Pseudo-Sensation of Walking Generated by Passive Whole-Body Motions in Heave and Yaw Directions

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***Abstract*—Walking is an innate human behavior that propels the body forward. Recent studies have investigated the creation of a walking sensation wherein, the body neither moves nor is forced to move. However, it is unclear which whole-body motions effectively induce the sensation of walking. Here, we show that passive whole-body motions, such as heave and/or yaw motions, produced by a motorized chair induced a sensation of walking for seated participants in virtual environments as if the participant were walking while viewing a virtual reality scene through a head-mounted display. Our findings suggest that the passive whole-body motions in the gravitational axis—and to a lesser extent in the yaw axis—provide a clear perception of pseudo-walking, but only with limited motion amplitudes, namely one-fourth or less than those of actual walking. In addition, we found a negative correlation between the scores of walking sensation and motion sickness.**

***Index Terms*—Bodily perception, multisensory, vestibular sensation, virtual reality, walking sensation.**

I. Introduction

WALKING in virtual reality (VR) space is necessary for various purposes such as education, training, and entertainment because it is a natural action in our daily lives and provides a sense of presence. Because a physical workspace in the real world is limited, a great number of methods have been developed to create a walking sensation in VR systems. An omnidirectional treadmill enables users to walk in place by cancelling the movement generated by their walking [1], [2]. The use of redirection techniques is another candidate solution that enables users to walk in an infinite VR space by manipulating their trajectories in a VR space to keep them within the boundaries of the physical workspace [3]–[6]. These methods allow a user to actually feel a sense of walking, mainly from motor commands and body actions.

Meanwhile, in addition to motor commands and body actions, other types of sensory information are involved in walking. Therefore, many studies have attempted to generate a sense of walking using multisensory information in a passive state, that is, without body action. It is known that optical motion flows induce a sense of self-motion, which can also be facilitated by motion cues in different modalities such as moving sound [7], or tactile motion on a seat pan, [8] or the soles of the feet [9]. The oscillation of a visual scene synchronizing with step frequency can facilitate the perception of walking in a virtual environment [10]. Other studies have focused on mimicking haptic interaction between the soles and the ground during walking; for instance, using frictional force [11], pressure [12], or vibrations [13]–[15] to create a sensation of walking for seated users. Still other studies have adopted motion platforms or motorized chairs that can present the users with multisensory cues including vestibular or proprioceptive ones. Motorized chairs have been applied to systems, presenting rotational motions as a translational acceleration in the upward and downward directions [16], or elevating or tilting the user's body to create a sensation of walking [17]–[19]. However, there is no psychological evidence regarding the effect of the heave and yaw motion amplitudes on the clear perception of pseudo-walking sensations and the critical factors affecting these sensations.

Here, we identified the critical parameters for enabling stationary users to experience virtual walking without whole-body action via psychophysical experiments. We focused on passive whole-body motions in the heave and yaw directions to enable seated users to experience virtual walking, which was created by a 4-degrees of freedom (dof) motorized chair with a large-field-of-view head-mounted display (HMD).

II. Experiments

We conducted two experiments to evaluate the impact of the heave and yaw motion amplitudes on walking sensations. In these experiments, seated participants were exposed to various levels of applied heave and yaw while viewing a VR scene in which, translational walking motion was simulated at two different speeds. The first experiment was designed to quantify the effect of heave and yaw motions separately on walking sensations. In the first experiment, we tested various amplitudes to select suitable ranges for the amplitudes of the heave or yaw motions that are required for the second experiment. The second experiment was designed to quantify the effect of the combination of heave and yaw motion amplitudes on walking sensations.

A. Participants

Twenty-one healthy paid volunteers (right-handed; 17 females; mean (M) = 37.1 years old, standard deviation (SD) = 8.8)

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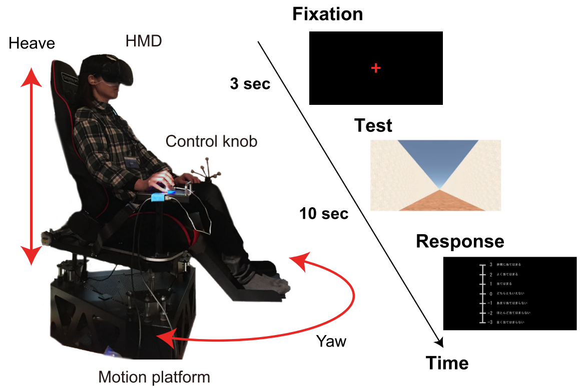

Fig. 1. Experimental setup for heave and yaw motions (A). Seated participants on a motorized chair wore an HMD and responded using a control knob. Experimental procedure (B).

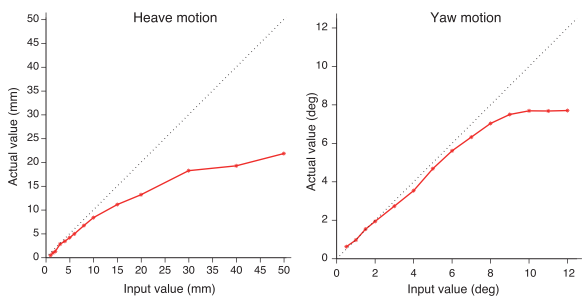

Fig. 2. Responsiveness between the input and output of the SIMVR.

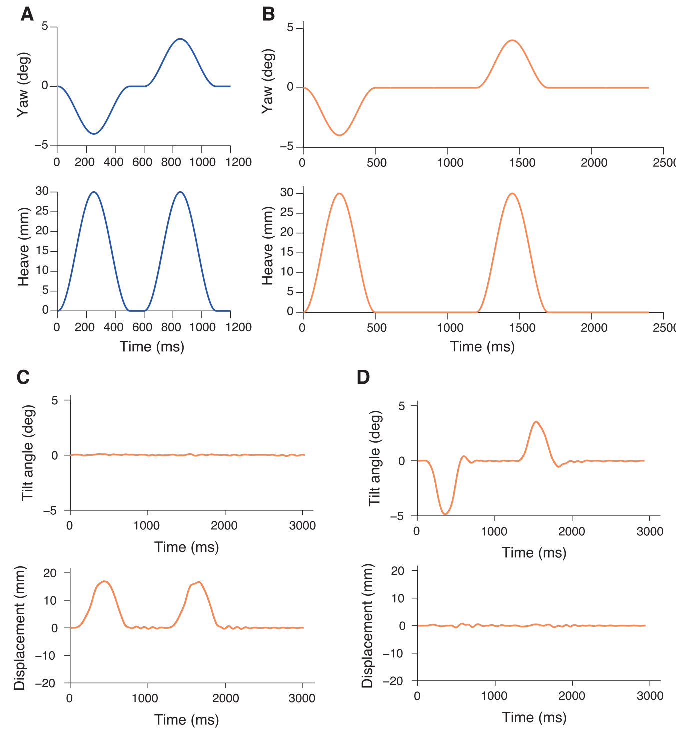

Fig. 3. An example of bodily stimuli provided by heave and yaw motions (30 mm and 4.0 deg, respectively). Input signals for the stimuli duration of 600 ms (A) and 1,200 ms (B). Output for heave (C) and yaw (D) motions for a walking cycle of 1,200 ms.

took part in Experiment 1 and fourteen (right-handed; 11 females; M = 38.8 years old, SD = 8.7) participated in Experiment 2. All the participants had normal or corrected-to-normal vision. None of them had previously reported any vestibular, tactile, neurological, or locomotion abnormalities. The recruitment of the participants and the experimental procedures were approved by the ethics committees at both the University of Tokyo (approval number: UT-IST-RE-191108-1) and NTT Communication Science Laboratories (approval number: H29-003), and the procedures were conducted in accordance with the Declaration of Helsinki. All participants provided a written informed consent and were naive about the aim of the study.

B. Apparatus and Stimuli

The stimuli of body motion were presented using a 4-dof motion ride simulator (SIMVR VR Ride Simulator, Wizapply Inc.), as shown in Fig. 1(A), which consists of four actuators: three linear actuators for moving up and down and one actuator for yaw rotation. Two step cycles of 600 and 1,200 ms were employed because a step cycle of 600 ms has been used as one of the general walking cycles in the AIST gait database [20] and that of 1,200 ms was the most preferred as per a pilot study. The motion consists of one cycle of a sinusoidal curve ($y = A/2$ (1-$cos(2\pi t/T)$); period: T = 500 ms, amplitude A), whose period was determined by reference to an actual gait motion [20].

Visual stimuli were presented with an HMD (Vive, HTC Inc.; refresh rate: 90 Hz, 1080 × 1200 px for each eye). The delay of the HMD was reported to be less than 40 ms [21]. Unity (2018.2.7f1, Unity Technologies) was used to create a VR scene for the visual stimuli. The VR scene consisted of two walls and a floor (Fig. 1(B)). The height of the viewpoint was set to 1.8 m from the floor. The viewpoint of the camera in the VR scene moved translationally at a constant speed of 4.8 km/h, which corresponded to 25.06 pixel/s of optic flow.

C. Experiment 1

Seventeen stimuli—nine amplitudes for heave motions (0, 2, 4, 6, 8, 10, 15, 20, and 30 mm) and eight angles for yaw rotations (0, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, and 5.0 degrees)—were selected. An example is shown in Fig. 3, which was recorded with an optical motion capture system (Vicon Bonita; sampling frequency: 100 Hz) and processed with a low-pass filter (cutoff frequency: 10 Hz). Actual output values corresponded to the amplitudes 0, 1.2, 3.4, 5.0, 6.7, 8.4, 11.1, 13.1, and 18.2 mm and the angles 0, 0.6, 1.0, 1.5, 1.9, 2.7, 3.5, and 4.7 degrees based on the relationship between the input and output (Fig. 2). Trials for each amplitude or angle were repeated thrice in a randomized order (see Section II-E for details).

D. Experiment 2

Thirty combinations of five angles of yaw rotations (0, 0.5, 1.0, 2.0, and 4.0 degrees) and six amplitudes of heave motions (0, 2, 4, 8, 15, and 30 mm) were selected. Actual output values corresponded to the amplitudes 0, 1.2, 3.4, 6.7, 11.1, and 18.2 mm, and the angles 0, 0.6, 1.0, 1.9, and 3.5 degrees based

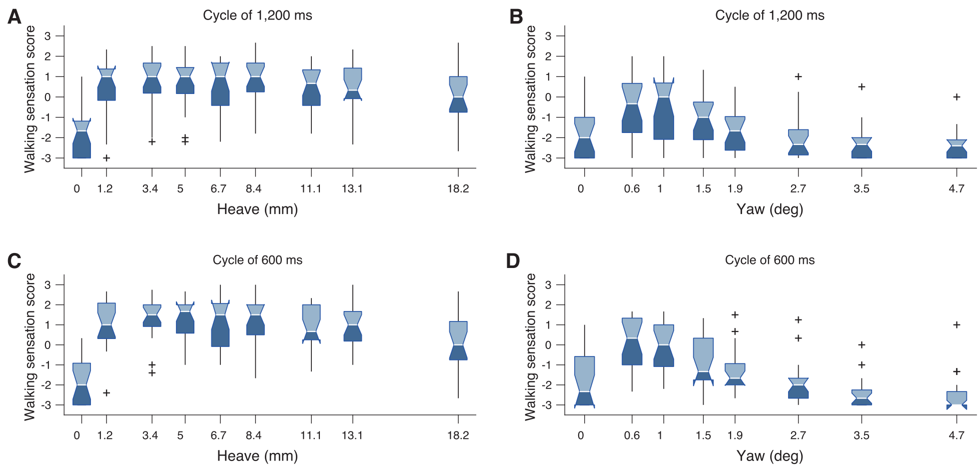

Fig. 4. Boxplots of subjective walking scores obtained with vertical (A, C) or yaw rotation (B, D) stimuli. The participants rated their level of agreement with the statement “I felt as if I were walking” on a 7-point Likert scale, ranging from −3 (strongly disagree) to +3 (strongly agree), with 0 indicating “neither agree, nor disagree.” The horizontal white bars indicate the medians, and the boxes represent the interquartile ranges. The whiskers extend from the top and bottom of the boxes to the farthest points and do not extend further than 1.5 times the interquartile range. Individual crosses represent outliers.

on the relationship between the input and output (Fig. 2). Each combination was repeated thrice with a randomized order (see Section II-E).

E. Procedure

The same procedure was used in both experiments. Participants were seated on the motion ride simulator and then wore the HMD and earplugs. In addition, auditory information of the motion ride stimulator was suppressed by white noise emitted from loud speakers located on the floor.

At the beginning of each trial, the participants were instructed to fixate on a cross displayed on the HMD screen for 3 s. Then, the fixation cross disappeared, and visual and bodily stimuli were presented for 10 s. The condition of the step cycles was blocked, and the order of the conditions was counterbalanced across participants using a modified Latin square and reversed using an ABCDDCBA design to minimize time-dependent effects. Each block was repeated thrice. The order of the stimulus in the blocks was randomized for each participant. The task of the participants was to grade their level of agreement with the statements “I felt like I was walking,” “I felt motion sickness,” and “I felt my body lifted up” using a 7-point Likert scale, where −3 denoted strongly disagree, +3 denoted strongly agree, and 0 referred to “neither agree, nor disagree.” The selections were made with a control knob (PowerMate, Griffin Technologies Inc.) placed on the table on the right-hand side. Prior to the experiments, the participants performed practice trials to get acquainted with the task. To eliminate the influence of fatigue, participants were provided at least a 5 min break after every block and could rest at any time. The total experiment time for a typical participant was roughly 3 h; they spent a total of 7 h in the lab, but 4 h of this time consisted of breaks.

III. Result

A. Experiment 1

Fig. 4 shows the rating scores for subjective walking provided by the participants. In the heave condition, the median of the rating scores was greater than 0 in both walking cycles and tended to decrease slightly with the increase in amplitude of the heave, particularly when it exceeded 11.1 mm. Moreover, in the yaw condition, the median of the rating scores was almost equal to or smaller than approximately 0 in both cycles, and tended to approach −3 as the yaw angle increased, particularly for values larger than 1.0 degree. The Friedman test revealed that the subjective ratings of a walking sensation were significantly different for each walking cycle and body swinging stimulus for each stimulus condition (heave motion with the 1,200 ms heave cycle: $\chi^2(8, N = 21) = 44.5$, $p < 0.001$; yaw motion with the 1,200 ms cycle: $\chi^2(7, N = 21) = 81.7$, $p < 0.001$; heave motion with the 600 ms cycle: $\chi^2(8, N = 21) = 61.2$, $p < 0.001$; and yaw motion with the 600 ms cycle: $\chi^2(7, N = 21) = 100.0$, $p < 0.001$). This shows that the feeling of walking experienced by the participants differed depending on the heave amplitude and the yaw angle of whole-body motions.

The results of a post hoc Wilcoxon signed-rank test with Bonferroni–Holm correction are summarized in Table I for a cycle of 1,200 ms and in Table II for a cycle of 600 ms. The subjective walking scores obtained for no added heave motion (0 mm) significantly differed from those for added heave motion at various amplitudes in both walking cycles, which indicates that the scores were significantly higher when bodily stimuli were applied. In addition, for the 600 ms cycle, the largest amplitude of heave motion (18.2 mm) was rated differently from all other amplitudes except for 1.2 mm. In contrast, the scores for yaw motions of 0.6 and 1.0 degrees significantly differed from those of the other angles for both walking cycles.

Fig. 5 shows the correlation between the combination of the medians of subjective walking, motion sickness, and body elevation scores of all the participants. Spearman’s rank correlation coefficient, which was calculated for the rating scores of all conditions, showed a significant negative correlation between the subjective walking sensation and motion sickness scores ($\rho = -0.37$, $p = 0.03$), as well as a significant positive correlation between subjective walking and body elevation sensation

TABLE I
POST HOC WILCOXON SIGNED-RANK TEST WITH BONFERRONI–HOLM CORRECTION IN EXPERIMENT 1

Adjusted p-values for heave motion with a cycle of 1,200 ms

mm	1.2	3.4	5	6.7	8.4	11.1	13.1	18.2
0	0.005	0.004	0.005	0.008	0.005	0.006	0.007	0.012
1.2		1	1	1	1	1	1	1
3.4			1	1	1	1	1	1
5				1	1	1	1	0.846
6.7					1	1	1	1
8.4						0.7347	1	0.547
11.1							1	1
13.1								1

Adjusted p-values for yaw motion with a cycle of 1,200 ms

deg	0.6	1	1.5	1.9	2.7	3.5	4.7
0	0.005	0.002	0.097	0.733	1	0.914	0.841
0.6		1	0.129	0.025	0.017	0.008	0.007
1			0.022	0.005	0.008	0.002	0.005
1.5				0.097	0.008	0.007	0.008
1.9					0.104	0.015	0.017
2.7						0.841	0.580
3.5							0.785

Shaded cells represent p-values < 0.05.

TABLE II
POST HOC WILCOXON SIGNED-RANK TEST WITH BONFERRONI–HOLM CORRECTION IN EXPERIMENT 1

Adjusted p-values for heave motion with a cycle of 600 ms

mm	1.2	3.4	5	6.7	8.4	11.1	13.1	18.2
0	0.003	0.004	0.004	0.005	0.004	0.004	0.003	0.020
1.2		1	1	1	1	1	1	0.829
3.4			1	1	1	0.532	1	0.017
5				1	1	0.682	1	0.026
6.7					1	1	1	0.074
8.4						0.824	1	0.013
11.1							1	0.012
13.1								0.026

Adjusted p-values for yaw motion with a cycle of 600 ms

deg	0.6	1	1.5	1.9	2.7	3.5	4.7
0	0.009	0.012	0.248	0.766	0.833	0.248	0.121
0.6		0.939	0.014	0.013	0.005	0.002	0.002
1			0.040	0.009	0.002	0.002	0.002
1.5				0.939	0.007	0.003	0.003
1.9					0.003	0.002	0.002
2.7						0.009	0.009
3.5							0.833

Shaded cells represent p-values < 0.05.

scores ($\rho = 0.87$, $p < 0.001$). However, Spearman's rank correlation coefficient did not show a significant correlation between the latter combination ($\rho = -0.15$, $p = 0.41$).

B. Experiment 2

Fig. 6 shows the walking sensation scores obtained in Experiment 2. The scores were higher than 0 when the heave motions were equal to or greater than 2 mm and the yaw motions were equal to or less than 0.5 deg. In addition, when the yaw motion was greater than 1 deg, the scores tended to be negative regardless of the amplitude of the heave motion.

We applied an aligned rank transform (ART) to the scores to analyze the interaction effects with nonparametric data (Likert scale) [22]. Then, we conducted a three-way repeated-measure ANOVA on the aligned ranks using heave conditions (0, 1.2, 3.4, 6.7, 11.1, and 18.2 mm) and yaw conditions (0, 0.6, 1.0, 1.9, and 3.5. degrees) as the factors using 7-scale data (-3: strongly disagree, $+3$: strongly agree) for walking cycles of 600 ms and 1,200 ms. Table III shows the ANOVA summary of the within-subject effects, indicating that the main effects for the heave and yaw conditions showed statistical significance, but those for the walking cycle condition did not. A significant interaction existed between the heave and yaw conditions. More importantly, the three-way interaction was also significant. None of the other interactions were significant.

To further investigate the role of the yaw motion, the three-way interaction was further analyzed with a repeated measures ANOVA on data that were split according to the yaw angles. The results revealed significant simple interactions between heave motion and walking cycle for the yaw angles of 0, 0.6, and 1.0 degrees ($F(5,65) > 2.47$, $p\text{s} < 0.05$). In contrast, for the yaw angles of 1.9 and 3.5 degrees, the interaction of heave motion with walking cycle was not significant. These results suggest that heave motions presented with small yaw motions (0, 0.6, or 1.0 degrees) influence the difference between the two walking cycles.

Fig. 7 shows the correlations between the combinations of the medians of subjective walking, motion sickness, and body elevation scores of all the participants. Spearman's rank correlation coefficient, which was calculated for the rating scores of all conditions, showed a significant negative correlation between the subjective walking sensation and motion sickness scores ($\rho = -0.70$, $p < 0.001$), a significant positive correlation between the subjective walking and body elevation sensation scores ($\rho = 0.89$, $p < 0.001$), and a significant negative correlation between the subjective walking and body elevation sensation scores ($\rho = -0.57$, $p < 0.001$).

IV. DISCUSSION

Our results consistently show that passive whole-body motion in the heave direction is effective at generating a simulated walking sensation for sitting users. However, passive motion in the yaw direction was not as effective because the highest subject scores did not exceed zero (Experiment 1). When the heave and yaw passive motions were presented together, rotation angles of 1.9 degrees or above in the yaw direction did not create a pseudo-walking sensation regardless of the amplitude of the heave motion (Experiment 2). Furthermore, the rating scores tended to approach -3 as the yaw angle stimulus increased in the first experiment, and a similar tendency was observed even when any heave motion was presented together in the second experiment. These results suggest that passive whole-body motion is effective for inducing a pseudo-walking sensation in the range of 1.2 to 11.1 mm for the heave motion and from 0 to 1.0 degree for the yaw motion. Overall, passive whole-body motion in the yaw direction is less effective at inducing a pseudo-walking sensation than that in the heave direction.

Our result could be explained by the changes in viewpoint caused by the whole-body motion. During the experiment, the VR scene presented to the participant moved in conjunction with the movement of his/her head due to the tracking function in the HMD worn by him/her. Therefore, the stimuli of heave and yaw motion affected not only the participant's somatosensation, but also his/her vision when passive body motion was presented. A previous study using a change in viewpoint without

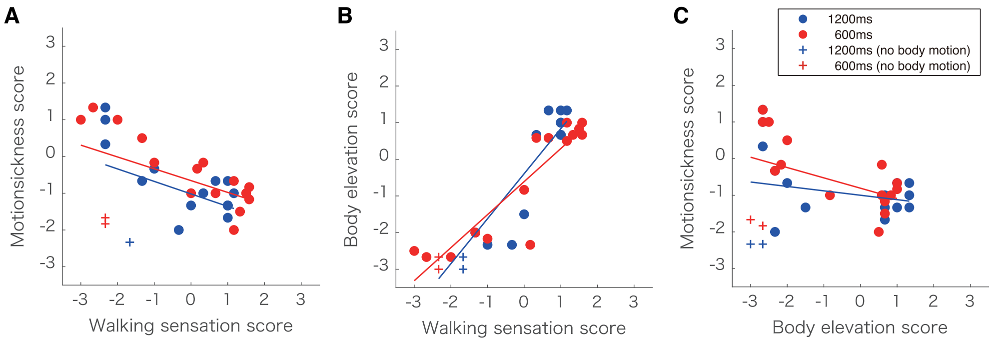

Fig. 5. Correlation between walking sensation and motion sickness scores (A), between elevation sensation and walking sensation scores (B), and between elevation sensation and motion sickness scores (C) in Experiment 1.

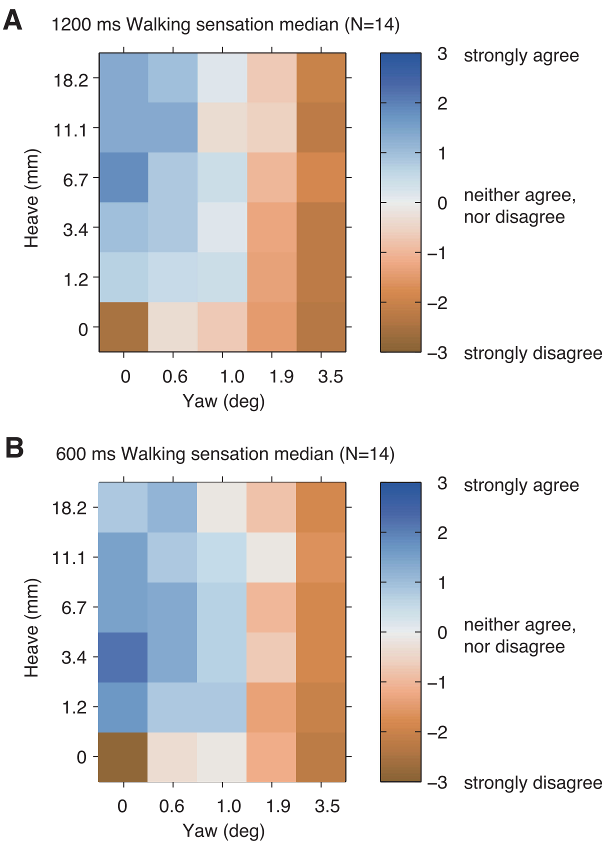

Fig. 6. Walking sensation scores against combinations of heave and yaw motions for walking cycles of 1,200 ms (A) and 600 ms (B) in Experiment 2.

TABLE III
THREE-WAY ANOVA TABLE WITH AN ART IN EXPERIMENT 2

Term	Df	Sum Sq	Mean Sq	F value	Pr(>F)	η_p^2
Heave	5	18212833.84	3642566.77	44.43	0.000	0.77
Yaw	4	687848.87	171962.22	7.13	0.000	0.35
Cycle	1	292320.12	292320.12	3.24	0.095	0.20
Heave×Yaw	20	11677011.75	583850.59	27.97	0.000	0.68
Heave×Cycle	5	91523.48	18304.70	1.11	0.363	0.08
Yaw×Cycle	4	65076.64	16269.16	1.15	0.343	0.08
Heave×Yaw×Cycle	20	772775.08	38638.75	1.64	0.043	0.11

body motion showed that vertical movement of the viewpoint was most effective at generating a walking sensation [10], and our result supports this finding. However, during actual walking, yaw motion occurs around the shoulders and hips, but yaw motion of the viewpoint rarely occurs. Therefore, the yaw motion of the viewpoint accompanying the body motion may lead to a decrease in the subjective rating of a walking sensation.

The yaw motion improved perception of walking relative to the baseline (with no applied yaw motion) but the median of the rating score did not exceed a neutral rating and decreases with the magnitude of the yaw angle. In a vestibular system, the perceptual threshold of angular acceleration has been reported to be around 0.5 deg/s^2 [23]. In our experiments, the mean angular acceleration of the yaw angle of 0.6 degree is 0.6 deg/s^2, which exceeds this threshold. For added yaw motion in the range 0 to 0.6 degree, there might be an effect at sub-threshold levels.

To compare the amplitude of heave motion during actual walking, we analyzed vertical displacement data of thirty Japanese subjects (11 men, 19 women; 20 to 50 years, average: 33.7 years) from the AIST gait database [20], which showed that a typical gait pattern in the vertical displacement near the vertebra prominens (marker #C7) was 50.5 ± 4.2 mm. In contrast, our result shows that the amplitude of vertical motion providing the highest walking scores ranges from 1.2 to 11.1 mm in both experiments, as described above. A previous study reported that a feeling of walking could not be obtained from motions that had the same amplitude as those of actual walking [18]. Therefore, it is unlikely that subjective walking scores would increase with heave motion amplitudes higher than those we tested. These results suggest that passive whole-body motion with a vertical amplitude that is one-fourth that of actual walking or less is most effective for generating a pseudo-walking sensation for sitting users. This is in line with a previous finding that a ratio of approximately one-fifth to one-fifteenth, which was estimated by the adjustment method, is optimal [18]. This difference in amplitude from actual walking is presumed to be due to the overestimation of the sensory feedback information because an efference copy of the motor command is not sent to the brain in passive whole-body motion.

In the absence of passive whole-body motion stimulation, the median of the walking sensation scores was approximately −2. In contrast, with passive whole-body motion stimulation, for example, the minimum change used in both experiments, 1.2 mm or 0.6 degree stimulation, increased the scores significantly. These results suggest that whole-body motion stimulation plays a major role in the generation of a simulated walking sensation.

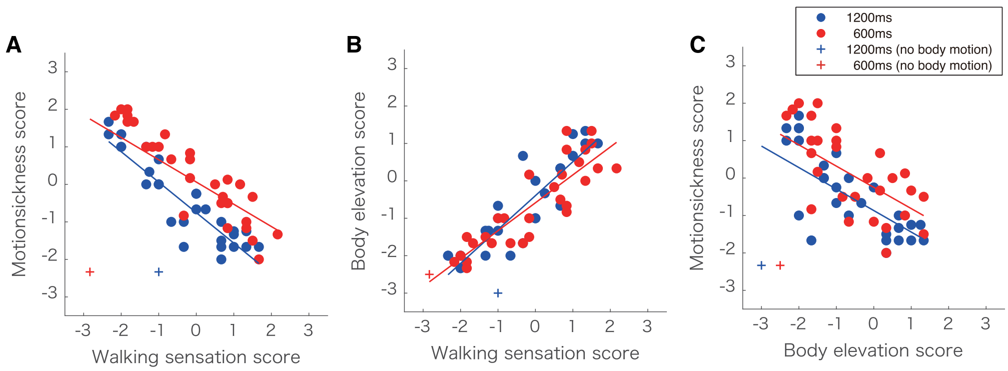

Fig. 7. Correlation between walking sensation and motion sickness scores (A), between elevation sensation and walking sensation scores (B), and between elevation sensation and motion sickness scores (C) in Experiment 2.

A negative correlation was found between the walking sensation and motion sickness scores in both experiments. Previous studies have reported that the sense of presence (particularly the feeling of “control” in the VR environment) and the intensity of cybersickness are negatively related [24]. Although the mechanism underlying motion sickness has not yet been elucidated, the discrepancy between visual and vestibular (and somatosensory) sensations is the most supported so far [25]. Notably, we can correct mismatched information with prediction; automobile drivers who can predict their direction of travel and changes in speed are reported to experience motion sickness less than passengers, and this is also true for drivers in VR space [26]. Further studies are necessary to understand the effects of the sense of agency on the causal relationship between pseudo-walking sensation and motion sickness.

With the passive whole-body motion stimulation, there was a latency between applied body motions and the corresponding updates to the HMD, resulting in a potential sensory conflict arising from the asynchrony between proprioception and visual information. As the latency would be almost identical across all conditions in this study, it is difficult to discuss the effect of this latency here. Future work will include adding a delay between the body motion and visual information to examine its effect on motion sickness as well as walking sensation.

A strong positive correlation was found between the elevation and walking scores in both experiments. This may be due to the fact that the body elevation was rated high for the heave stimulation because the body actually lifted, and that the walking sensation was rated high because of the heave motion. However, while there was no significant correlation between the elevation and motion sickness scores in the first experiment, the opposite was true in the second experiment, suggesting that a strong walking sensation rather than a strong elevation sensation of the body might be strongly related to the reduction in motion sickness.

The evaluation scores in our experiments varied among participants. Although we performed practice trials and explained the statements of the three questionnaires before the experiments, the interpretation of a sensation was also considered by the ambiguity of the statements. Instead of using a subjective scale to estimate the strength of a walking sensation, a previous study proposed a method using tactile RT as a proxy of peripersonal space [15]. In future, we will adopt this method to evaluate the sensation; we will also use an objective index by limiting the number of conditions based on the results of this experiment. Note that we did not estimate the space near the body in this study because of the large number of conditions; the purpose of this study was to identify the optimal parameters for creating a pseudo-walking sensation and to investigate the relationship between the pseudo-walking sensation and motion sickness.

Notably, the evaluation method described in this paper has not fully proved whether or not the pseudo-walking sensation is actually created by body motion stimulation. The optimal value of the parameter was found by within-subject comparison. It might be possible to directly compare the passive whole-body motion with actual walking as a baseline; however, it is doubtful whether judging the occurrence of the “feeling of walking” when actually walking is appropriate. In addition, to ensure that the actual walking condition is consistent with the other conditions of passive body motion, it is necessary to control the walking speed and cycle, which would force the participant to walk unnaturally. It is necessary to resolve this issue, namely that walking should not become unnatural if we were to directly compare it with actual walking.

Finally, we note that the pose of the participants will affect the occurrence of a “feeling of walking.” However, the pose was consistent throughout this study. Instead of using a seated pose for participants, we could ask participants to stand on a motion platform, which might better induce a sensation of walking.

V. Conclusion

In this study, we examined the optimal amplitudes of heave and yaw body motions to create a sensation of walking for seated participants through psychophysical experiments. Our results consistently showed that heave body motion with a vertical amplitude that is one-fourth that of actual walking or less could effectively generate a sensation of pseudo-walking while sitting.

In future, we will attempt to understand the mechanism of a pseudo-walking sensation caused by passive whole-body motion by adding other sensory stimuli and conduct experiments with a controlled viewpoint movement.

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