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Rendering of Walking Sensation for a Sitting User by Lower Limb Motion Display

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Abstract

This paper describes the characteristics of presentation of a lower limb motion display designed to create a walking motion sensation for a sitting user. It has the function of lifting and translation independently applied to both legs to generate a walking sensation by moving the feet alternately as in the real walk. According to the results of the experiments, our system enables to render a walking sensation by drawing a trajectory with an amplitude of about 10% of the real walking. Although the backward amplitude was larger than the forward amplitude in real walking, our system created walking sensation to the sitting user better when the forward amplitude was larger than the backward amplitude having opposite characteristics to the real walking.

CCS Concepts

- ***Human-centered computing*** → Human computer interaction(HCI) → Interaction paradigms → Virtual reality;
- ***Human-centered computing*** → Human computer interaction(HCI) → Interaction devices → Haptic devices;

1. Introduction

In recent years, researches to create VR experiences have built a system that provides not only visual information but also a physical (haptic) stimulation in order to enhance the sensation of walking [YNT*09, HXCJ00, YKSI03]. As walking is an indispensable basic behavior for our activity in the real world, the virtual walking sensation needs to be created in a VR space experience as part of enhancing sense of immersion through which the user enjoys a different world.

The VR experience is valuable in both application cases of autonomous navigation in the new world and heteronomous reception of a new physical skill or various bodily performances of others in the replicated world. In the latter application, all the information the person received from the world in the past, including one received from his/her own body, the sensation of physical (bodily) motion, needs to be reproduced.

Some researchers [SBJ*10] [MBN*16] [BHK*14] [NHK16] have focused specifically on presenting walking sensation. These studies move and modify the viewpoint in a visual world shown to the HMD to induce a walking sensation as if the user is in a large VR space even though he/she walks within a limited area in a real environment. These studies are not organized to transfer walking sensation of a person to the other, because the physical (bodily) sensation originate from his/her own motion.

In our study, we focus on walking sensation induced by passive motion of body in which the both feet and legs of the user are moved following a specially designed trajectory by a mechanical device. The user just sits on a chair and perceives the sensation of motion of the feet and legs given by the device. We selected the sitting posture for the user, since it reduces the user's physical load during the VR experience, and it is easy to apply to various VR contents. On the other

Figure 1: *Lower limb motion display.*

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hand, using passive motion may reduce the reality of walking sensation, so that the rendering method needs to be investigated.

The present paper introduces our lower limb motion display shown in Fig. 1 that creates lifting and translating motion sensation to the feet and legs. The display enables long-time experience by reducing the physical load to the user, and improves the sense of immersion into the VR space. The result of investigation on the motion trajectories for rendering a walking sensation is discussed.

2. Related works

2.1. Virtual walking by an exoskeletal device

There are many researches and developments on exoskeleton type devices applied to lower limbs for a walking support and rehabilitation [BVZ*15] [KS05] [JV12] [CJSD00]. These devices torque the hips, knees and ankles to support the entire body, and have a high degree of freedom reflecting the human body. These devices may be applied to virtual walking, which can solve the problem of reducing the physical load on the user. However, they are made to support the user's voluntary motion, so that it may not be applied simply to the purpose of reproducing the motion sensation observed by another person.

2.2. Virtual walking in a standing posture

Some researchers have developed systems to provide walking sensation for a standing user [HSRJ05] [YNT*09]. As an advantage of these systems, it can provide similar motion to the real walk in reproduction of the walking sensation, since the posture is almost the same as actual walking. However, to allow a natural body motion, the equipment takes a very large space for supporting and moving the standing user, bearing its weight. In addition, an operation in the standing posture imposes a considerable load on the user, and it may be difficult to use the system for a long time.

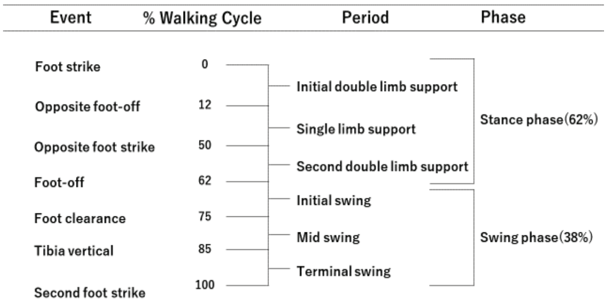
2.3. Virtual walking in a sitting posture

Some systems have focused on presenting stimuli to the foot sole of a sitting user to render a walking sensation [KKKT18] [JMDO12] [AIHM16] [TBS13]. Since the physical load of the user of these systems is reduced compared to those with standing posture, a VR experience with a long duration is possible. In addition, the display device can be built more compactly, since the system for a sitting user does not require a structure to support the entire body weight of the user. However, it is insufficient only with the stimulus to the foot sole to evoke various walking sensations.

Among the methods of virtual walking, some researchers have developed systems to render the walking sensation by stimulus to the upper limbs [SIA*16] [YNYP10] or stimulation from the seat [IKK*16] [OSET16]. It is considered that high quality virtual walking can be realized by combining these devices with that stimulates the lower limbs.

In our study, we developed a lower limb motion display that combines vertical motion of the heel by the pedal and anteroposterior translational motion by the slider. In this system, we aim to render walking sensation by moving the lower limb of a sitting user.

Table 1: *Temporal profile of a walking cycle*



Event	% Walking Cycle	Period	Phase
Foot strike	0		Stance phase(62%)
		Initial double limb support	
Opposite foot-off	12		
		Single limb support	
Opposite foot strike	50		
		Second double limb support	
Foot-off	62		Swing phase(38%)
		Initial swing	
Foot clearance	75		
		Mid swing	
Tibia vertical	85		
		Terminal swing	
Second foot strike	100		

3. Walking motion in a real space

Basic characteristics of human biped locomotion was reviewed before we designed the rendering method of a walking sensation. Human walking motion is controlled by coordinating multiple degrees of freedom of the body skeletal system. Although the behavior of the whole control system is extremely complex reflecting a highly structured biomechanical system, we first simply refer to an apparent trajectory of foot motion to find appropriate motion presented by our device.

3.1. Temporal profile of walking motion

Human walking is periodic motion in which one cycle time is defined as the interval from the moment a heel hits the ground to that the same heel hits the ground again. The cycle is divided into two phases. The period when a foot contacts to the ground is called a stance phase, and the rest is called a swing phase where the foot leaves the ground [Hat13]. The phases are further subdivided according to the event of both feet. Table 1 shows a general temporal profile of a walk. The stance phase occupies about 60 % of a walk cycle, while the swing phase about 40 %.

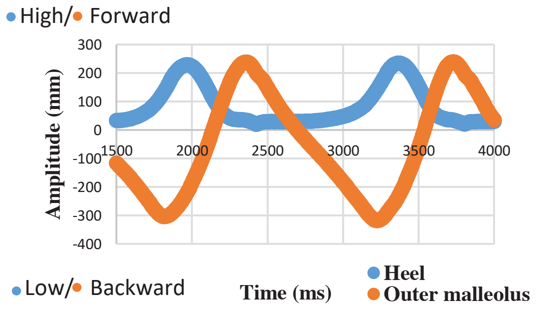


Figure 2: *Trajectories of a heel and outer malleolus from the center of body of a participant.*

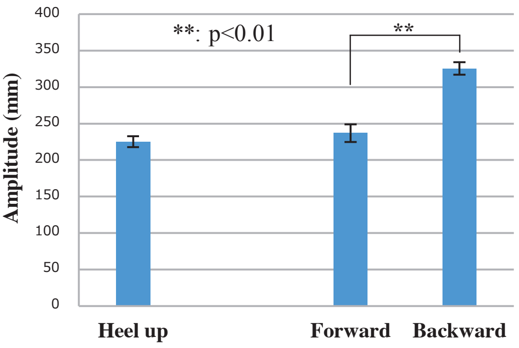


Figure 3: *Average maximum amplitudes of real walking. (n=5)*

3.2. Trajectory of a foot in real walking

We measured a spatial trajectory of a foot during real walking by an optical motion capture sensor. Five university students of the mean age of 22.8 years participated in the experiment. The all were with normal lower limb condition. Each participant walked three times on a treadmill. Markers were attached to the hipbone, the outer malleolus and the heel of the participant. The speed of the treadmill was adjusted so that they could walk naturally with a walk period of 1400 ms.

Figure 2 shows the trajectories of the heel and the outer malleolus of a participant. Figure 3 shows the average largest amplitude of the all participants. The result showed that the stance phase was about 60 % in a walking cycle, and the swing phase was about 40 %. The vertical lifting amplitude of the heel was about 225 mm and the ratio of rise time to fall time was about 2:1. The anteroposterior translational amplitude of the outer malleolus was about 570 mm where the forward movement was about 240 mm from the center of the body, about 40 % of a period, and the rear movement 330 mm, about a 60 % period. This indicates that the rear amplitude was larger than the forward in actual walking.

As a method to render walking sensation to a sitting user, we developed a lower limb motion display that combines vertical movement of a heel and anteroposterior translational movement. Figure 4 shows our device. The device consists of two parts: a vertical drive unit for moving the heel up and down, and a translational drive unit for moving the foot forward and backward. We render walking sensation by driving these two units synchronously following a shape of the real walking trajectory.

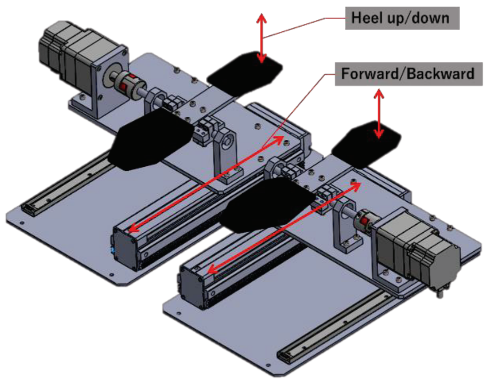
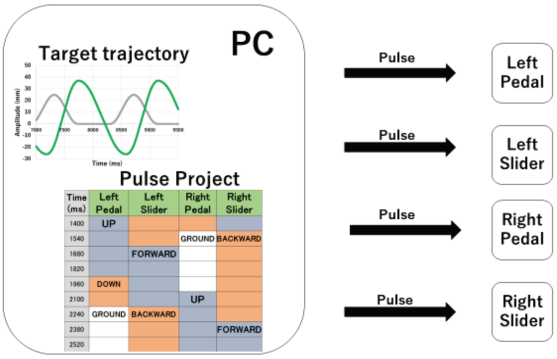


Figure 4: *Design model of a lower limb motion display.*

The distance between two pedals is about 240 mm. The pedal lifts the heel up to 182 mm and lowers -73 mm to downward direction. The stepper motor (RK564AAE-PS36) was used for this unit. The maximum torque of the motor is 20 Nm with a static torque 8 Nm. The allowable speed range is 0 to 83 r/min. The basic step angle is 0.02 rad/pulse. The rotation angle of the pedal is determined by the number of pulses from a PC driver board.



Time (ms)	Left Pedal	Left Slider	Right Pedal	Right Slider
1400	UP	🟧	🟧	🟦
1540	🟦	🟧	GROUND	BACKWARD
1680	🟦	FORWARD		🟧
1820	🟦	🟦		🟧
1960	DOWN	🟦		🟧
2100	🟧	🟦	UP	🟧
2240	GROUND	BACKWARD	🟦	🟧
2380		🟧	🟦	FORWARD
2520		🟧	🟦	🟦

Figure 5: *Schematic of the lower limb motion display control.*

The lower limb is also driven backward and forward by the linear slider motor (EASM4LXD-015ARMC, EASM4RXD-015ARMC). The slider has a stroke of 150 mm, a maximum velocity of 800 mm/s, a payload of 15 kg, a thrust of 70 N, and a resolution of 0.012 mm. This linear unit moves the vertical drive unit on which the user's foot is placed.Figure 5 shows a schematic diagram of system control of the lower limbs motion display. The device is controlled by synchronized pulses from the PC to each motor. The motion trajectory is created by setting pulse trains that correspond to the rotation angle, the rotation speed and the start time according to the trajectory made of quadratic and linear function of angles. It is made of a quadratic curve for the first 1/3 segment, a linear progress for the second 1/3, and a quadratic curve for the last 1/3.

4. Sensation evoked by lower limb motion display

4.1 Leg joints rotation for walking sensation

In real walking, the ankles, the knees, and the hip joints rotates synchronously to make smooth leg movement. We investigated the relation of joint rotations that contributes to walking sensation that is evoked by integrated rotation of lower limb motion.

The participants in the experiment were four university students (mean age: 22 years) who declared normal lower limb condition. Figure 6 shows the stimulus levels of rotational movement :(1) knee, coxa, ankle joints all rotate, (2) knee, coxa joint rotate (ankle fixed), and (3) ankle joint rotates (knee and coxa fixed). We set five vertical amplitudes of the pedal {5, 10, 20, 30, 40} mm. A visual analogue scale (from ‘no walking sensation’ to ‘feel as if walking with realistic sensation’ mapped as 0 to 100, respectively). The participant wore headphones emitting white noise, and closed eyes during the experiment. No translation (forward/backward) motion was used in this rating.

Figure 7 shows the evaluation results of the walking sensation for each condition. It indicates that the condition in which all joints rotated shows the highest value at any amplitude. In particular, at the amplitude of 30 mm, the rating value of all joints rotate is the highest with the largest difference from other joint conditions. This result shows that the both of the rotational and the vertical motion of all joints of the lower limb are better to evoke walking sensation. In addition, it was found that fixing the ankle or ankle rotation only was inappropriate as a stimulus to present walking sensation.

4.2 Vertical amplitude and temporal profile for walking sensation

In order to find an effective trajectory of vertical motion of the pedal for rendering walking sensation, multiple combinations of the vertical amplitude of the pedal lift and the rise/fall time ratio were compared regarding walking sensation.

The participants were seven university students (mean age: 22.7 years) who reported normal lower limb condition. Figure 8 shows the initial posture of the participant. The participant was asked to sit on a chair with the knee joint at a right angle, the lower leg vertically set, and both feet placed horizontally on the lower limb motion display. The participant was also asked to relax without applying force to the lower limb. Seven conditions for vertical amplitudes {2, 5, 10, 15, 20, 30, 40} mm, five conditions for temporal ratio of rise and fall {1:5, 1:2, 1:1, 2:1, 5:1}. Then, 35 stimuli in total were tested in a random order. Rating was reported on a visual analogue scale (from ‘no walking sensation’ to ‘feel as if walking with realistic sensation’ mapped as 0 to 100, respectively). The participant wore headphones with white noise and closed eyes.

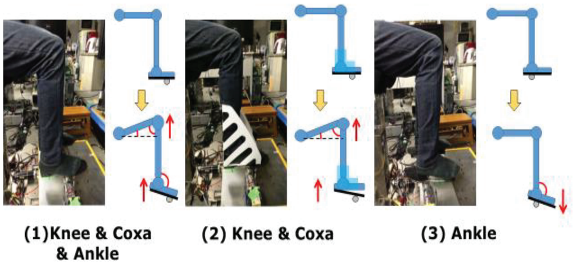


Figure 6: *Stimulus conditions of rotational movement.*

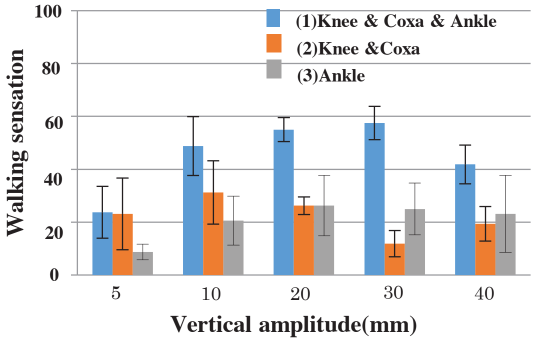


Figure 7: *Walking sensation for joint and amplitude levels. (n=4)*

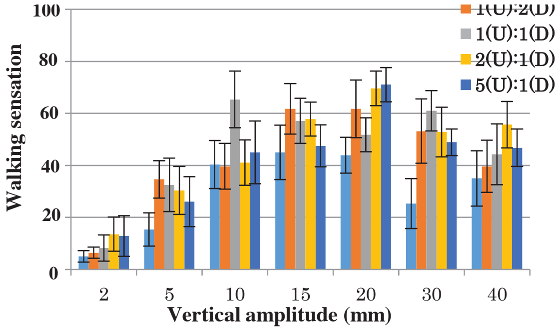


Figure 9: *Walking sensation for vertical amplitude and lifting time ratio. (n=7)*

Figure 9 shows the rating results of the walking sensation. The intensity of walking sensation was highest when the vertical amplitude was in the range of 15 to 30 mm. Since the vertical amplitude of the heel was about 200 mm in real walking, it seems that passive movement of about 1/10 amplitude of real walking is appropriate for evoking the walking sensation. The rise/fall ratio did not indicate significant difference.

4.3 Translational amplitude and temporal profile for walking sensation

As the same way in the previous section, translational motion of the pedal for rendering walking sensation was investigated by using the slider mechanism. The combinations of the translational amplitude and the forward/backward time ratio were compared regarding walking sensation.

Nine university students (mean age: 23 years) with normal lower limb condition participated this evaluation. Seven levels for translational amplitudes {20, 30, 40, 50, 60, 70, 80}

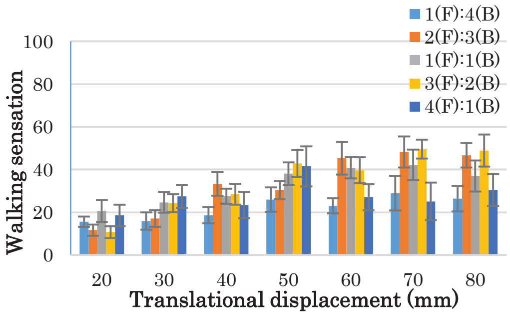


Figure 10: *Walking sensation for translational amplitude and anteroposterior time ratio. (n=9)*

mm, and five levels for time ratio of forward/backward {1:4, 1:2, 1:1, 2:1, 4:1}. Then, 35 stimuli in total were presented in a random order. The same visual analogue scale as the previous experiment was used. The participant wore headphones with white noise and closed eyes.

Figure 10 shows the evaluation result of the walking sensation. The walking sensation looked increased proportionally to the amplitude. The difference in the walking sensation for the time ratio was small when the translational amplitude was in the range of 20-40 mm. On the other hand, in the amplitude range from 60 to 80 mm, the difference by the time ratio was large. In addition, the walking sensation was high when the time ratio was at 2:3 and 3:2.

The result indicated that the amplitude from 60 to 80 mm, which was about 10 % of real walking, was suitable for reproducing walking sensation. In addition, as for the anteroposterior time ratio, the walking sensation looked higher in a longer rise (U) time as in real walking shown in Fig. 2.

4.4 Optimal trajectory by the method of adjustment

Twenty-four university students (mean age: 22.7 years) with normal lower limb condition participated in the experiment. The optimal trajectory of the lower limb motion device was searched by the method of adjustment. After walked in a real space at 1.4 s cycle time, the participant was asked to sit on a chair with the initial posture shown in Fig. 8 wearing headphones with white noise and with closed eyes. The initial amplitude of the device before adjustment was set randomly. The participants adjusted three parameters: (1) Heel up amplitude, (2) forward amplitude, and (3) backward amplitude, by using a game controller pad, for twice respectively.

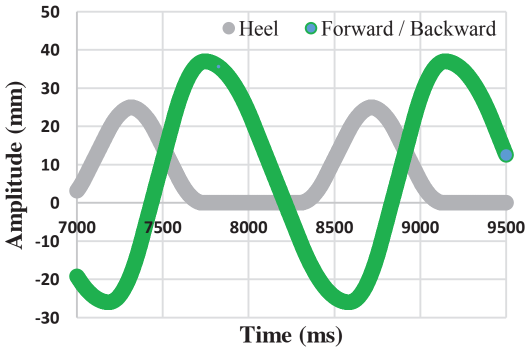


Figure 11: *The trajectory by the average adjusted amplitude. (n=24)*

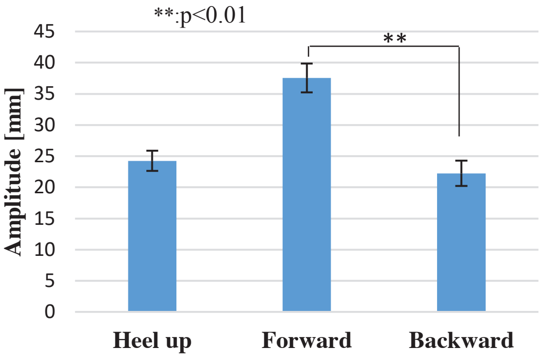


Figure 12: *Adjusted amplitude of the lower limb motion display. (n=24)*

Figures 11 and 12 show the trajectory and amplitudes of the result of adjustment. The vertical amplitude at the heel was 24.3 mm, which supported the result of section 5.1. The forward amplitude was 37.5 mm, and the backward about 22.2 mm. This rotates the ankle joint about 9.3 degree, the knee joint about 6.8 degree, if the length below the knee is 500 mm. The forward amplitude was significantly larger than the backward amplitude. While in real walking, the backward amplitude was larger than the forward amplitude.

The reason for the difference that the larger forward amplitude than the backward was required for a sitting user from the real walking to evoke walking sensation has not been elucidated yet. However, it might be related to the posture difference and the passive nature of the display. The latter is the prerequisite in the context of receiving reliving experience from other's. The interesting relation between active and passive motion is discussed in another paper of this conference. The former, the sitting posture, is also related to the possible way to implement reliving experience in which the sensation of motion of the body is freely imparted to the user. The sitting posture allows the participant to perceive backward amplitude easily compared to real walking since the foot moves toward the body, not goes away from it. In addition, larger forward motion of the foot might cause attention to the forward direction to walk.

4.5 Sensation of motion and walking sensation by the lower limb motion display

In order to show how effectively our device operates, the sensation of movement and walking sensation were evaluated with three presentation conditions: the slider only, the pedal only, and both of the slider and the pedal motion.

Ten participants of university students (mean age: 22.8 years) with normal lower limb condition participated in this experiment. Immediately after a real walk (1.4 s cycle period,

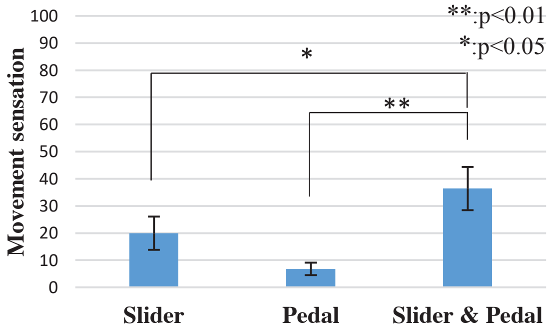


Figure 13: *Sensation of motion by the lower limb motion display. (n=10)*

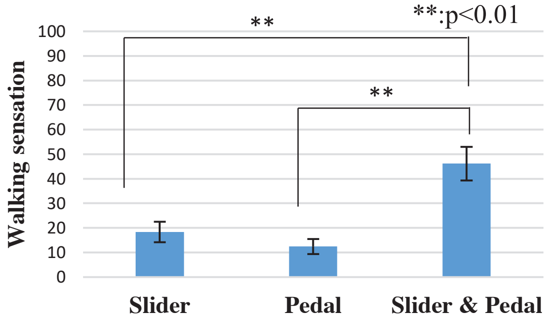


Figure 14: *Walking sensation by the lower limb motion display. (n=10)*

20 m straight path), they sat on a chair with the initial posture, wore headphones with white noise presentation and closed the eyes. The slider, the pedal, both of these drive units were presented in a random order. The participant evaluated the sensation of movement and the walking sensation using the same method as the previous section. The presented amplitude was what was obtained by the experiment of section 5.4 (vertical amplitude: 24.3 mm, forward amplitude: 37.5 mm, and backward amplitude: 22.2 mm).

Figure 13 shows the evaluation result of the sensation of movement, and Figure 14 shows the result of the walking sensation. For both sensations, the intensity of sensation evoked by both of the slider and the pedal was significantly higher than the slider or pedal single stimulus.

It is considered that there was a synergistic effect in the stimuli of both the slider and the pedal, because the sensation was more than a summation of both sensations. The two degree-of-freedom integrated motion stimulation had a closer trajectory to real walking compared to stimulation with only either a slider or a pedal.

5. Discussion

According to the results of the present research, walking sensation induced by our system was most enhanced at the same time ratio as actual walking, while with about 10% amplitude of actual walking. In this system, the sitting posture of the user is different from standing posture in actual walking, so it was necessary to adjust the motion parameters that match to the sitting posture, not just reproducing the actual walking parameters.

In the case where the feet are moved passively, i.e. passive walking condition, it may be naturally thought that walking sensation will not be evoked because the feet are not moved by the user's own will and force. However, according to the result of our research, it was confirmed that walking sensation was created, and the trajectory to move the lower limb changes the strength of the walking sensation. In the trajectory where the sensation of walking was felt the highest, the sensation intensity was about 40 % of an actual walk. Although this intensity was not sufficient to be perceived as 100 % of actual walking, this may not necessary be thought as too low value since the actual walking gives multisensory input other than the sensation of feet motion. We use the passive feet motion as a part of whole body integrated stimulation as shown in a demonstration combining the device and other displays including visual image presentation [KAY*18] [SSY*18].

In the future work, we plan to investigate how the image and other stimulus affect the walking sensation. In addition, because this device has only 2 degrees of freedom, we will enhance the sensation of walking by increasing the degree of freedom of the device.

6. Conclusion

Our system was able to render walking sensation by implementing a trajectory similar to the real walking with an amplitude of about 10 % of a real walk. While the backward amplitude was larger than the forward amplitude in a real walk, the present research revealed that the larger forward amplitude than the backward amplitude was better in creating walking sensation by using our system for a sitting user.

Acknowledgment

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