Detection Threshold of the Height Difference between a Visual and Physical Step

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ABSTRACT

In recent years, virtual reality (VR) applications that accompany real-space walking have become popular. In these applications, the expression of steps, such as a stairway, is a technical challenge. Preparing a real step with the same scale as that of the step in the VR space is one alternative; however, it is costly and impractical. We propose using a real step, but one physical step for the expression of various steps, by manipulating the viewpoint and foot position when ascending and descending real steps. The hypothesis is that the height of a step can be complemented to some extent visually, even if the heights of the real step and that in the VR space are different. In this paper, we first propose a viewpoint and foot position manipulation algorithm. T hen we measure the detection threshold of the height difference between the visual and physical step when ascending and descending the physical step using our manipulation algorithm. As a result, we found that the difference can be detected if there is a difference of approximately 1.0 cm between the VR space and the real space, irrespective of the height of the physical step.

CCS CONCEPTS

• **Human-centered computing** → Virtual reality.

KEYWORDS

Height difference, Redirected walking, Viewpoint manipulation, Virtual reality

ACM Reference Format:
Masato Kobayashi, Yuki Kon, and Hiroyuki Kajimoto. 2019. Detection Threshold of the Height Difference between a Visual and Physical Step. In *Augmented Human International Conference 2019 (AH2019), March 11–12, 2019, Reims, France.* ACM, New York, NY, USA, 4 pages. https://doi.org/10.1145/3311823.3311857

AH2019, March 11–12, 2019, Reims, France

ACM ISBN 978-1-4503-6547-5/19/03.
https://doi.org/10.1145/3311823.3311857

1 INTRODUCTION

In recent years, virtual reality (VR) applications that accompany real space walking have become popular with the spread of wireless head mounted displays (HMD). In such applications, the presentation of terrain information to a person's feet is one of the important factors in experiences that involve walking. Therefore, research to present the material feeling of the ground, such as hardness, stickiness, and texture, have been widely conducted [4][8] [11] Moreover, the reproduction of large topographical differences, such as bumps and slopes, is also important.

Several studies have been conducted to present the height difference of the terrain using devices attached to the feet or by actuating the ground floor [2][5][7][10]. These can present an arbitrary height; however, its actuation typically requires time. By contrast, Cheng et al. proposed TurkDeck, which presented topographical information by placing static objects that simulate slopes, stairs, and others in the path of the user [1]. It is inexpensive and the sensation is real; however, the preparation of numerous objects for the VR scene is not practical.

We propose a complementing method of presenting height information, by using small number of real steps and visual manipulation of viewpoint and foot position. Hypothesis under this approach is that height of step can be complemented to some extent visually even if the height of real step and that in VR space is different.

In this paper, we first introduce a visual manipulation technique. Then we report the result of measurement of the detection threshold of height difference between visual and physical step.

2 RELATED WORK

Several works have manipulated the visual scene while walking: one typical example is redirected walking. Redirected walking is a technique of expressing a VR space that is larger than the real space using complemented visual information. Razzaque et al. presented a larger VR space than the real space using a visual presentation in which the amount of rotation in the yaw axis direction was changed for the user walking in the VR space [9]. Steinicke et al. reported that the user is unaware of the change in visual rotation within the range of -20% to + 49%, and VE can be scaled from -14% to 26% [12]. Nagao et al. reported that ascending and descending stairs can be expressed by manipulating the viewpoint in the vertical direction when stepping on and off a bump placed on the floor [6]. However, the relationship between the physical height change and visual height change has not been discussed. Kim et al. extended the feeling of ascent when jumping using a system that reduces gravity by pulling up the body using a cable and using viewpoint manipulation in the vertical direction [3]. They reported that this system can change the feeling of ascent in the range of -31% to 31%.

3 METHOD

In this research, we complement the height perception of a step by combining a physical step with a constant height and visual manipulation. The perception of height is a complex phenomenon that accompanies, for example, the joint angles of the legs, skin sensation, and acceleration sense. As redirected walking techniques have demonstrated visual dominance, to some extent, we speculate that even if there is a difference between the physical height and visual height, it can be complemented by the visual presentation. When ascending a step whose height is visually extended in the VR scene, there is a difference between the position of the body in the physical space and the position of the body in the VR space given by the height of the extended visual step. Therefore, it is necessary to complement the position of the body in the VR space according to the expanded height.
In this research, we complement the height perception by manipulating the viewpoint and foot position shown in Figure 1.

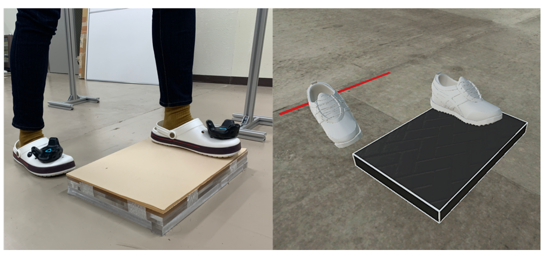

Figure 1: Experiment space: (a) real scene; (b) virtual scene. The step is installed in same position.

3.1 Viewpoint Manipulation

As a preliminary study, we measured the relationship between the movement of the foot and the movement of the viewpoint while the participant ascended the step in the real space. This measurement was the result of one of the authors and demonstrated that the height change of the viewpoint starts after the first step ends. This is considered natural because lifting the body requires one foot to be on the step as the base point. After that, the viewpoint is changed by the height of the step. In the case of descending, the viewpoint changes at the time when the foot used for the first step is lowered from the step to the ground. The height of the step in the VR space, H_{VRstep}, is expressed by as

$$H_{VRstep} = g_H \times H_{step} \tag{1}$$

where H_{step} is the height of the physical step and g_H is the height gain. Figure2(a) shows that the viewpoint in the VR space, H_{VRhead}, is expressed as

$$H_{VRhead} = g_H(H_{head} - H_0) + H_0 \tag{2}$$

where H_{head} is the viewpoint in the real space and H_0 is the initial height of the viewpoint.

3.2 Complementing the Foot Position

Similar to the viewpoint, the position of the foot in the VR space also needs to be moved according to the extent of the step height. For example, if a person ascends a step whose height was extended by 3.0 cm, the individual needs to draw the foot 3.0 cm higher than the physical step.Particularly because the haptics of the sole becomes a strong indication, it is necessary that the foot in the real space and the foot in the VR space contact the ground simultaneously; that is, it is necessary to change the height of the foot position in the VR space as the foot moves toward the step.
The distance (D_{step}) of between the foot raised on the step and the extended step is expressed as

$$D_{step} = h_{foot} - g_H H_{step} \tag{3}$$

which uses Equation (1) and the foot height h_{foot} is the foot height in the real space. Figure2(b) shows that when the distance between the foot and the step at the moment of up on the step is D_0, the foot height H_{VRstep} until the foot is grounded to the step is expressed as

$$H_{VRfoot} = h_{foot} + H_{step}(1 - \frac{D_{step}}{D_0})(g_H - 1) \tag{4}$$

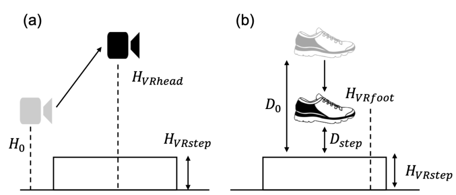

Figure 2: Image of the view of the manipulation technique in the VR space: (a) viewpoint manipulation; (b) complemented foot position.

3.3 Measurement of our Manipulation Technique

The measurement results when ascending and descending the step in the experimental space explained in Section 4.1 are shown in Figure 3. A physical step with a height of 5.0 cm was prepared on in the real space, and a step with a height of 10.0 cm ($g_H = 2.0$) was prepared on in the VR space. When ascending and descending the extended step, we complemented the viewpoint and foot position using our technique. The graph in Figure 3 shows the change in height when ascending sequentially from the right foot to the step in front of the participant, then both feet on the step, and then descending the step from the right foot. When ascending the physical step of 5.0 cm, we confirmed that the foot position in the VR space was on the 10.0 cm step. Simultaneously, the viewpoint was also 5 cm higher than the real head position.

4 EXPERIMENT

In the experiment, the allowable height difference between the physical and virtual step was measured. We used three physical heights and observed whether the allowance was proportional to the physical height.

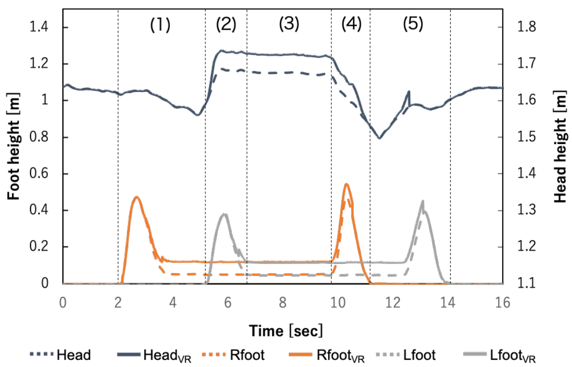

Figure 3: Height viewpoint and foot when ascending and descending the step. The height of the physical step was 5.0 cm, and visual step in the VR space was 10.0 cm. (1) The participant ascended the step with his right foot. (2) The left foot ascended the step. (3) Both feet were on the step. (4) The right foot descended the step. (5) The left foot descended the step.

4.1 Experimental Environment

We conducted the experiment in a 3 m × 1 m space in our laboratory. A physical step with an upper surface of 30 cm × 60 cm was installed near the center of the experiment space, and the VR step was installed at the same position in the real space as shown in Figure 1. Additionally, the shoe CG model was displayed at the foot position of the participant. The size of the step and the shoe model in the VR space were adjusted to provide the same sense of scale as the real object.

Participants participated in the experiment while wearing a wireless HTC VIVE HMD and shoes with a VIVE Tracker attached. For safety, a handrail was installed next to the step to support the body balance, but it was rarely used during the experiment.

4.2 Methods

Eleven height gains $g_H \in \{0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5\}$ were prepared for each of three types of physical steps: of 3.0 cm, 5.0 cm, and 7.0 cm. Particularly when $g_H = 1.0$, the height of the visual step and the height of the physical step coinsidecoincided. One set included 33 trials, which was composed of three trials for each of the 11 kindtypes of gainsgain. The 33 trials were conducted in a random order. The participants performed three sets for three types of physical height conditions. The order of these sets was balanced among the participants.

4.3 Procedure

Ten participants from the laboratory, nine males and one female, 22 to 26 years of age, 23.4 years on average, participated in the experiment while wearing an HMD and shoes with trackers attached. All participants had experience of wearing an HMD before the experiment.

A red line was drawn 50 cm in front of the step in the VR space, which was the starting point. The participants approached the step from the starting point and stepped on the step, without being instructed on which foot they stepped on. In one trial, the participants ascended the step step by step, then after the entire body climbed up to the step, the participants descended the step and returned to the starting point. After returning to the starting point, the participants answered a question regarding whether the height of the step in the VR space was higher or lower than the height of the physical step (two alternatives forced choices). After they provided an answer, the next trial was conducted immediately; 33 trials were conducted consecutively during one set. There were three minutes-long short breaks between the sets.

For some experimental conditions, the physical height of the step was larger than the visual height, and there was a possibility that the foot may collide with the step. Therefore, even if it seemed to be small visually, we instructed the participants to raise their legs higher than visual step.

4.4 Results

Figures 4, Figure 5, and Figure 6 show the measurement results when the physical height used as the reference is was 3.0 cm, 5.0 cm, and 7.0 cm. The horizontal axis shows the height gain $g_H \in \{0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5\}$, and the vertical axis shows the probability of evaluating that the visual step was larger than the physical step. The intersection of the graph with at the 25% line was is marked as the lower DT (Detection ThresholdDT), the 50% intersection is the PSE (point of subjective equality Point of Subjective Equality(PSE), and the 75% mark represents is the Upper upper DT. These plotted points were fitted by a psychometric function (sigmoidal psychometric function), subjective equivalence points, and each detection thresholdDT were was determined by this function.

Table 1 shows the DT values and subjective equivalence points for each experimental condition. To conduct a significant difference test, DTs and subjective equivalence points for all participants.

A Kruskal-Wallis test was performed between each physical condition for each DT. As a result of the significant difference test, we could not confirm a significant difference between the lower DT, PSE and upper DT among all the experimental conditions.

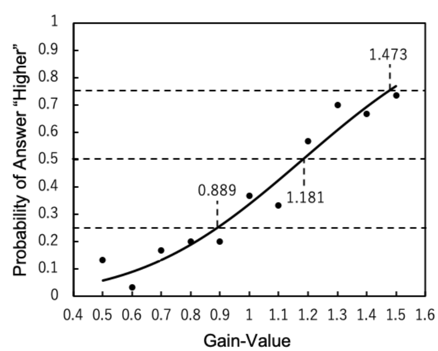

Figure 4: Measurement results of physical height 3.0 cm.

4.5 Discussion

For all experimental conditions, the subjective equivalence value was greater than 1.0, which means that the participants had the general tendency of evaluating the visual step as being smaller than the physical step. It is thought that this tendency was caused by the viewing angle, resolution, and assumed between-eye distance

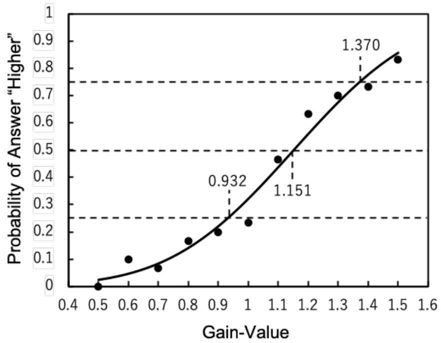

Figure 5: Measurement results of physical height 5.0 cm.

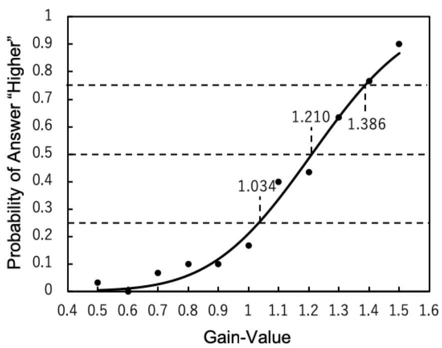

Figure 6: Measurement results of physical height 7.0 cm.

Table 1: Lower and upper detection thresholds (DTs) and points of subjective equality (PSE) for all three physical conditions.

Condition (cm)	Lower DT	PSE	Upper DT
3.0	0.889	1.181	1.473
5.0	0.932	1.151	1.370
7.0	1.034	1.210	1.386

of the HMD. Additionally, several participants commented that the step in the VR space felt smaller than the actual step in the real space.

When the physical height was 3.0 cm, the lower threshold was 25% lower than the PSE and the upper threshold was 25% higher than the PSE. Similarly, in the case of 5.0 cm, they were 21% and 20%, respectively, and in the case of 7.0 cm, they were 15% and 15%, respectively. A significant difference was not confirmed between the thresholds caused by the change of the experimental conditions; however, as the physical height of the step was increased, the range of the DT tended to become smaller in ratio. Furthermore, the physical values of these thresholds showed that, for the case of 3.0 cm, the allowable range of height calculated by (75% threshold - 25% threshold)/2 was approximately 0.88cm; for the case of 5.0 cm, it was approximately 1.10 cm; and in the case of 7.0 cm, it was approximately 1.23 cm. Therefore, the allowable inconsistency of the visual and physical height was almost constantly around 1.0 cm, which is surprising considering that the reference height changed from 3.0 cm to 7.0 cm.

5 CONCLUSION

In this study, we proposed modulating the height of a step in the physical world by visually changing the step and viewpoint. After introducing the algorithm, we conducted a psychophysical experiment to investigate the allowable range of the height difference between the physical and virtual steps. We prepared three types of physical step, and measured 25% and 75% DTs between the visual and physical step heights. As a result, a significant difference was not confirmed between each experimental condition, but we observed that the allowable inconsistency between the visual and physical steps was almost constantly 1.0 cm, when 3.0 cm to 7.0 cm physical steps were used.

We used a relatively small step size of up to 7.0 cm; however, actual steps, such as stairs, typically have a height of 15 cm. Therefore, we need to investigate how the allowable inconsistency between the physical and visual steps changes if the step becomes larger. Furthermore, the experimental environment in this study placed no objects capable of comparing heights other than the step. We need to investigate the effectiveness of the proposed method in a rich virtual environment.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant Number JP18H04110.

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