking experience with other people by watching the live video image, talking with each other, and sharing the sensation of walking.

6. SHARED WALKING 1: MASTER–SLAVE WALKING

A master–slave walking system was implemented as an initial example of the shared walking environment.

The walking style of the master site was set as active walking ($P_{master,i} = P_{local,i}$, where $C_{local,i}$ was 1.0, and $C_{remote,i}$ was 0.0, and $i = j$ in Equation 1), whereas 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 instead followed the data of the foot position from the master site ($P_{slave,i} = P_{master,i}$, where $C_{local,i}$ was 0.0, and $C_{remote,i}$ was 1.0, and $i = j$ in Equation 1). Thus, the footpads of the slave site traced the motion of the footpads of the master site.

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 or her feet on the footpads. On the other hand, the user at the master site could teach his or her feet motion directly to the remote user without fatigue. In addition, he or she could also adjust the motion of the slave site user by intuitive adjustments tohis or her own motion.

To show the effectiveness of the master–slave walking environment, an experiment was conducted to measure the trajectory of feet positions both at the master and slave sites with five pairs of healthy individuals. In this experiment, the participant at the master site walked actively and the participant at the slave site stood on the footpads of the slave LI and walked by following the motion of the footpads. The participant at the master site could observe what had occurred at the remote site with the aid of the live video image and sound.

Figure 8 shows representative trajectories of right foot motion of the master site (GM2) and of the slave site (GM1). Because of the differences in the working volumes of each of the LIs, the positional data from the GM2 (the master site) were scaled down by 50% when transmitting the GM2 data to the GM1. In addition, the coordinate system of the graph in Figure 8 was that of the GM2, and the positional data of the GM1 were scaled up by 200%, with an adjusted origin.

As a result, the participant on the GM1, the slave site, could follow the motion of the foot on the GM2, the master site. The maximum time delay was 40 msec. Experiments were also conducted with a condition in which the GM1 was set as the master site and the GM2 as the slave site. Figure 1 shows the representative trajectories of the right foot at each site. The coordinate system of Figure 1 is that of the GM1. The positional data of the GM1 (the master site) were not scaled up by 200% when transmitted to the GM2. Because a magnetic sensor—FASTRAK, made by Polhemus (USA)—was used for sensing the positional data of a user's feet on the GM1, and the data included greater sensor noise than that of the GM2 (the GM2 used potentiometers for position sensing), the data of the GM1 was not scaled to minimize influence of the noise.

The results of the experiments showed that the participant of the slave site on the GM2 could follow the trajectory of the master site when the vertical foot position was higher than 365 mm. When the vertical foot position was less than 365 mm, the distance between feet on the GM1 and the GM2 was within 10 mm. This was caused by the sensor noise of the GM1. However, when the vertical foot position was under 365 mm, the system determined that the foot was in stance phase. Therefore, the motion was not affected. Also, because the threshold height of the swing phase on the GM2 was higher than that of the GM1, the vertical interval of the trajectory in Figure 8 was larger than that in Figure 1.

The mean distances, adjusted for the communication time delay, between the master and the slave were 2.7 mm (*SD* = 0.3 mm) in the case in which the GM1 was the master and 1.6 mm (*SD* = 0.3 mm) in the case in which the GM2 was the master. In the case in which the GM1 was the master, the errors due to sensor noise increased with respect to the other configurations. 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.

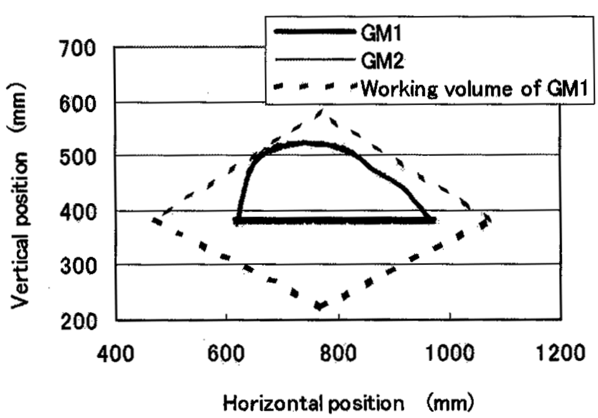

FIGURE 8 Trajectories of the user's right foot on the GaitMaster2 (GM2; the master) and the GaitMaster1 (GM1; the slave) in the GM2 coordinate.

7. SHARED WALKING 2: SYNCRONIZED WALKING

As a second example of the shared walking environment, a synchronized walking system was implemented. In this system, the right foot of the GM1's user and the left foot of the GM2's user were virtually bound together. The motion data of the binding foot was exchanged between them simultaneously ($P_{GM1,right} = P_{GM2,left}$, $P_{GM1,left} = P_{local,left}$ at the GM1 and $P_{GM2,left} = P_{GM1,right}$, $P_{GM2,right} = P_{local,right}$ at the GM2). The data exchange was available when their feet were in swing phase to avoid loss of balance of the users on the LIs. Thus, the LIs restricted the foot motion of each user as though they were actually tied. Accordingly, the users had to synchronize their walking steps.

Figure 9 shows a trajectory of the horizontal movements of three steps of the bound feet. At the first step, the foot of the GM1's user moved ahead of the GM2's user. When the GM2 user's foot shifted to the swing phase, the foot of the GM1's user moved further away. Therefore, the footstep of the GM2 user was reduced. At the second and third steps, the users were able to synchronize their motion step by step and the footsteps became larger than that of the first step. In addition, because the footpads of the GM1 moved more slowly than the user's feet, the feet moved ahead of the footpads. Also because of the safety wire strings on the sandals, the distance between both users' feet was 100 mm maximum. The distance error could be improved by shortening the strings or fixing the sandals to the footpads included with force sensors. Although those solutions might present users some difficulty in walking as if they were wearing very heavy sandals, this approach could be taken to balance the preciseness of the feet position and the feeling of walking.

To estimate the degree of synchronization, two time lags of the motion of their bound feet for each step were also measured. One time was the lag in starting the swing phase, and the other was the lag in finishing the swing phase. Figure 10 shows the mean time lags of both measurements for the first minute of the experiments. Because there could be several modes of harmonization in walking motions depending on each pair's strategy, it seemed that the time lags did not reach zero but some steady value depending on each pair of participants.

These results led to a conclusion that the participants became aware of their partner's motions through the LIs and adjusted their motion by referring to their partner's movement.

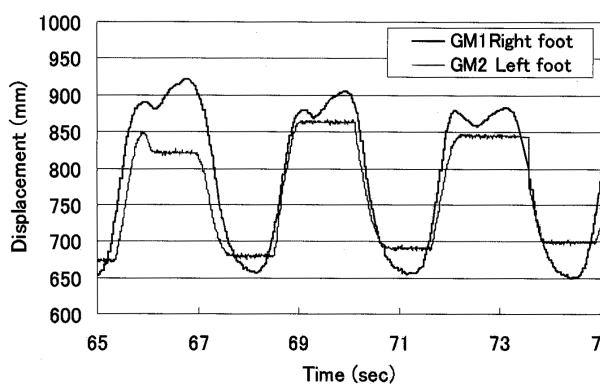

FIGURE 9 Trajectories of the user's bound feet in the synchronized walking. GM1 = GaitMaster1; GM2 = GaitMaster2.

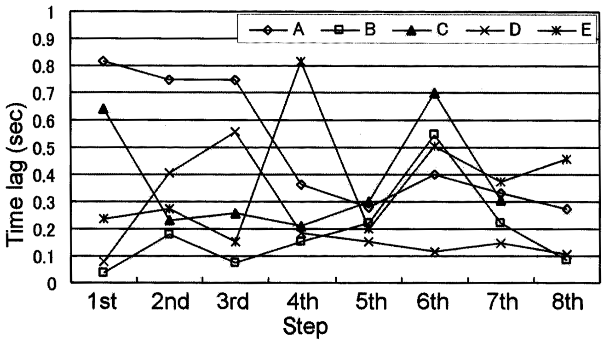

FIGURE 10 Time difference of each step between the users in the synchronized walking.

8. DISCUSSION

In this article, we proposed a method for sharing the sensation of walking in a VE. That is, sharing could be achieved by executing several operations on foot position data in the shared walking environments that connected LIs via a network. We constructed master–slave walking and synchronized walking environments using this method, and they were verified to be effective. However, the following is worthy of discussion.

In the master–slave walking and synchronized walking environments, the coefficients in Equation 1 (i.e., ratios of contribution of the local user and the remote user for walking) took values of only 1.0/0.0 or 0.0/1.0. However, these parameters could be set at intermediate values, for example, 0.5/0.5. In this configuration, both feet are pulled to their median point, and this configuration might be used for a type of remote collaboration environment using the sensation of walking.

We showed it to be possible to achieve walking in a VE in a manner similar to normal real walking with the GM2 with the aid of a physiological index, the PCI, recently introduced for the evaluation of LIs. This result could not have been obtained without using PCI to measure influences of LIs on users.

Although it could be shown that physiological indexes of internal aspects are effective additions to external aspects such as the trajectory of users' feet, there are still problems to be solved and improvements to be made. For example, the precision of PCI tends to worsen when a participant walks more slowly than normal.

Other problems still remaining in our method are the communication time delay via a digital network and the instability of the time delay. Time delay itself cannot be completely solved, but the instability problem can be overcome as far as possible by using a guaranteed type of network such as ISDN, ATM.

The walking velocity (27 m/min) on the GM2 is still only one third of that in real walking (60–80 m/min), mainly for safety reasons, even though it was greatly improved when compared with the GM1. In that sense, the algorithm for generating the sensation of walking and the power of the actuators should be improved, and new mechanisms for the LIs may have to be developed.

One of the possible application areas of sharing the sensation of walking is in gait rehabilitation (Yano, Kasai, Saitoh, & Iwata, 2003). Automatic gait rehabilitation systems using robots have been developed (Deutsch, Latonio, Burdea, & Boian, 2001; Hesse & Uhlenbrock, 2000; Kawamoto & Sankai, 2001). Although these systems are designed to be automatic, it is difficult for them to detect any subtle change in a patient and adjust their training method as physical therapists would. Our proposed system has the great advantage that it can be easily adopted for such automatic training. For example, footpads could iteratively move along a trajectory of foot motion captured from a healthy individual, and a patient could learn from this foot motion. Therapists could change the trajectory interactively by connecting an LI using this method. For remote medical services, a networked LI also would be particularly suitable. By connecting LIs, the system could send motion information from the therapist/trainer directly to the remote patient (Yano et al., 2000). It is expected that the necessity for systems for sharing the sensation of walking will increase with the advent of the "aging society." Another application could be in humanoid robot operation interfaces. By connecting an LI to a humanoid robot, the reaction force applied to the remote robot from a floor could be felt, and the robot could be controlled by using the master–slave walking environment.

9. CONCLUSIONS

In this article, we proposed a method for the sharing of the sensation of walking in a VE. By using several LIs, gathering feet positional data from users of the LIs, and carrying out operations with the positional data, various types of shared walking environments have been constructed, and it has been verified that it is possible to share the sensation of walking in a VE.

Initially, a footpad-type of LI named GM2 was developed for the construction of a shared walking environment. In addition, recently introduced physiological indexes were employed to consider a user walking behavior for the evaluation of LIs, and the research showed them to be effective. Second, we proposed an algorithm for the execution of several operations on foot positional data to control LIs for sharing the sensation of walking. We then developed a prototype system by connecting two footpad-type LIs via a digital network. Finally, we demonstrated the method to be effective in achieving a shared sense of walking from experiments in two shared walking environments: the master–slave and the synchronized walking environments.

Remaining issues include investigations into the influences of shared walking environments on users through physiological indexes and into methods of providing a walker with visual information, locating a suitable position to set cameras and/or a screen. Additionally, there are plans to develop gait rehabilitation systems and shared walking systems for more than two people.

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