

# Utilization and Evaluation of a Pneumatic Cylinder-Based Acceleration Device for Long-Distance Ascent Sensation Presentation in Virtual Reality Environments

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**Abstract**—Using a head-mounted displays (HMDs) and an acceleration device to present the sensation of ascent in a virtual reality (VR) environment offers various advantages, such as enhancing immersion and aiding in the treatment of acrophobia. However, existing studies have primarily used large-scale ascent sensation presentation devices, as smaller devices face limitations in the achievable ascent distance in VR. In this study, a shoe-type acceleration device developed in previous research was utilized to examine the presentation of long-distance ascent sensations. This study demonstrated that combining the device with VR visuals was more effective in presenting ascent sensations compared with using VR visuals alone. Furthermore, in environments where the operational range of devices, such as shoe-type devices, was limited, increasing the ascending speed was found to be desirable. However, discrepancies between the VR visuals and operation time of the device were identified as a challenge in presenting long-distance ascent sensations. Additionally, although increasing the initial velocity of the VR visuals enhanced the perception of ascent, a better ascent experience required more than simply synchronizing the movement of the device with the VR visuals. The appropriate handling of the VR visuals after the operation of the device ended was crucial. The findings of this study clarify key challenges for future research on presenting ascent sensations using small wearable devices.

## I. INTRODUCTION

Recent advancements in virtual reality (VR) technology have enabled users to experience highly immersive environments using head-mounted displays (HMDs), allowing for a heightened sense of realism across various types of content. For instance, vertical motion experiences, such as ascent and descent, can provide a degree of realism through visual effects alone [1-4]. For example, these research results have been applied to the treatment of acrophobia [5-7]. However, because HMDs primarily deliver sensory information through visual and auditory channels, the realism of such experiences remains inherently limited when relying solely on these modalities. Therefore, to provide users with higher levels of immersion, incorporating devices capable of presenting actual acceleration is essential.

Existing acceleration presentation devices include hydraulic lifters [8] and ground-based low-gravity simulators [9]. However, these devices are typically large and fixed in place, which restricts user mobility and poses challenges in presenting rapid acceleration and deceleration. Moreover, several methods have been proposed to provide an ascent sensation using relatively portable support-type devices, such as Virtual Super-Leaping (VSL) [10] and a VR ride system that integrates a mobile slope with an HMD and electric wheelchair [11]. JumpMod [12] has been developed for wearable

devices that can be used while walking. JumpMod provides a jumping sensation by altering the center of gravity of a backpack. Additionally, systems specifically designed to present the sensation of vertical movement include Level-Ups [13] and shoe-type devices that utilize pneumatic balloons and vacuum pumps [14]. However, all these devices and methods primarily focus on short-distance vertical movement or climbing sensations, making them unsuitable for conveying the sensation of long-distance ascent. Furthermore, shoe-type devices for fall sensation presentation have been developed [15][16]. These devices use cylinders or pneumatic actuators to generate downward acceleration, thereby providing a realistic falling sensation. The same structural approach could theoretically be applied to present an ascent sensation; however, this has not yet been explored.

Hence, this study aims to develop a device capable of presenting a long-distance ascent sensation without causing discomfort to users, even for scenarios that are difficult to achieve in reality, such as high-speed elevator motion over long distances or catapult-like rapid launches to high altitudes. As illustrated in Fig. 1(a), we propose a method that combines the VR-based visual presentation of an ascending image with a physical device that elevates the user over a short distance to enhance the sensation of ascent. However, a key challenge lies in seamlessly presenting the sensation of long-distance ascent within the limited stroke length of the device to ensure a natural and immersive experience for users.

In this study, the effect of presenting upward acceleration on the perception of ascent in a VR environment was investigated using an existing air-cylinder-based fall sensation device [15]. To examine this effect, two experiments were conducted in which users experienced vertical parabolic motion in a VR space.

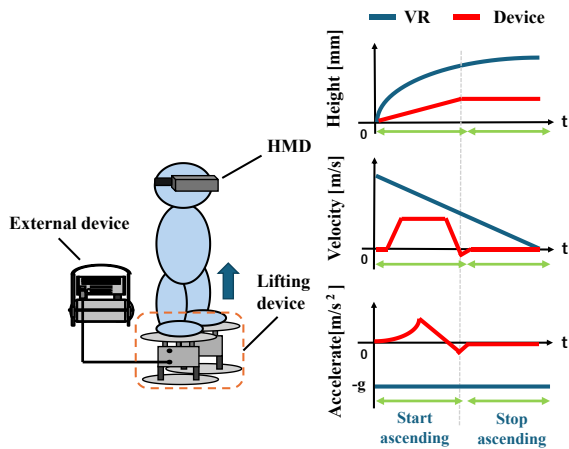
The structure of this paper is as follows. Section II describes the device used for presenting the sensation of ascent. Section III examines the effect of the actuation of the device on enhancing the perception of ascent in users and discusses the evaluation of ascent perception at different heights under low and high acceleration conditions. Section IV evaluates the impact of exaggerated VR-based ascent representation on the perception of ascent. Finally, Section V presents the conclusions of the study.

## II. METHOD FOR PRESENTING THE SENSATION OF ASCENT

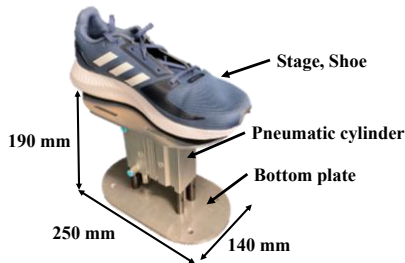
An air-cylinder-based fall sensation device (Fig. 1(b)) developed in previous research [15] was utilized to present upward acceleration. This device consists of an air cylinder (TCM32X75S, AirTAC) and upper and lower aluminum plates. The upper plate moves vertically to present a falling sensation to the wearer. The air cylinder used in this study has a stroke length of 75 mm and a maximum output force of 800 N per foot. The device can generate sufficient force to lift a wearer with an approximate body weight of 80 kg and provide a downward acceleration sufficient to elicit a falling sensation.

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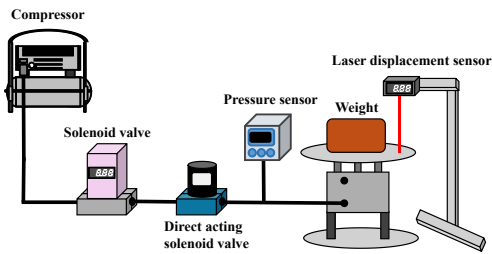
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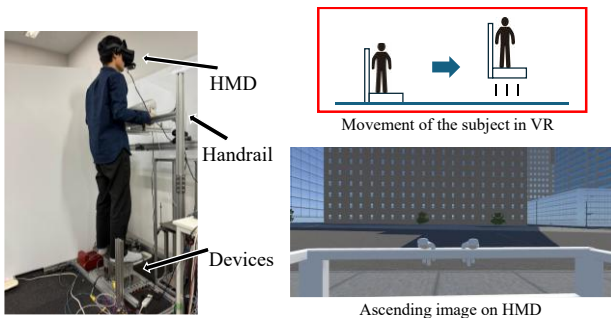
(a) Outline diagram of lifting device



(b) Dropping device [15]



(c) Pneumatic equipment for achieving upward motion



(d) Experimental apparatus and subjects in evaluation experiments

Figure 1. Overview of the experimental system

TABLE I.

INITIAL VELOCITY AND ARRIVAL TIME AT EACH HEIGHT

Height [m]	10	30	50	100
Initial velocity [m/s]	14	24.3	31.3	44.3
Arrival time [s]	1.43	2.48	3.19	4.52

Furthermore, this device can also present acceleration in the upward direction. For a user with a body weight of 70 kg, the maximum upward acceleration achievable by the device is  $2.86 \text{ m/s}^2$ . The threshold acceleration required to perceive an ascent sensation is approximately  $0.07 \text{ m/s}^2$  [17]. Because the acceleration presented in this experiment exceeds this threshold, the device is expected to enhance the perception of ascent. However, owing to the stroke length limitation, continuous ascent cannot be physically sustained. After reaching the maximum stroke, thevection effect induced by visual stimuli in the VR environment can supplement and extend the sensation of ascent. Thevection effect refers to visually induced self-motion perception, where visual stimuli create an illusory sensation of movement [18-20]. By integrating this effect with the physical motion provided by the device, an enhanced sense of reality and immersion is expected for the user.

### III. EXPERIMENT 1: INFLUENCE OF ACCELERATION PRESENTATION BY THE DEVICE ON ASCENT PERCEPTION

This section investigated whether the perception of ascent is enhanced by the presentation of upward acceleration using the device. The experiment evaluated the perceived ascent sensation under two conditions: one in which upward acceleration was presented using the device and another in which only VR visuals were provided. Additionally, the influences of initial velocity and ascent height in the VR environment on the perceived ascent sensation were analyzed. All experiments in this paper were reviewed and approved by the Human Research Ethics Committee of Chuo University (Approval No. 2024-115).

#### A. Experimental Environment

The pneumatic system is illustrated in Fig. 1(c). Compressed air from the air compressor is supplied to the air cylinder of the ascent device via a pressure control three-way proportional solenoid valve (ITV2050-213L5, SMC) and direct-acting solenoid valve (AB21-01-1-A00B, CKD). The system utilizes tubing with an outer diameter of 6 mm and inner diameter of 4 mm.

Fig. 1(d) illustrates the experimental setup. The user stood on the ascent sensation presentation device while wearing an HMD and experienced the sensation of ascent in conjunction with a VR-based visual representation. To prevent falls, the device was securely fixed to the floor, and users lightly held onto a handrail during the experiment. The HMD received visual output from a VR-dedicated PC while the device received control signals from a separate control PC. To synchronize the ascent initiation between both systems, the two PCs were connected via an Arduino-based interface. To simplify the control of the device, users were limited to those with a body weight of approximately 70 kg. In cases in which the weight of the user differed from 70 kg, additional weights were placed on the device to ensure a total system mass of 70 kg during operation.

#### B. VR Contents

In the VR environment, the user ascends while standing on a platform that moves according to a vertical parabolic motion, which is expressed by the following equation:

$$x = v_0 t - \frac{1}{2} g t^2. \quad (1)$$

Based on (1), the ascent in the VR environment begins with an initial velocity, and the platform comes to a stop in midair when the velocity reaches  $v=0$ , marking the end of the experience. This motion was adopted because vertical parabolic motion is generally perceived as an ascent motion that induces a stronger sensation of upward movement. Additionally, in ascent motions, such as those in an elevator, acceleration presentation is required even at the stopping phase. Therefore, a simpler ascent motion was initially selected for use in this study.

TABLE II. ACCELERATION TABLE FOR LOW AND HIGH ACCELERATIONS BETWEEN 0.1 AND 64 MM

	Max acceleration [m/s <sup>2</sup> ]	Average velocity [mm/s]	Max velocity [mm/s]	Time to reach maximum displacement [s]
Low acceleration (0.61 MPa)	0.877	80.7	131	1.105
High acceleration (0.9 MPa)	2.86	106	209	0.775
Differential	1.98	25.3	78	0.33

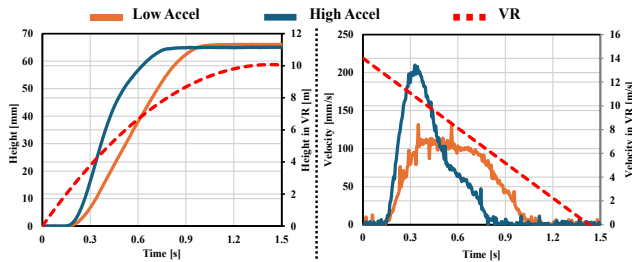


Figure 2. Displacements for low and high acceleration and 10m ascent in the image in VR.

Four different ascent heights were set in the VR environment: 10, 30, 50, and 100 m. The initial velocity and time to reach each height are summarized in Table 1. The time required for the device to reach its stroke limit under low acceleration conditions is approximately equivalent to that of real-world vertical parabolic motion over a 6 m ascent. However, considering factors such as the time required for air intake and minor signal delays within Unity, 10 m was chosen as a reference height owing to its ease of standardization. The 100 m condition was established as an extreme height setting in the VR environment. The 30 and 50 m conditions were selected as intermediate values between 10 and 100 m.

### C. Equipment Operating Conditions

This device can vary the acceleration presented to the user by adjusting the applied pressure. Specifically, applying a higher pressure generates a higher acceleration, whereas applying a lower pressure result in a lower acceleration. In this study, the experimental conditions were defined based on the acceleration: a visual-only condition without device actuation (No Device), a high-acceleration condition (High Accel), and a low-acceleration condition (Low Accel). Fig. 2 presents examples of ascent representation in the VR environment as well as the displacement and velocity changes of the device. Under the High Accel condition, a pressure of 0.9 MPa was applied to the air cylinder, whereas under the Low Accel condition, a pressure of 0.61 MPa was used. In both conditions, the cylinder ascended to a height of 65 mm. The corresponding acceleration, velocity, time to reach the peak, and their differences are summarized in Table 2. The High Accel condition represents the maximum achievable acceleration with this device, whereas the Low Accel condition corresponds to the minimum acceleration required to completely lift a 70 kg user, considering body inclination.

### D. Experimental Procedure

The experiment was conducted according to the following procedure.

1. The user received an explanation of the experimental procedure. The body weight of the user was measured, and additional weights were placed on the plate to ensure that the total weight of the user and the additional weights was 70 kg.
2. As shown in Fig. 1(d), the user stood on the device while wearing an HMD and holding onto a handrail.
3. At an arbitrary timing, the experimenter issued an ascent command, initiating both the ascent motion in the VR environment and the physical ascent motion of the device.
4. After the ascent was completed, the user removed the HMD, and the device was returned to its original position. The user then

responded to a questionnaire described later in the study. This procedure was repeated once for each experimental condition, totaling 12 trials per user. To eliminate order effects, the presentation order of the conditions was fully randomized. The experiment involved 13 healthy adult participants (9 males and 4 females; age:  $22 \pm 1$  yr, weight:  $70 \pm 1$  kg).

After each condition, users responded to the following eight questions using a Visual Analog Scale (VAS).

- Q1. Did you feel that you physically ascended in accordance with the visual representation?
- Q2. To what extent did you feel a sense of ascent in the VR environment?
- Q3. How fast did you perceive the ascent speed to be?
- Q4. How intense did the experience feel?
- Q5. How high did you feel you ascended?
- Q6. How long did you perceive the ascent duration to be?
- Q7. Did you find this VR ascent experience enjoyable?
- Q8. Did you find this VR ascent experience boring?

Multiple comparisons across all groups were performed on the results obtained using the Wilcoxon signed-rank test. The Benjamini–Hochberg procedure was applied to adjust the  $p$ -values for multiple comparisons. The significance level for all statistical tests was set at 5 % ( $\alpha = 0.05$ ). All statistical analyses were conducted using IBM SPSS Statistics.

### E. Results and Considerations

The results of the questionnaire evaluation from the experiment (Q1–Q8) are presented in Fig. 3. For Q1–Q7, higher scores indicate a better ascent experience, whereas for Q8, lower scores indicate a more favorable perception of the ascent experience. In the comparison between the VR-only condition and the condition combining VR visuals with device actuation, the latter exhibited significantly higher scores across all questionnaire items. These results indicate that incorporating both visual representation and physical actuation enhances the perception of ascent compared with visual representation alone.

Next, the low acceleration and high acceleration conditions were compared. Excluding Q1, and Q8, a general trend was observed in which higher ascent heights resulted in higher scores for both conditions. These results suggest that when presenting an ascent sensation to users, it is preferable to set the ascent height as high as possible. For Q2–Q7, the high acceleration condition generally yielded higher scores and exhibited less variation in responses compared with the low acceleration condition. These results suggest that the high acceleration condition provides a more effective and stable ascent sensation, regardless of ascent height. For Q1, Q7, and Q8, some users assigned lower scores at the 50 and 100 m ascent heights in both the low and high acceleration conditions, possibly owing to some users perceiving a discrepancy between the physical device, which remained stationary after reaching its stroke limit, and the VR visuals, which continued to move. This discrepancy became more pronounced at greater ascent distances, as the VR visuals continue for a longer duration after the physical motion of the device ceases. However, participants who still gave high scores under these conditions were assumed to have recognized the discrepancy between the device and VR visuals but focused more on the visual aspects of the experience, and it is highly likely that they gave favorable scores for questions related to preference and boredom.

In summary, combining VR visuals with the presentation of acceleration using the device effectively enhances the perception of ascent. Additionally, the results indicate that users experienced a better sensation when the ascent height in the VR environment was increased. A faster ascent velocity is assumed to be more effective. However, when the difference between the VR ascent duration and the actuation duration of the device exceeded 2 s, some users recognized a discrepancy between the device motion and VR visuals owing to the limited stroke of the device. To present an ascent sensation at even greater heights, setting the VR ascent speed as high as possible while ensuring that users do not feel discomfort will be necessary. Additionally, the maximum allowable discrepancy between the VR visuals and device motion should be adjusted to complete the ascent motion without causing users to perceive inconsistencies.

#### IV. EXPERIMENT 2: EFFECTS OF EXAGGERATED ASCENT REPRESENTATION ON THE PERCEPTION OF ASCENT

Based on the findings of Experiment 1, which indicated that effectively conveying the sensation of long-distance ascent requires minimizing the discrepancy between the ascent durations of the device and the VR visuals while maximizing the initial velocity in the VR space, Experiment 2 investigated whether an exaggerated ascent representation could further enhance this sensation. In this experiment, the gravitational acceleration in the VR environment was set to values exceeding real-world gravity while the ascent durations of the device and the VR visuals were synchronized. By varying the gravitational acceleration, the experiment examined how

changes in initial velocity and ascent height influence the perceived sensation of ascent.

##### A. VR contents

The user in the VR environment ascended following the same motion as described in (1). When determining the reference height in the VR environment, the difference between the actuation duration of the device and ascent duration of the VR visuals (the time from the start of the ascent until reaching  $v = 0$ ) was considered. As a result, an ascent of 30 m based on vertical projectile motion was set as the reference condition. In addition to this reference condition, five additional conditions in which the initial velocity was increased by factors of 2, 3, 4, 5, and 6, resulting in a total of six conditions, were presented to the users. The initial velocity, gravitational acceleration, and ascent height for each condition are shown in Table 3. To eliminate the influence of ascent duration on the perception of ascent, the gravitational acceleration was increased proportionally with the initial velocity to ensure that the ascent duration was consistently 2.48 s across all conditions.

##### B. Experimental Procedure

The experimental environment and methodology were identical to those described in the previous section. The device was actuated using the same applied pressure of 0.9 MPa as in the high-acceleration condition described in Section III. Each comparison condition was tested once, for a total of six trials. To avoid order effects, the presentation sequence of the conditions was fully

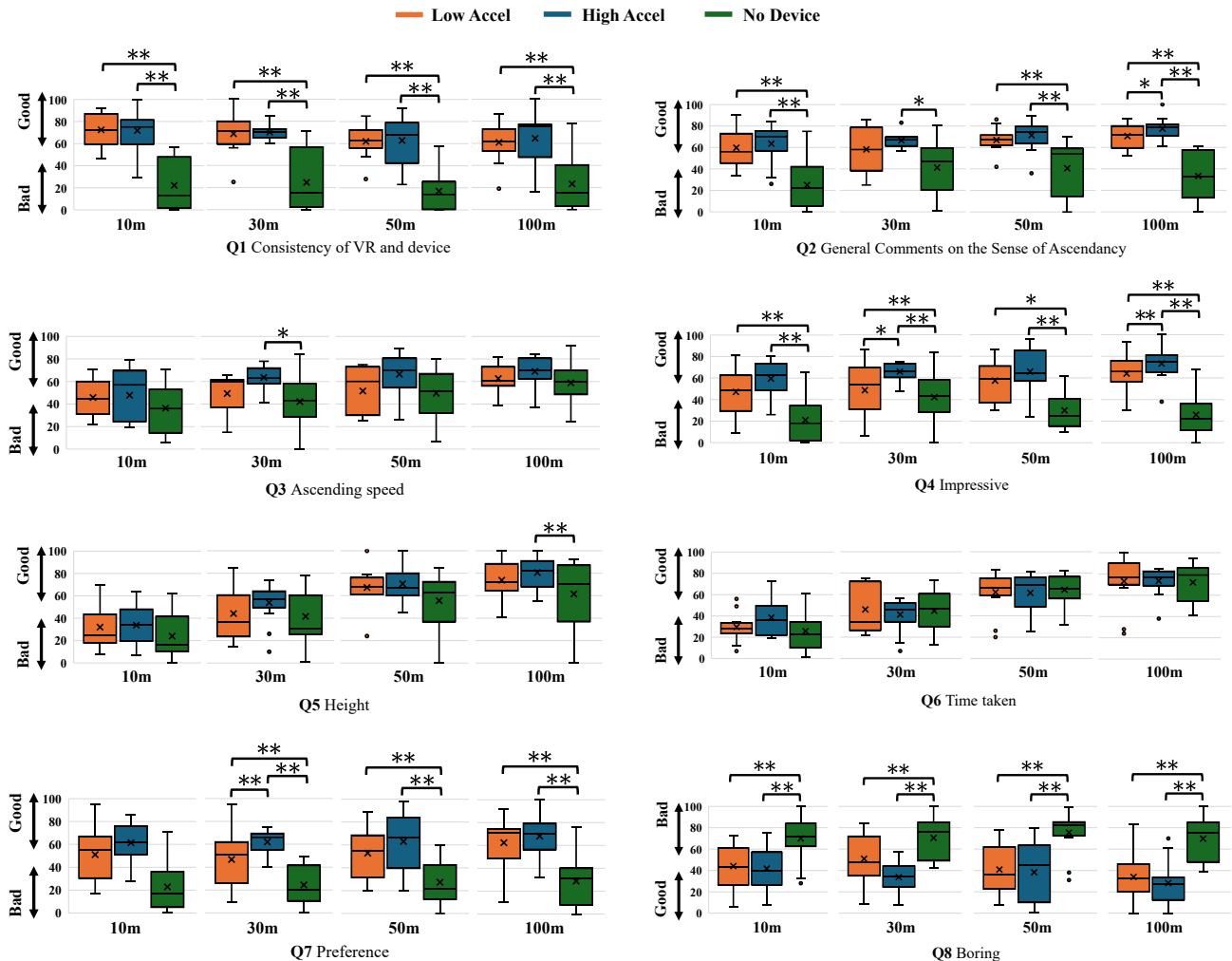


Figure 3. Questionnaire results (\*\*:  $p < 0.01$ , \*:  $p < 0.05$ )

randomized. The experiment involved 17 healthy adult participants (10 males and 7 females; age:  $22 \pm 1$  yr, weight:  $70 \pm 1$  kg).

After each condition, users responded to the following seven questions using a VAS.

- Q1. Did you feel that you physically ascended in accordance with the visual representation?
- Q2. To what extent did you feel a sense of ascent in the VR environment?
- Q3. How fast did you perceive the ascent speed to be?
- Q4. How intense did the experience feel?
- Q5. How high did you feel you ascended?
- Q6. Did you find this VR ascent experience enjoyable?
- Q7. To what extent did you feel a sense of discomfort during the ascent in the VR environment? (This question also included an open-ended response section.)

Multiple comparisons across all groups were performed on the results obtained using the Wilcoxon signed-rank test. The Benjamini–Hochberg procedure was applied to adjust the p-values for multiple comparisons. The significance level for all statistical tests was set at 5% ( $\alpha = 0.05$ ). All statistical analyses were conducted using IBM SPSS Statistics.

### C. Results and Considerations

The questionnaire results for Q1–Q7 from the evaluation experiment are shown in Fig. 4. For Q1–Q6, higher scores indicate a more positive ascent experience, whereas for Q7, lower scores indicate a better experience.

In Q1, a significant difference was observed between the reference condition and the condition with an initial velocity five times the reference value, while in Q7, a significant difference was found between the reference condition and the condition with an initial velocity six times the reference value. No significant differences were observed among the other conditions. In the open-ended responses for Q7, several participants in the five-times condition reported that “it felt as if the ascent continued even after it had ended” or “the visual scene seemed to ascend faster.” These comments suggest that participants perceived a discrepancy between the device and the visual motion in conditions with initial velocities of five times or greater. Although no clear differences were confirmed in Q1, there was a tendency for the discrepancy between the device and the visuals to increase as the initial velocity increased. These results indicate that discrepancies are more likely to be perceived when the visual scene continues to ascend rapidly after the device motion has stopped.

The results of Q2–Q5 showed a significant increase in scores when the initial velocity exceeded three times the reference value. This finding suggests that the perception of ascent in the VR environment is strongly influenced by both the velocity and the height of the visuals. Furthermore, based on the conditions presented in this study, the range in which users begin to strongly perceive the sensation of ascent appears to be between three and four times the reference initial velocity (initial velocity: 70–100 m/s, ascent height: 90–120 m). In contrast, Q6 showed no significant differences in preference due to variations in initial velocity or ascent height. This

result differs from the tendency observed in Experiment 1, in which a greater ascent height was associated with a more favorable ascent experience. It is possible that, while increased visual height provided participants with a stronger impression and a greater sense of preference, the larger discrepancy between the device motion and the visuals diminished the consistency of the experience, with these two factors exerting complementary effects on the evaluation.

The present results indicate that setting the initial velocity to between two and four times the reference value can enhance the perception of ascent while maintaining a certain degree of naturalness in the experience. However, even within this range, participants did not always report a favorable experience. Moreover, when the initial velocity exceeded five times the reference value, discrepancies between the device motion and the visuals became pronounced, increasing the likelihood of discomfort and a sense of incongruity. These findings suggest that simply increasing the initial velocity or ascent height in the VR environment does not necessarily yield a natural ascent experience, and that excessive increases in velocity may impair the perceived naturalness. Therefore, ensuring consistency between the device motion and the VR visuals is essential for providing a better ascent experience. In particular, reducing the velocity of the VR visuals after the device has stopped is expected to minimize the perception of discrepancy and discomfort.

Experiments III and IV confirmed that adjusting the upward acceleration of the device and the initial speed of the visual stimulus enables the presentation of a sensation of ascent to approximately 50 m. To effectively present the sensation of ascending to a greater height through appropriate visual stimuli, it is important to examine the threshold speed at which users begin to perceive a discrepancy between the visual motion and cessation of device movement as well as the time required for this discrepancy to be recognized. However, with the current drive method, there may be limitations in comfortably conveying the sensation of ascending over longer distances, such as 200 m, solely by adjusting visual stimuli. To achieve a more comfortable sensation of long-distance ascent, it is necessary to modify the acceleration presentation pattern. To present the sensation of ascending a longer distance without discomfort, it is necessary to change the acceleration presentation pattern.

## V. CONCLUSION

This study investigated the feasibility of presenting the sensation of ascent using an air-cylinder-based acceleration display device developed in previous research. The results of this study indicated that in an ascending visual scene based on real gravitational acceleration, higher device acceleration and greater ascent height in the visuals enhanced the perceived ascent experience. Conversely, for presenting an exaggerated ascent over long distances, consistency between the motion of the device and the visual representation was crucial. Discrepancies were particularly noticeable when the VR visuals maintained a high velocity after the device ceased motion, leading to a diminished experience quality. In these experiments, only upward acceleration was presented. Future research should explore more effective acceleration presentation patterns to improve the perception of long-distance ascent.

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TABLE III.

INITIAL VELOCITY, GRAVITY, AND HEIGHT OF VR IMAGES

	Initial velocity [m/s]	Gravity [m/s <sup>2</sup> ]	Height [m]
1 x	24.3	9.81	30
2 x	48.5	19.6	60
3 x	72.8	29.4	90
4 x	97	39.2	120
5 x	121	49.1	150
6 x	146	58.9	180

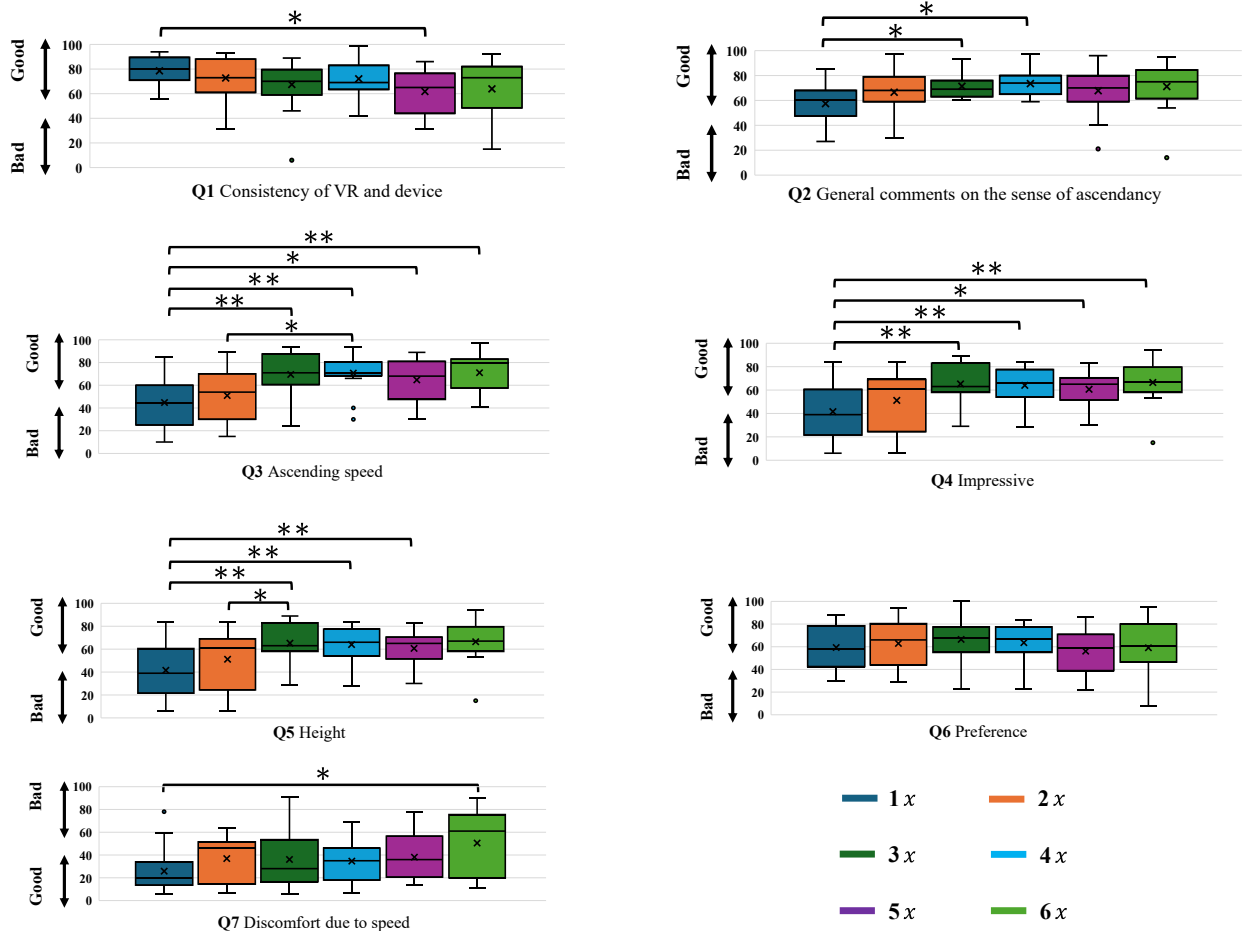


Figure 4. Questionnaire results (\*\*:  $p < 0.01$ , \*:  $p < 0.05$ )

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