Ascending and Descending in Virtual Reality: Simple and Safe System using Passive Haptics

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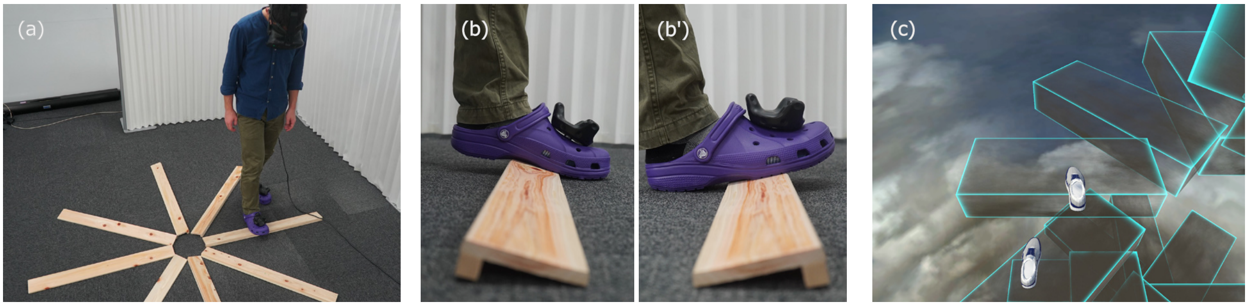

Fig. 1: Overview of the proposed system that enabled the user to ascend and descend spiral stairs infinitely in the virtual environments (VEs). (a) The user steps on small bumps attached to a flat floor in the real space corresponding to the edge of steps in the VEs. The user feels a strong sensation of ascending and descending by stepping on the small right-angled bumps (i.e., ascending case: (b), descending case: (b')). (c) The visual stimuli that simulated staircase walking provides via head-mounted displays.

Abstract—This paper presents a novel interactive system that provides users with virtual reality (VR) experiences, wherein users feel as if they are ascending/descending stairs through passive haptic feedback. The passive haptic stimuli are provided by small bumps under the feet of users; these stimuli are provided to represent the edges of the stairs in the virtual environment. The visual stimuli of the stairs and shoes, provided by head-mounted displays, evoke a visuo-haptic interaction that modifies a user's perception of the floor shape. Our system enables users to experience all types of stairs, such as half-turn and spiral stairs, in a VR setting. We conducted a preliminary user study and two experiments to evaluate the proposed technique. The preliminary user study investigated the effectiveness of the basic idea associated with the proposed technique for the case of a user ascending stairs. The results demonstrated that the passive haptic feedback produced by the small bumps enhanced the user's feeling of presence and sense of ascending. We subsequently performed an experiment to investigate an improved viewpoint manipulation method and the interaction of the manipulation and haptics for both the ascending and descending cases. The experimental results demonstrated that the participants had a feeling of presence and felt a steep stair gradient under the condition of haptic feedback and viewpoint manipulation based on the characteristics of actual stair walking data. However, these results also indicated that the proposed system may not be as effective in providing a sense of descending stairs without an optimization of the haptic stimuli. We then redesigned the shape of the small bumps, and evaluated the design in a second experiment. The results indicated that the best shape to present haptic stimuli is a right triangle cross section in both the ascending and descending cases. Although it is necessary to install small protrusions in the determined direction, by using this optimized shape the users feeling of presence of the stairs and the sensation of walking up and down was enhanced.

Index Terms—Virtual reality, locomotion, haptic feedback, perception, stairs, staircase

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1 INTRODUCTION

Many studies in the research field of virtual reality (VR) have been conducted that enable a user to walk horizontally in 3D virtual environments (VEs), for example locomotion devices [3, 6] or redirected walking techniques (RDW) [14, 25].

Conversely, very few VR techniques exist that enable a user to walk up and down stairs or a slope in VEs. By adding a vertical transportation to VR experiences, it is possible to express a large multileveled VE in a single real space with just one floor. In particular, staircases exist in most buildings and are seen in everyday life, so vertical transportation by walking will play an important role in VEs. In this research, we focused on the simulation of stairs in VEs. However, most previous techniques that simulate virtual stairs are based on complicated systems that generates physical steps by using actuators [6, 7, 22]. They are expensive and present an injury risk for users wearing head-mounted displays (HMDs), so a simple and low-cost system that allows users to walk safely and freely in the vertical direction in VEs is highly desirable.

Meanwhile, human spatial perception is composed of multiple sensations. Based on this knowledge, several attempts were made to manipulate spatial perception by combining passive haptics with visual stimuli. Passive haptics are the haptic feedback for a virtual object using a real physical object, and are a simple and low-cost means of providing the sense of touch and enhancing a user's experience. Azmandian et al. proposed Haptic Retargeting that enables a single physical

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object to provide passive haptic feedback for multiple virtual objects [1]. Moreover, by exploiting visual dominance, a single physical object can produce haptic feedback for multiple virtual objects with different shapes [2,5,9]. These methods change the spatial perception around a user's hand.

In this research, we used passive haptics to change a user's spatial perception of movement in the vertical direction, and built a simple and safe system that enables a user to ascend and descend stairs in VEs. By using passive haptics, this novel system makes a user feel that the shape of the flat floor is that of the stairs; hence, the user is provided with a strong sensation of walking up and down stairs in the VEs. Given that the user felt like they were walking up and down in the VEs, despite walking on a flat floor in the real world, VEs have the potential to be expanded infinitely in the vertical direction.

1.1 Contributions

The contributions of this work are summarized by the following three points:

- We were able to simulate a realistic sense of ascending and descending steps, without any complicated system that requires actual physical steps using actuators, enabling users wearing HMDs to safely experience VR content, including vertical movement.
- We adopted multimodal techniques, such as passive haptics, to produce realistic sensations in a system that simulates virtual stairs. This system presented users with a sense of presence and a sense of ascending and descending stairs, contrary to previous techniques that only manipulate a user's viewpoint.
- Given that a user does not require proficiency in the proposed system, the user can walk naturally as they do in real space.

2 RELATED WORK

Our system is related to systems that provide users with the sensation of walking on uneven terrain or leverage passive haptics techniques. Previous techniques for simulating virtual stairs are mostly based on a complicated system that generates physical steps by using actuators. The Gait Master uses treadmills, where it is possible for users to walk up and down by taking physical steps [7]. However, this system is too large and complicated for most applications.

The Circula Floor system [6] builds on the same concept, but consists of robot units that move in place under the user's feet. This robot system allows the user to walk both horizontally and vertically. In the case of elevation, it is necessary for the user to become familiar with the system, and it takes a certain amount of time to eliminate the steps created by the actuator.

Level-Ups [22] are computer-controlled stilts that enable users to experience both ascent and descent. This system does not require proficiency and the height of the stilts can be changed at the time of free leg footfall, so that the user can ascend and descend one step without any discomfort. However, as with Circula Floor, it is necessary to eliminate the height difference as a user cannot walk continuous steps like a staircase in real space. It is also difficult for a user to walk naturally on a flat plane because the stilts are heavy.

These systems require a certain amount of time to eliminate the physical steps generated by the actuators; hence, the user's walking method is restricted and their feeling of presence in the VEs may be impaired. They are also expensive and pose a risk of injury for users wearing HMDs.

There are also several systems that allow the user to move vertically in VEs by simulating a lifting device other than stairs. Nordahl et al. described an experiment investigating whether haptic simulation of the feet can induce vertical self-motion while participants are in a virtual elevator [16]. Their results demonstrated that such illusionary self-motion can be elicited by haptic feedback delivered at the feet. March-and-Reach is a realistic ladder climbing technique in VEs and use both the user's arm and leg motions to provide the sensation of climbing a ladder [12]. Given that a ladder is not a tool frequently used in everyday life, the ladder VR technique is not easily generalized for other applications.

In a VR setting, it is commonly known that when walking in VEs it is more effective to walking in real space [27]. Likewise, when touching a virtual object, providing haptic feedback corresponding to the object increases the sense of realism for the user [5,15].

In addition to visual stimuli, other sensory modalities (e.g., touch and audition) are important for providing compelling VR experiences. Thus, recently systems using visually-induced illusions (e.g., through visuo-haptic interaction) have been gaining attention. Visuo-haptic interaction is a phenomenon that modifies a user's proprioceptive perceptions according to visual stimuli, while haptic and visual sensations are presented simultaneously. Several studies have attempted to modify a user's spatial perception by using both visual and haptic stimuli to generate the effect of visuo-haptic interaction [1,2,5]. In particular, Ban et al. revealed that by presenting the passive haptics of a small edge, it is possible to change shape perception of an entire object that a user touches with their hand in the VE [2].

In addition, redirected walking is a technique that manipulates a user's spatial perception of the horizontal direction by viewpoint manipulation [20,25]. By using this technique, it is possible to express vast VEs in limited real space. Matsumoto et al. demonstrated that the addition of passive haptic signals strengthen the effect of redirected walking techniques in the case where users are touching a wall in VEs [14].

A method similar to redirected walking was proposed by Marchal et al. in which the user experiences walking up and down a single step without performing physical steps; this method employed viewpoint manipulation to achieve this effect [13]. However, it is difficult to strongly change the spatial perception in the vertical direction of a user walking horizontally on a flat surface, using only viewpoint manipulation.

We propose that by adding passive haptics to viewpoint manipulation, a strong sensation of walking up and down can be produced, while the users are walking on a flat surface in real space.

3 SIMPLE AND SAFE TECHNIQUE THAT SIMULATES STAIRS BY USING PASSIVE HAPTICS

3.1 Concept

The purpose of this novel technique is to present a strong sensation of ascending and descending stairs, safely and simply without a complicated system or using an actuator that generates physical steps. Our novel technique consists of two ideas (Fig. 2).

The first is to modify a users' perception of the shape of the floor surface on which they walk, simulating a stairway by adding passive haptics corresponding to the edge of a stair step to the plantar of the users.

The second idea is to combine viewpoint manipulation and passive haptics, like visuo-haptic RDW. Visuo-haptic RDW (combining passive haptics and RDW techniques) enhances the effectiveness of RDW techniques and reduces sickness and discomfort [14]. We hypothesized that the idea of visuo-haptic RDW can also be applied to vertical viewpoint manipulation. Moreover, Nordahl et al. also described that the addition of vibrotactile feedback creates a more compelling illusion of vertical self-motion when riding a virtual elevator [16]. Based on this knowledge, we also hypothesized that our idea can induce vertical self-motion by the addition of passive haptics at a user's feet.

Given that physical stairs are not used, there are few physical risks for the user. As the space is expanded in the vertical direction, it is possible to make complete use of a VE consisting of a 3D space. For example, our system can be applied to building simulations in architectural design.

3.2 Haptic Feedback

Haptic stimuli corresponding to the edge of a step in a stairway are provided to the user's sole. When walking on the stairs, the edge that the user feels on his/her sole can be considered as an important plantar sensation characteristic of stairs.

Previous studies revealed that the walking motion of the subject can be changed by reducing the plantar sensation [4,18], and several VR

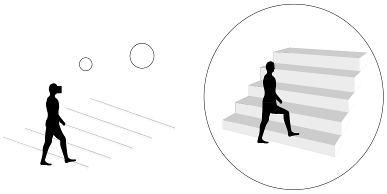


Fig. 2: Concept of the novel system that provided the sensation of walking up and down stairs in virtual environments. The visual stimuli that simulated staircase walking were provided via a HMD. Passive haptics for the edge of virtual steps were provided by small bumps.

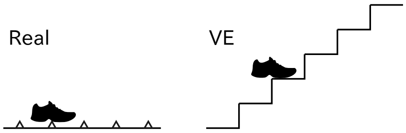
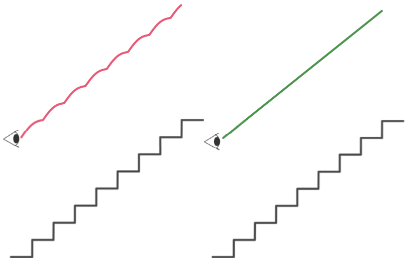
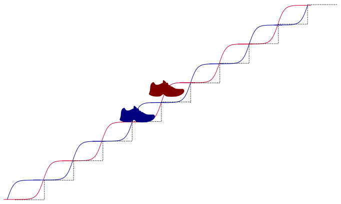


Fig. 3: The plantar sensation of the edge of a step was produced by the user stepping on small bumps attached to a flat surface in real space.



(a) *Move Up/Down* (Equation 1) (b) *Line* (Equation 2)



(c) *Foot* (Equation 3)

Fig. 4: Manipulation of viewpoint height according to the translation of the user's viewpoint, via Equation 1, Equation 2 in the virtual environments. The ground in the shoe models are also manipulated via Equation 3.

systems using haptic feedback to the user's sole to provide a walking sensation have been proposed [11, 26]. For simulating foot-ground interactions, Nordahl et al. showed that haptic feedback delivered at foot level can enhance realism in VEs [17]. Therefore, we believe that plantar sensation plays an important role in the sensation of walking.

We adopted passive haptics for presenting haptic stimulus to a user's sole because of its advantages (low-cost and no time delays). As illustrated in Fig. 3, we used a small bump on a flat floor as the haptic feedback for virtual stairs. We believe that the shape perception of the ground surface can be changed to that of stairs by presenting haptic stimuli corresponding to the edge of a stair step to the user's sole, i.e., our system can create visuo-haptic interaction like the method described by Ban et al. [2].

3.3 Visual Feedback

Marchal et al. demonstrated that it is effective to manipulate the height and orientation of the viewpoint for the sense of walking up and down [13]. It was also revealed that combining these two manipulations will improve the effect. However, their study was limited to overcoming a single step or hole. However, we considered the method of viewpoint manipulation for continuous steps in this study. Due to the difficulty of gaze measurement during staircase walking and the simplification of experiments, we limited the parameters of the viewpoint manipulation to height only.

For an understanding of the viewpoint of height during stair walking, we measured actual motion data by using a motion capture suit (Noitom Perception Neuron) and corrected the ground level in the data. Actual stair walking motion data can be directly applied as a viewpoint manipulation, but this method cannot take into account individual differences or various types of stairs. Therefore, from the actual motion data, we extracted the features of periodic up and down motion according to the positions of stair steps obtained and created the following Equation 1: *Move Up/Down* (Fig. 4(a)). We thought that this method reflects not only the gradient of the entire staircase but also the feature of the staircase consisting of multiple steps.

$$MoveUp/Down: H_{\mathrm{VE}} = H_{\mathrm{Real}} + \frac{h}{d}\cdot\Delta_x + a\cdot|(cos(\frac{\Delta_x}{d}\cdot\pi))| \qquad (1)$$

Here, $H_{\mathrm{VE}}, H_{\mathrm{Real}}$ are the height of the user's viewpoint in VEs and real space, respectively; Δ_x is the translation amount of the viewpoint in a real space; and h and d are the height and depth of a virtual step, respectively. The amplitude of the small up and down movement was set to $a = 2.5$cm, which was chosen as a value for which the user did not feel discomfort. All parameters that transformed the user's viewpoint, except the height, were reflected as they are in real space. We compared the above equation with the simplest Equation 2: *Line*, which linearly manipulates the height of the viewpoint according to the gradient of the stairs (Fig. 4(b)).

$$Line: H_{\mathrm{VE}} = H_{\mathrm{Real}} + \frac{h}{d}\cdot\Delta_x \qquad (2)$$

To evoke a visuo-haptic interaction, it was important to align the physical and virtual objects in the passive haptics. The shoe models were displayed at the position of a user's foot so that users knew the position of their feet on the virtual stairs. The height of the shoe models in the VEs were also manipulated via Equation 3 (Fig. 4(c)).

$$H'_{\mathrm{VE}} = H'_{\mathrm{Real}} + (i-1)\cdot h + 2h\cdot sigmoid(\Delta'_x - i\cdot d) \qquad (3)$$

Hence, $H'_{\mathrm{VE}}, H'_{\mathrm{Real}}$ are the height of the users shoes in VEs and a real space, respectively; Δ'_x is the translation amount of each shoe in a real space; and i is the ordinal number of a step in relation to where the other foot is. All parameters that transformed the shoes models, except the height, were reflected as they are in real space.

4 PRELIMINARY USER STUDY FOR OUR TECHNIQUE

By simulating virtual stairs based on passive haptics in our system, we investigated the user's perception of ascending and sense of presence. We assumed that the proposed system was more effective for the ascending case because many people walk upstairs by hooking their soles on the edges of the steps. Moreover, a user's motion during ascent differs from that during descent [19], and therefore, this preliminary user study was carried out for the ascending case.

4.1 Method

4.1.1 Participants

Twelve participants (21-24 years old, mean age 21.9, no females) from our institution were recruited in the preliminary user study. Six participants had used HMDs before. All participants had normal or corrected-to-normal vision.

4.1.2 Hardware

We performed the preliminary user study in a 4m × 4m space in our laboratory room. As illustrated in Fig. 5 (a), the participants wore an HTC Vive HMD and Vive Trackers; these trackers were attached to the

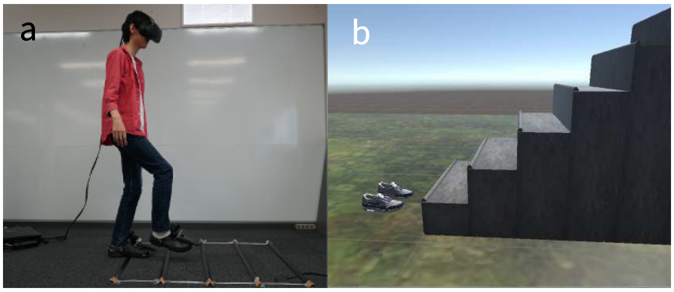


Fig. 5: (a) Participant wearing a HMD and shoes, which were attached with Vive Trackers. Small bumps for passive haptics in the real world and (b) stairs corresponding to the bumps in the virtual environments.

Fig. 6: Schematic of the bumps set on the floor with the corner turned up.

shoes. The HMD provided a resolution of 1080 × 1200 pixels per eye with a refresh rate of 90 Hz and approximate 110 diagonal field of view. The HMD and Trackers were tracked by HTC/Valve's Lighthouse.

To display VEs, we used an Intel computer with a Core i7 processor, 32 GB memory, and Nvidia GeForce 980M graphics card. The virtual environments were rendered with the Unity3D engine. For presenting passive haptics, plastic L angle bumps (height $\sim$ 1 cm) were set on the floor in positions corresponding to the edge of steps in the VEs (Fig. 5 (a)).

The VEs consisted only of virtual stairs, which had five steps and a flat ground (Fig. 5 (b)). The small bumps for providing passive haptics were also placed so that these corners faced up (Fig. 6). For the haptic feedback condition, participants stepped on these bumps. In the no haptic condition, participants walked on the flat surface. Before the experiment, the participants did not see our laboratory room.

4.1.3 Materials

The 16-item Simulator Sickness Questionnaire (SSQ) [8] was used for checking for any discomfort caused by the techniques. To evaluate the participants' sense of presence, the original version of the Slater-Usho-Steed Presence Questionnaires (SUS PQ) [24] including three items was used. In addition to these questionnaires, to evaluate the participants sense of height, participants were asked to provide numerical values corresponding to perceived height of the stairs (five steps in total).

4.1.4 Design and Procedure

We used a 2 × 3 within-subjects experimental design. We tested two haptic conditions *with haptics* and *without haptics* (i.e., with or without bumps on the floor in the real world), 3 visual conditions (i.e., 75, 100, and 125 cm as the height of the stairs in total) and 6 repetitions for each of the 6 conditions. The order of the conditions was randomized.

The preliminary user study was conducted in two hours per person divided into two days, including explanations of the user study, and answering the questionnaires. Before the user study, all participants signed an informed consent form and received explanations on the user study. Each participant completed a background survey (i.e., age, sex, experience of wearing HMDs, and visual acuity). They also filled out an SSQ before and after the sessions of each day. After that, every participant practiced the trial session of flat walking to get used to the VEs before the user study began. In the trial session of flat walking, they walked on a flat floor in the condition of the real world (without bumps) and VEs (without virtual stairs).

In every trial, the participants were guided to the starting position and instructed to go upstairs until the fifth step. After each trial, the participants were guided and seated to answer the SUS PQ and questionnaire about their experienced sense of height. The experimental conditions could not be seen from their seat and the participants removed the HMDs and shoes while completing the questionnaires. Six randomized conditions were combined as one block and this block was repeated six times. Participants took five-minute breaks every six trials.

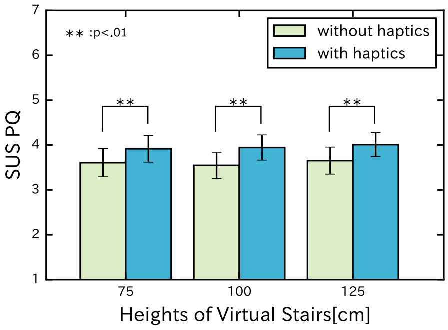


Fig. 7: Presence scores from the Slater-Usho-Steed Presence Questionnaires (SUS PQ) for each haptic and visual condition (mean ± SE).

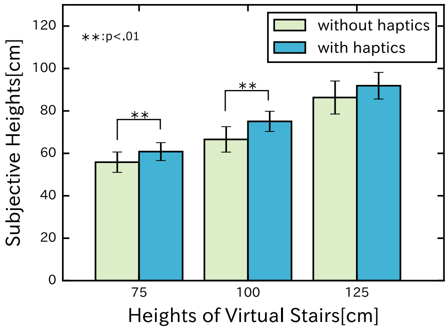


Fig. 8: Subjective height of the stairs in each haptic and visual condition (mean ± SE).

4.2 Results

4.2.1 Sense of Presence

Fig. 7 shows the presence scores (SUS PQ) in each condition. In order to compare the score of overall presence between conditions, we add each item and use the average value. We ran the Shapiro-Wilk normality test to check the assumption of normality and found a violation in the assumption ($W = .968, p < .01$). Given that what we wanted to measure in this experiment is the effect of haptic conditions, we conducted a Wilcoxon signed-rank test under each visual condition. The result demonstrated that the presence scores of *with haptics* were significantly higher than that of *without haptics* under each visual condition ($75cm : p < .01; r = .383, 100cm : p < .01; r = .372, and 125cm : p < .01; r = .418$).

4.2.2 Sense of Height

Fig. 8 shows the subjective heights of the stairs in each condition. We ran a Shapiro-Wilk normality test to check the assumption of normality and found a violation in the assumption ($W = .980, p < .01$). We conducted a Wilcoxon signed-rank test under each visual condition as Sect. 4.2.1. The result showed that the perceived heights of *with haptics* were significantly higher than that of *without haptics* under 75cm and 100cm visual conditions ($75cm : p < .01; r = .318, 100cm : p < .01; r = .362, and 125cm : p = .125; r = .180$).

4.2.3 Simulator Sickness and Safety

There was no significant difference between before and after the user study. There were no participants who stumbled on a bump.

Table 1: Comparison of the differences in the average subjective heights of a virtual step between the two haptic conditions and the height of the small bumps in real space.

Total heights of virtual stairs	Difference in subjective heights (with haptics - without haptics)
75cm	57.7 - 53.5 = 4.2cm > 1cm
100cm	71.7 - 64.3 = 7.4cm > 1cm
125cm	87.5 - 83.6 = 3.9cm > 1cm

4.3 Discussion

As shown in Fig. 7, the presence scores demonstrated that the passive haptic feedback corresponding to the virtual stairs enhanced the participant's sense of presence and this result agrees with previous Meehan's research [15]. Therefore, to produce passive haptics corresponding to stairs, small bumps on the floor in the positions corresponding to the edge of steps in the VEs would be an effective method. The small bumps used in this user study are very primitive shapes, so there is scope for improving the shape of the rod set on the floor. We discuss this shape problem in Experiment 2 below.

The perceived height of the stairs in each visual condition was higher *with haptics* (i.e., 57.7, 71,7, 87.5 cm, corresponding to the visual conditions 75, 100, and 125 cm, respectively) than *without haptics* (53.5, 64.3, 83.6 cm, corresponding to the visual conditions 75, 100, and 125 cm, respectively) (See Table 1). The differences in each visual condition (4.2, 7.4, and 3.9 cm) were higher than the height of a small bump in the real world (1 cm). This result demonstrates that our system enhanced the participants sense of height. On the other hand, in all visual conditions, the participants underestimate the height of the stairs. The possible reason is that the VE used was very simple with only stairs and ground, so there were few clues for the participants to estimate correct height.

Conversely, the visual effect was greater than the haptic effect in the values of subjective heights. Due to the ambiguity of the question, there was a possibility that the participants answered the subjective height question using the image seen through the HMDs. In order to correctly evaluate a participant's sensation of walking up and down stairs, it is necessary to leverage indices not affected by a visual effect. Specifically, a method of measuring the participants motions during the use of our system. We discuss this index problem in Experiment 1, below. We found from this preliminary user study that our simulated virtual stairs system based on passive haptics was effective for ascending virtual stairs.

5 Experiment 1: Efficiency of Visual and Haptic Effects on Sense of Ascending/Descending

In the preliminary study, the effectiveness of the passive haptics on presenting the sensation of ascending virtual stairs was confirmed. Then, in Experiment 1, we considered the viewpoint manipulations for both ascending and descending and the haptic effect for descending virtual stairs using our system. Indices that evaluate the sense of walking up and down were also introduced in Experiment 1.

5.1 Method

5.1.1 Participants

Twenty-four participants (20-45 years old, mean age 24.5, four females) were recruited in Experiment 1 via a recruitment web site. Eighteen participants reported they had used HMDs before. Participants were provided a false experimental purpose (*a study on sickness when moving up and down in VEs)*), so that they did not have prior knowledge regarding this experiment. All participants had normal or corrected-to-normal vision.

5.1.2 Hardware

To present the passive haptics and visual stimuli, we used the same hardware as in the preliminary user study. In addition, infrared markers were attached on both knees and both toes of the participants. For the measurement and evaluation of a participant's motion during the experiment, we tracked the position of the markers within the room (4 m × 7 m) using another motion-capture system consisting of six Flex13 cameras from Optitrack. A PC of the same model as the PC used in the preliminary user study was used for the Optitrack motion capture system.

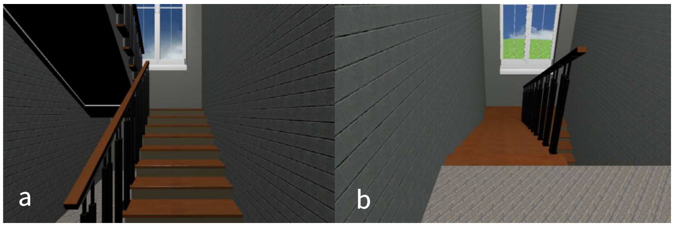
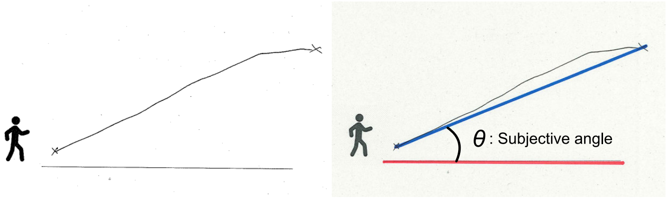


Fig. 9: Virtual environment used in experiment 1. The half-turn stairs had 11 steps to its landing.



(a) Entry Example (b) Analysis Example

Fig. 10: Method used to obtain the ascending/descending sensation data. The angle between the red and blue lines is used as the subjective angle that the users felt when they moved up/down.

As illustrated in Fig. 9, the VE consisted of a two-story building with half-turn stairs (with 11 steps to its landing) in Experiment 1.

5.1.3 Materials

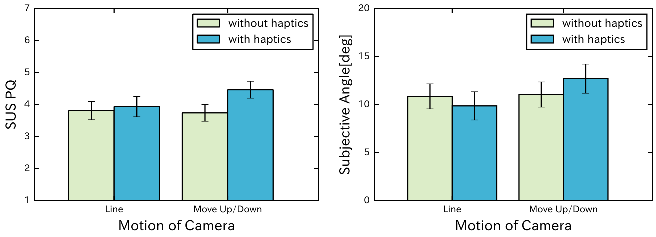
The SUS PQ and SSQ were also used for the same purpose as in the preliminary user study. As illustrated in Fig. 10, for the evaluation of the sense of ascending and descending, we created a *subjective angle*: the inclination of the line drawn as a trajectory from the participants body. The participants were asked to draw the path they felt when walking up or down virtual stairs. To simplify the analysis, the angle of the straight line connecting the starting point and the ending point of the path is used as an index. In addition to these questionnaires, we compared the average of the peak heights of the participants' knees and that of participants' toes between each condition pairwise. In order to reduce the influence of sensor error, we used the average of multiple peak values obtained in one trial.

5.1.4 Design and Procedure

We used a 2 × 2 within-subjects experimental design. We tested 2 haptic conditions (i.e., *with haptics* and *without haptics*), 2 viewpoint manipulation conditions (i.e., *Move Up/Down* and *Line*) and no repetitions for each of the 4 conditions. The order of these conditions was randomized. Participants performed 4 trials of descending after 4 trials of ascending.

Experiment 1 was conducted in 30 minutes per person, including explanations of the experiment, and answering the questionnaires. Before the experimental trials, we carried out the same procedure as in the preliminary user study. In every trial, the participants were guided to the starting position and instructed to go up or down the stairs using the stairway landings. During each trial, we tracked four markers attached on both knees and both toes of the participants.

After each trial, the participants were guided and seated to answer the SUS PQ and subjective angle questions. The experimental conditions could not be seen from the seat and the participants removed the HMD



(a) SUS PQ (b) Subjective angle

Fig. 11: Ascending questionnaires: Slater-Usho-Steed Presence Questionnaires (SUS PQ) and subjective angle (mean ± SE).

and shoes while filling out the questionnaires.. The participants took five-minute breaks between the ascending and descending trials.

5.2 Results

It was not possible to measure the motion data of two participants due to a software error. We then analyzed the motion data obtained from 22 participants. There was no significant difference between the before and after experiment SSQs. There were no participants who stumbled on a bump.

5.2.1 Ascending

Presence Fig. 11(a) shows the presence scores (SUS PQ) in each condition of ascending. We ran a Shapiro-Wilk normality test and a Mauchly's sphericity test to check the assumption of normality and sphericity. There was no violation in the assumption of normality $(W = .98, p = .274)$ or sphericity (each condition: $W = 1, p = 1$). We conducted two-way repeated ANOVA measures and found a limited and medium-sized effect of the haptic condition $[F(1,23) = 3.58, p = .071, \eta^2 = .135]$. A limited and a large effect size of the haptic × viewpoint manipulation interaction $[F(1,23) = 3.94, p = .059, \eta^2 = .146]$ was also found. There was no significant effect of the viewpoint manipulation conditions $[F(1,23) = 2.23, p = .149, \eta^2 = .088]$.

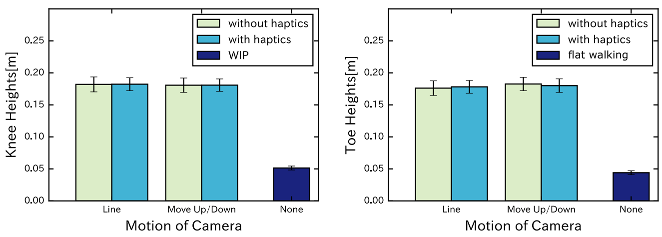
Subjective Angle Fig. 11(b) shows the subjective angle results obtained from participants drawings. We ran the Shapiro-Wilk normality test to check the assumption of normality, and the results showed a violation in the assumption of normality $(W = .965, p = .013 < .05)$. We conducted a non-parametric Friedman rank sum test of differences among repeated measures. The result showed a Chi-square value of 0.95, which was not significant $(p = .81)$

Motions Fig. 12 shows the vertical displacement of the participants toes from the standing state. For a comparison with level walking, the value when walking on a flat surface in the same VEs as the exercise before Experiment 1 is also shown in Fig. 12. We ran a Shapiro-Wilk normality test and Mauchly's sphericity test to verify the assumption of normality and sphericity. We found no violation in the assumption of normality (knees: $W = .983, p = .328$, toes: $W = .976, p = .114$) and sphericity (each condition: $W = 1, p = 1$). The ANOVA revealed that there were no significant effects of the haptic and viewpoint manipulation conditions, or the interactions of the motions of toes and knees.

5.2.2 Descending

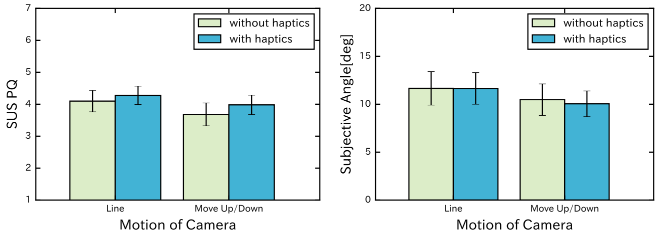
For the descending case, we performed a statistical analysis similar to that of the ascending case.

Sense of Presence Fig. 13(a) shows the SUS PQ for each descending condition. We ran the Shapiro-Wilk normality test to check the assumption of normality and found a violation in the assumption $(W = .956, p < .01)$. We conducted a non-parametric Friedman rank sum test of differences among repeated measures. The result showed a Chi-square value of 6.57, which was not significant $(p = .086)$



(a) Knees (b) Toes

Fig. 12: Ascending motions : average of the peak heights of the participants knees and that of the participants toes (mean ± SE).



(a) SUS PQ (b) Subjective angle

Fig. 13: Descending questionnaires: Slater-Usho-Steed Presence Questionnaires (SUS PQ) and subjective angle (mean ± SE).

Subjective Angle Fig. 13(b) also shows a descending subjective angle. We ran a Shapiro-Wilk normality test for checking the assumption of normality, and the results showed a violation in the assumption of normality $(W = .950, p < .01)$. We conducted a non-parametric Friedman rank sum test of differences among repeated measures. The results showed a Chi-square value of 0.9, which was not significant $(p = .82)$

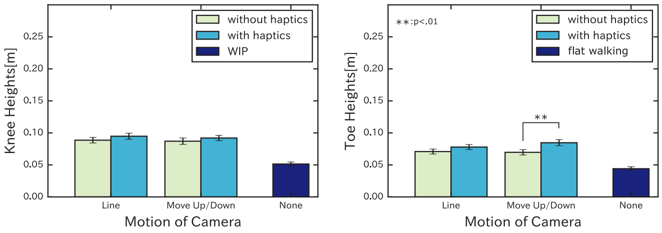
Motions Fig. 14 shows the vertical displacement of the participants toes from the standing state. We ran a Shapiro-Wilk normality test and Mauchly's sphericity test to check the assumption of normality and sphericity. No violation was found in the assumption of normality (knees: $W = .973, p = .067$, toes: $W = .980, p = .195$) and sphericity (each condition: $W = 1, p = 1$). The ANOVA revealed that there was no significant effect of the viewpoint manipulation conditions or the interaction on the motion of toes and knees. However, large effect sizes of the haptic conditions in the displacements of both the knees and toes were found; $[F(1,21) = 4.02, p = .057, \eta^2 = .161]$ and $[F(1,21) = 11.0, p < .01, \eta^2 = .345]$, respectively. A Holm post hoc test revealed a significant difference for the haptic conditions under *Move Up/Down* $(p < .01)$.

5.3 Discussion

5.3.1 Ascending

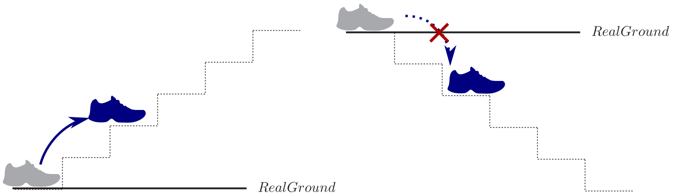
From the results of the presence score, the *with haptic* under *Move Up/Down* condition scored best in our system. These results suggest that by applying this condition to our system, we can produce a sensation closest to that of actually ascending the stairs for the user.

Conversely, we did not observe an effect of *with haptics* on the vertical displacements of the participants knees and toes. If the whole body is captured there may be some differences, but the height of the foot raised by the user between the conditions has not changed. This is because the displacement may be greatly affected by the height of stairs in VEs. In the preliminary user study, although a motion capture is not done, the height that the participants felt seems to depend heavily on the height of the virtual stairs.



(a) Knees (b) Toes

Fig. 14: Descending motions: average of the peak heights of the participants knees and that of participants toes (mean ± SE).



(a) Ascending (b) Descending

Fig. 15: Problem of spatial restriction in descending virtual stairs.

5.3.2 Descending

Although, for the with haptic condition the scores improved slightly, the results of the SUS PQ and subjective angle tests for the *with haptics* condition were not so effective. Another possible reason for the limited results with respect to presence could be that the employed measure of presence was not sensitive to the difference in presence, or reliably measured it for that matter. Indeed it has been questioned whether it is sufficient to rely on questionnaires as the sole measure of presence [23].

As illustrated in Fig. 15, this may have been because there is a spatial restriction that the user cannot lower his/her foot under the floor. In the descending case, *Line* is better than *Move Up/Down*. It is thought that this is because we created *Move Up/Down* only from the height of the actual head motion in walking up/down stairs, without a view orientation. There is a possibility that the gaze direction changes greatly when descending actual stairs.

5.3.3 Evaluation of sensation of walking up/down

For the evaluation of the sense of walking up and down, we introduced a subjective angle and the participants' motions. We discuss the usefulness of these two indicators below.

Subjective Angle Although we cannot provide a definite judgment, because there was no significant difference, in the ascending case, the same condition as SUS PQ, is the maximum. Hence, the subjective angle may be a useful indicator to some extent. In the case of descending, there is also no significant difference between the conditions in SUS PQ and the usefulness of the subjective angle cannot be judged because the main effects of the conditions are small. The subjective angle as an indicator needs to be updated in order to be actually utilized like SUS PQ.

Motions It is thought that participants motions cannot be used because there is no difference between the conditions in the ascending and descending case. This is considered to be due to participants judging the height of the stairs from the visual stimuli and then taking walking action [28]. There was a significant difference in the height of the toe in the descending case because the amount of displacement is very small and the influence of the small bump (height of 1 cm) on the floor is considered to be large.

6 EXPERIMENT 2: INVESTIGATION OF THE BEST SHAPE OF BUMPS FOR PRESENTING PASSIVE HAPTICS

The results of Experiment 1 demonstrated that there were no significant differences among the conditions in the descending case, this was probably due to the spatial restriction shown in Fig. 15. In order to solve this problem, we redesigned the shape of the small bumps used in the proposed system. The following experiment was conducted to investigate the best shape for the small bumps attached to a flat floor to present passive haptics corresponding to stairs and whether the proposed system is effective in simulating the descending of virtual stairs.

6.1 Method

6.1.1 Participants

Twelve participants (22-40 years old, mean age 28.1, 3 females) participated in a second experiment. Eight participants reported they had used HMDs before. All participants had normal or corrected-to-normal vision.

6.1.2 Hardware

To present the visual stimuli, we used the same hardware as in Experiment 1. Three shapes were prepared as the small bumps, presenting passive haptics to the participant's plantar.

The cross sections of the three bars were a right triangle, an equilateral triangle, and a circle, as illustrated in Fig. 17. Given that it was the minimum height when creating other haptic conditions shown below, the height of the bumps used in this experiment is 2 cm.

The right triangles (Fig. 17(a) and Fig. 17(b)) were compared to determine the importance of the cross section being asymmetric. By using these right-angled triangle bars, we expressed the tread surface of the stairs, so we could consider the demonstrated effects of the system, even for the descent. In order to investigate the effect of passive haptics on the descending case in our system, a no haptics condition (Fig. 17(e)) was added as a baseline. The equilateral triangle bar (Fig. 17(c)) had the same shape as in Experiment 1, but its size was different. A circle bar (Fig. 17(d)) was prepared to verify whether roundness is required for the triangular protrusion.

The VEs used in Experiment 2 consisted of a closed room with stairs consisting of five steps (Fig. 16).

6.1.3 Design and Procedure

In the previous experiments, the haptic condition was represented by binary values (presence or absence), but in this experiment five haptic conditions with multiple subtle differences were prepared. Owing to the fact that the evaluation of haptic sensation is subjective, in order to compare each haptic condition more accurately, we applied Scheffe's pairwise comparison method [21]. This allowed us to determine the scale values of realism and sensation of moving up and down for the five passive haptics conditions as illustrated in Fig. 17. All participants provided pairwise comparisons for all combinations of the five conditions (in this case $5(5-1) = 20$ pairwise) with upward and downward stairs.

In each comparison pair, the participant walks the stairs while exposed to the first condition. When the first condition is over, they return to the initial position according to a guidance line displayed in the VEs. Next, after walking the stairs under the second condition, they answer

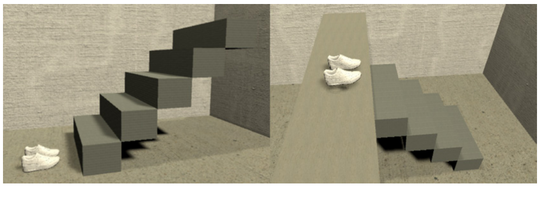
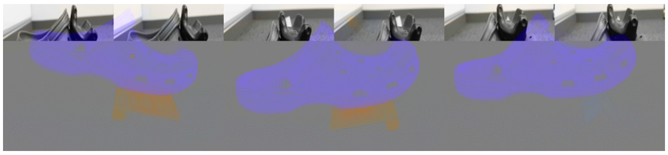
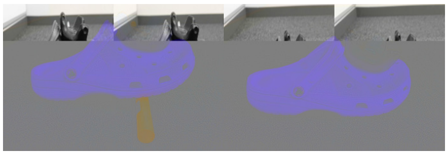


Fig. 16: The VEs used in Experiment 2 consisted of a closed room with stairs.



(a) Right triangle (b) Opposite right triangle (c) Equilateral triangle



(d) Circle (e) None

Fig. 17: Five passive haptics conditions with the travelling direction towards the right.

two questions (see Sect. 6.1.4) displayed on the wall of the VEs by operating the slider on the HTC Vive controllers.

Experiment 2 was conducted in an hour per person, including the experiment explanations, and the answering of the questionnaires. Before the pairwise comparisons, we carried out the same procedure as in the preliminary user study and Experiment 1, except the SSQ was not answered.

The participants took five-minute breaks for each ten pairwise comparisons. The experimental conditions could not be seen by the participants after removing the HMDs and shoes during their breaks.

6.1.4 Measures

In this experiment, participants answered the following two questions (translated from Japanese), consisting of 5 grades {-2,-1, 0, 1, 2}, regarding the pairwise comparison of the two different haptic conditions:

- *Question1 : In which condition did it feel more like a real staircase? Please answer in 5 grades (-2 means condition A was the very realistic and 2 means that condition B was the very realistic).*
- *Question2 : In which condition did you feel a stronger sensation of ascending/descending? Please answer in 5 grades (-2 meant condition A was the very strong and 2 meant that condition B was the very strong).*

The questions were displayed with a slider in the wall of the VEs and the participants answered them by controlling the slider with HTC Vive controllers. Numbers or other values are not displayed, and only the question and the slider that moves at equal intervals are displayed. The aim of the first question *reality of stairs* is to compare the reality of the stairs. The goal of the second question *strength of ascending/descending sensation* is to compare the sensation strength of ascending or descending stairs.

6.2 Results

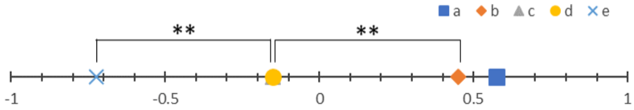
The scale values displayed in Fig. 18 and Fig. 19 and the yardstick values of each questionnaire displayed in Table 2 and Table 3 are derived from Scheffe's method of paired comparison [21]. In Fig. 18 and Fig. 19, points farther to the right on the line indicate that the selection was chosen more frequently or rated more highly. The conditions (a) to (e) in each figure and table agree with Fig. 17. There were no participants who stumbled on a bump.

6.2.1 Ascending

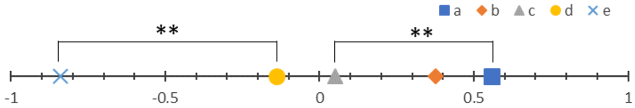
As illustrated in Table 2 and Fig. 18, the right triangle (a) became the maximum in both Q1 (reality of stairs) and Q2 (strength of ascending). In Q1 (reality of stairs), there were significant differences between (b) and (c) and between (c) and (e) (both: $p < .01$). There were also significant differences between (a) and (c) and between (d) and (e) in Q2 (strength of ascending stairs) (both: $p < .01$).

Table 2: Ascending case: subjective evaluation values of *reality of stairs* and *strength of ascending sensation*.

	Conditions					Yardstick	
	(a)	(b)	(c)	(d)	(e)	$Y_{0.05}$	$Y_{0.01}$
Q1	0.575	0.450	-0.150	-0.150	-0.725	0.407	0.488
Q2	0.558	0.375	0.050	-0.142	-0.842	0.388	0.466



(a) Q1 : Reality of stairs



(b) Q2 : Strength of ascending sensation

Fig. 18: Ascending case: average evaluation values of *reality of stairs* and *strength of ascending sensation*.

6.2.2 Descending

As illustrated in Table 2 and Fig. 18, the opposite right triangle (b) became the maximum in both Q1 (reality of stairs) and Q2 (strength of descending). In Q1 (reality of stairs), there was a significant difference between (c) and (d) (both: $p < .05$). There were also significant differences between (b) and (d) and between (d) and (e) in Q2 (strength of ascending stairs) ($p < .05, p < .01$).

6.3 Discussion

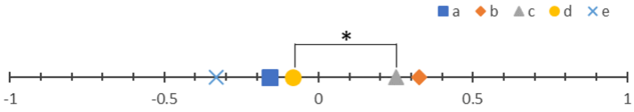
In the ascending case, the values of the condition (a) was maximum for both Q1 (reality of stairs) and Q2 (strength of ascending). Conversely, in the descending case, the values of the condition (b) was maximum for both Q1 (reality of stairs) and Q2 (strength of ascending).

From these results, using the right triangle, as shown in Fig. 20, the staircase can be simulated more effectively by leveraging our technique. In addition, for the cases with no haptic condition (e) indicated the lowest values for any index in the descending staircase, and showed that the proposed technique is also effective for walking down stairs. This result agrees with Sect. 4 and Sect. 5. From the results, it was found that the spatial restrictions shown in Fig. 15 can be improved by the shape of the right-triangle bar placed on the floor. This result seems to be natural considering the cross section when tilting the stairs as illustrated in Fig. 20. For the ascending case, we believe that the tread surface is important, in addition to the plantar sensation of the edge, because the values of the conditions (a) and (b) were so high. Conversely, the values of (a) were much lower than that of the best condition in the descending case (i.e., condition (b)).

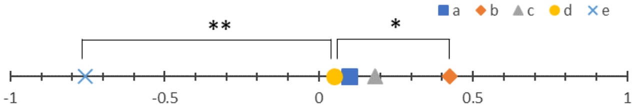
However, the result in the descending case is not as simple as the ascending case. In regards to the perception of reality of when descending the stairs, it is thought that the bump corners that were not round and the narrow angle of the corner of the bumps (less than 45 degrees)

Table 3: Descending case: subjective evaluation values of *reality of stairs* and *strength of descending sensation*.

	haptic Conditions					Yardstick	
	(a)	(b)	(c)	(d)	(e)	$Y_{0.05}$	$Y_{0.01}$
Q1	-0.158	0.325	0.250	-0.083	-0.333	0.377	0.452
Q2	0.100	0.425	0.183	0.050	-0.758	0.354	0.425



(a) Q1 : Reality of stairs



(b) Q2 : Strength of descending sensation

Fig. 19: Descending case: average evaluation values of *reality of stairs* and *strength of descending sensation*.

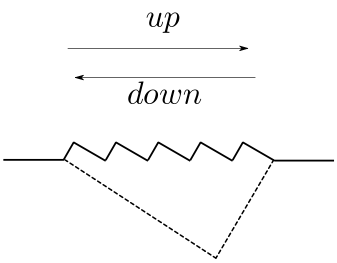


Fig. 20: Most successful passive haptic conditions for both the ascending and descending cases. The cross section of the staircase is also superimposed by a broken line.

are important. In terms of the strength of descending sensation result, there is no significant difference between the conditions with the haptic stimulus excluding (b), and it is clearly understood that (b) is the best condition.

We hypothesized that the tread surface and its gradient were important in both ascending and descending. Moreover, since the value of condition (d) was not high in either visual conditions, it was assumed that the roundness of the protrusion was not important.

In this experiment, given that height is controlled and the shapes of the bumps are compared, it is not possible to provide a clear analysis of the effect of bump height, but there is a possibility that there may have been some influence since the bump height is different from other experiments. Owing to the fact that the bumps in the proposed system act as the edge of a step, it is expected that discomfort will increase if the bumps become high, to some extent. We should consider the relationship between bump height and system effectiveness in the future.

7 CONCLUSION

In order to safely and simply provide the sensation of ascending and descending stairs for a user, we designed a novel technique using passive haptics for simulating stairs in a VR setting. In our technique, passive haptics, provided by small bumps under the feet of the users, corresponded to the edge of a stair in the VE, and the visual stimuli of the stairs and shoes provided by the HMD evoked a visuo-haptic interaction for the user.

In the preliminary user study, we investigated the ascending condition and determined whether users perceived a sense of ascending and a sense of presence by using our system that simulated virtual stairs based on passive haptics. The results demonstrated that small bumps on the flat floor enhanced a sense of presence and perceived height of stairs.

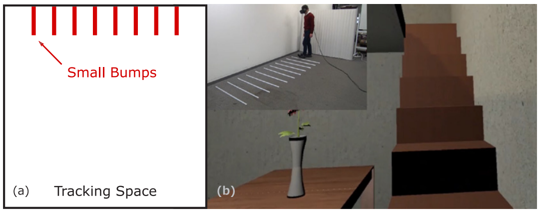


Fig. 21: Expression of multiple hierarchies by placing the small bumps at the end of the tracking space. (a) Schematic of a tracking space with small bumps. (b) The user in a real space and a virtual environment with multiple hierarchies

In Experiment 1, we discussed viewpoint manipulations limited by the height of the viewpoint and the haptic effect in both the ascending and descending cases. From the results, it was revealed that different conditions are needed for the simulations of walking up and down. The *with haptics* under *Move Up/Down* case was more successful in simulating the ascending stairs case. Conversely, there was no significant difference among the conditions in the descending case, most likely due to a spatial restriction that the user cannot lower his or her foot under the floor.

To solve this problem, we changed the shape of the small bumps installed on the flat surface in the real space. We compared five conditions with bumps of different shape to produce passive haptics in Experiment 2. We found that the best condition was to use a right triangle bump (i.e. ascending case: Fig. 17(a) and descending case: Fig. 17(b)) for simulating stairs, even in the descending case.

By applying the conditions found in this survey, our system allowed users to walk up and down stairs in VEs, even though the users walked on flat ground in the real space. Throughout all of the experiments, the participants were able to walk safely without issues and the proposed system was able to present a realistic up and down feeling of the stairs. This novel system can simulate any type of virtual stairs by changing the arrangement of the small bumps according to the edges of the stair steps in VEs. For example, by arranging the bumps radially on a flat floor, we can simulate a spiral staircase (Fig. 1). Moreover, to simulate buildings, it is possible to express multiple hierarchies by placing the small angle bars at the end of the tracking space (Fig. 21).

Our system can be used widely in practice, and we will provide some examples below. The first is to implement a low-cost showroom with VR. By using our system, users can actually walk around buildings with staircases and view multiple floors on foot. In this respect, our system will be very useful in the real estate industry due to its low cost and space efficiency.

Recently, interest in applications of VR in relation to entertainment has been increasing (e.g., FPS games). Hence, by applying our system to this type of entertainment, that can only be used in flat VEs, users can enjoy playing games in a more complicated and realistic space.

Finally, by taking advantage of the safety of our system, it may be possible to leverage our system for the rehabilitation of people who encounter difficultly walking up and down stairs. Our system is able to provide patients with a successful experience of being able to walk the stairs in VEs.

However, there are some limitations to the technique. Given that the user has to step on small bumps, the large steps of the tread face cannot be reproduced. To accurately install bumps on the floor and manipulate the user's viewpoint, the dimensions of the 3D model of the stairs must be known. The direction of the right triangle bumps depends on whether the user is walking up or down the stairs in the VE. In addition, it can be considered that the stairs cannot be displayed interactively in order to maintain the correspondence between the small bumps in real space and the VEs. However, as in the study of combining redirected walking and passive haptics [10], given that it is possible to manipulate freely VEs, except in the area where the bumps are placed, it is thought that the user will perceive that they are walking on different stairs in VEs even if they are actually walking on the same floor with the same protrusions.

In this paper, assuming a setting that allows a user to freely explore

VEs, we adjusted all of the bumps to the position of the edges of virtual stairs so that the haptic and visual consistency is correct when the user looks at his or her feet. However, the user does not always look at their feet. Especially when walking up or down stairs without looking at their feet, the consistency of the self-estimated position and haptic information of the sole of the foot is considered to be important. We should investigate how much deviation it can tolerate. If the position of the haptic feedback presented on the sole when not looking at the feet is rough, an equivalent system can be created with a device that turns on / off the haptic feedback at the same position on the user's sole.

Several subjects reported that there was a feeling of stepping out of the steps, especially in the case of walking up a set stairs throughout all the experiments. Conversely, there were no subjects who made the same comments in the case of descending stairs. As such, there are some people who feel upward misalignment, and it seems that our system is not very effective for them.

Given that the user walks on an uneven surface while wearing the HMD, the walking speed may become slow and the possibility of feeling discomfort is considered. However, in all experiments, there were no subjects reporting discomfort with regard to the ease of walking and walking speed. This possibility does not seem to pose a significant problem for our system, as the visual stimulus, rather than the uneven terrain seems to have a greater influence on walking speed.

Furthermore, there are individual differences in walking, and our system may not be effective for some users. For example, a woman wearing high heels does not step on the edge of the step when ascending stairs. Previous research demonstrated that the realignment of virtual objects and the body shown in VEs can solve the contradiction between visual stimuli and passive haptics [1]. By manipulating shoe motion in the VE, it may be possible to lead the user to step on small bumps and therefore solve this problem.

In future research, we will apply gaze manipulation to our technique, which is based on real gaze data obtained from a user walking up and down stairs. Based on the findings of this study, we believe that we can devise a new type of shoe device capable of providing haptic and gradient stimuli to the user's plantar for same purpose.

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REFERENCES

[1] M. Azmandian, M. Hancock, H. Benko, E. Ofek, and A. D. Wilson. Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 1968–1979, 2016. doi: 10.1145/2858036.2858226

[2] Y. Ban, T. Kajinami, T. Narumi, T. Tanikawa, and M. Hirose. Modifying an identified curved surface shape using pseudo-haptic effect. *Haptics Symposium 2012, HAPTICS 2012 - Proceedings*, pp. 211–216, 2012. doi: 10.1109/HAPTIC.2012.6183793

[3] R. P. Darken, W. R. Cockayne, and D. Carmein. The omni-directional treadmill. In *Proceedings of the 10th annual ACM symposium on User interface software and technology - UIST '97*, pp. 213–221. ACM Press, New York, New York, USA, 1997. doi: 10.1145/263407.263550

[4] E. Eils, S. Behrens, O. Mers, L. Thorwesten, K. Völker, and D. Rosenbaum. Reduced plantar sensation causes a cautious walking pattern. *Gait and Posture*, 20(1):54–60, 2004. doi: 10.1016/S0966-6362(03)00095-X

[5] B. E. Insko. *Passive Haptics Significantly Enhances Virtual Environments*. PhD thesis, 2001.

[6] H. Iwata, H. Yano, H. Fukushima, and H. Noma. CirculaFloor. *IEEE Computer Graphics and Applications*, 25(1):64–67, jan 2005. doi: 10.1109/MCG.2005.5

[7] H. Iwata, H. Yano, and F. Nakaizumi. Gait Master: a versatile locomotion interface for uneven virtual terrain. *Proceedings IEEE Virtual Reality 2001*, pp. 131–137, 2001. doi: 10.1109/VR.2001.913779

[8] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness, jul 1993. doi: 10.1207/s15327108ijap0303_3

[9] L. Kohli. Redirected touching: Warping space to remap passive haptics. *3DUI 2010 - IEEE Symposium on 3D User Interfaces 2010, Proceedings*, pp. 129–130, 2010. doi: 10.1109/3DUI.2010.5444703

[10] L. Kohli, E. Burns, D. Miller, and H. Fuchs. Combining passive haptics with redirected walking. In *Proceedings of the 2005 international conference on Augmented tele-existence*, pp. 253–254. ACM, 2005.

[11] E. Kruijff, A. Marquardt, C. Trepkowski, R. W. Lindeman, A. Hinkenjann, J. Maiero, and B. E. Riecke. On Your Feet! In *Proceedings of the 2016 Symposium on Spatial User Interaction - SUI '16*, pp. 149–158. ACM Press, New York, New York, USA, 2016. doi: 10.1145/2983310.2985759

[12] C. Lai, R. P. McMahan, and J. Hall. March-and-Reach: A realistic ladder climbing technique. *2015 IEEE Symposium on 3D User Interfaces, 3DUI 2015 - Proceedings*, pp. 15–18, 2015. doi: 10.1109/3DUI.2015.7131719

[13] M. Marchal, A. Lecuyer, G. Cirio, L. Bonnet, and M. Emily. Walking up and down in immersive virtual worlds: Novel interactive techniques based on visual feedback. *2010 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 19–26, 2010. doi: 10.1109/3DUI.2010.5446238

[14] K. Matsumoto, Y. Ban, T. Narumi, T. Tanikawa, and M. Hirose. Curvature manipulation techniques in redirection using haptic cues. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 105–108. IEEE, mar 2016. doi: 10.1109/3DUI.2016.7460038

[15] M. Meehan, B. Insko, M. Whitton, and F. P. Brooks. Physiological measures of presence in stressful virtual environments. *Proceedings of the 29th annual conference on Computer graphics and interactive techniques - SIGGRAPH '02*, p. 645, 2002. doi: 10.1145/566570.566630

[16] R. Nordahl, N. C. Nilsson, L. Turchet, and S. Serafin. Vertical illusory self-motion through haptic stimulation of the feet. *2012 IEEE VR Workshop on Perceptual Illusions in Virtual Environments, PIVE 2012*, pp. 21–26, 2012. doi: 10.1109/PIVE.2012.6229796

[17] R. Nordahl, S. Serafin, L. Turchet, and N. C. Nilsson. A multimodal architecture for simulating natural interactive walking in virtual environments. *PsychNology Journal*, 9(3):245–268, 2011.

[18] M. A. Nurse and B. M. Nigg. The effect of changes in foot sensation on plantar pressure and muscle activity. *Clinical Biomechanics*, 16(9):719–727, 2001. doi: 10.1016/S0268-0033(01)00090-0

[19] A. Protopapadaki, W. I. Drechsler, M. C. Cramp, F. J. Coutts, and O. M. Scott. Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. *Clinical Biomechanics*, 22(2):203–210, feb 2007. doi: 10.1016/j.clinbiomech.2006.09.010

[20] S. Razzaque, Z. Kohn, and M. C. Whitton. Redirected Walking. *Proceedings of EUROGRAPHICS*, pp. 289–294, 2001.

[21] H. Scheffe. An Analysis of Variance for Paired Comparisons. *Journal of the American Statistical Association*, 47(259):381–400, sep 1952. doi: 10.2307/2281310

[22] D. Schmidt, R. Kovacs, V. Mehta, U. Umapathi, S. Köhler, L.-P. Cheng, and P. Baudisch. Level-Ups: Motorized Stilts that Simulate Stair Steps in Virtual Reality. *Proceedings of the ACM CHI'15 Conference on Human Factors in Computing Systems*, 1:2157–2160, 2015. doi: 10.1145/2702123.2702253

[23] M. Slater. How Colorful Was Your Day? Why Questionnaires Cannot Assess Presence in Virtual Environments. *Presence: Teleoperators and Virtual Environments*, 13(4):484–493, 2004. doi: 10.1162/1054746041944849

[24] M. Slater, M. Usoh, and A. Steed. Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction*, 2(3):201–219, 1995. doi: 10.1145/210079.210084

[25] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. *Visualization and Computer Graphics, IEEE Transactions on*, 16(1):17–27, 2010.

[26] L. Terziman, M. Marchal, F. Multon, B. Arnaldi, and A. Lécuyer. The King-Kong Effects: Improving sensation of walking in VR with visual and tactile vibrations at each step. *IEEE Symposium on 3D User Interfaces 2012, 3DUI 2012 - Proceedings*, pp. 19–26, 2012. doi: 10.1109/3DUI.2012.6184179

[27] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks. Walking > Walking-in-Place > Flying, in virtual environments. *Proceedings of the 26th annual conference on Computer graphics and interactive techniques - SIGGRAPH '99*, pp. 359–364, 1999. doi: 10.1145/311535.311589

[28] W. H. Warren. Perceiving affordances: visual guidance of stair climbing. *Journal of experimental psychology. Human perception and performance*, 10(5):683–703, 1984. doi: 10.1037/0096-1523.10.5.683