PseudoJumpOn: Jumping onto Steps in Virtual Reality

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2022 IEEE on Conference Virtual Reality and 3D User Interfaces (VR) | 978-1-6654-9617-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/VR51125.2022.00084

Abstract

Jumping onto steps is a promising action for creating an instant height movement in VR, but installing physical steps is impractical. We propose PseudoJumpOn, a novel locomotion technique using a common VR setup that allows the user to experience virtual step-up jumping motion by applying two types of viewpoint-manipulation methods to a physical jump on a flat floor. The core idea is to replicate the physical characteristics of ascending jumps, and thus we designed two viewpoint-manipulation methods: gain manipulation, which differentiates the ascent and descent height, and peak shifting, which delays the peak timing. We conducted a user study asking participants ($N = 20$) to experience two-legged step-up jumps onto 0.2–0.8-m heights in VR as the two methods were applied in combination (gain manipulation: five conditions where the ascending gain was 1.0–5.0; peak shifting: four conditions where the peak timing in VR was delayed by 0–1.0 ratios of the original timing). The results showed that the participants in most conditions felt positively in terms of reality and naturalness of actually jumping onto steps, even though knowing no physical steps existed. In addition, subsequent analyses also derived practical guidelines for determining the appropriate gains and the potential use of peak shifting to achieve a natural step-up jumping experience.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual Reality;

1 Introduction

Locomotion is one of the most fundamental interactions in the room-scale virtual reality (VR) experience. Because of its high sense of presence [31], researchers have been actively working on achieving user walking in a larger VR space within a limited physical space (such as Redirected Walking [25], RDW). However, conventional VR setups currently require horizontal physical floors without any obstacles, which limits the variety of user actions possible in VR. In representation, it would be quite difficult to reproduce movements in the vertical direction like those frequently seen in many video games or everyday life (e.g., climbing stairs, stepping up onto a platform).

To deal with this limitation, researchers have explored methods of enabling a user to experience ascending/descending slopes or stairs by applying viewpoint manipulations and/or presenting tactile sensations while walking [19, 20]. However, these methods require the user to make long horizontal movements for ascending/descending or placing physical objects in the space, limiting the flexibility of the user experience and/or the physical space.

Meanwhile, jumping motion is also one of the body motions that can achieve vertical locomotion (i.e., ascending/descending jumps), which is highly compatible with full-body VR applications (e.g., games, sports, exercise). In addition, vertical locomotion with jumping is completed in a shorter time and with less horizontal movement compared to ascending/descending slopes or stairs, and thus it will be promising as a method to casually achieve vertical locomotion in VR. The work of a previous study achieved the capability of jumping onto virtual objects as the user physically jumps on a flat physical floor [13]. However, that study focused on simulating the special situation of a low-gravity environment, requiring a large-scale setup for a cable-driven system.

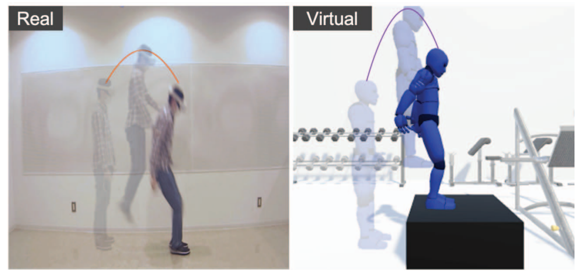

Figure 1: PseudoJumpOn is a vertical locomotion technique that transforms a physical jump on a floor (left) into a virtual step-up jumping motion (right).

By contrast, Redirected Jumping (RDJ) is a concept that involves jumping movements in VR using only an off-the-shelf VR setup. RDJ techniques [7, 10] and their follow-up studies [6, 16, 17] generally explored manipulating the mapping of the number of physical jumping movements to that in VR at a specific ratio (called "gain"). Notably, the original RDJ study [7] investigated the imperceptible gain ranges and revealed that jumping height was much less noticeable than horizontal distance or direction. Although that study only covered the VR jumping experience on a flat surface, we believe that its fundamental mechanism can be further extended to achieve more challenging actions of ascending jumps onto virtual steps by designing more elaborate viewpoint manipulation.

In this paper, we propose PseudoJumpOn, a novel vertical locomotion technique that visually manipulates jumping motions performed on a physical floor (Fig. 1 left) to give the experience of jumping motions onto steps in VR (Fig. 1 right), using only a common VR setup. The core idea is to replicate two characteristics of ascending jumps in motions made on a flat surface: 1) the ascent height is greater than the descent height, and 2) the ascent time is longer than the descent time. To achieve these effects, we designed two corresponding viewpoint-manipulation methods: 1) gain manipulation, which differentiates the amount of ascent and descent in VR by applying different gains for ascent and descent, and 2) peak shifting, which differentiates the duration of ascent and descent in VR to delay the virtual peak point. To investigate the perceived subjective reality (i.e., how much the user perceived the feeling of actually jumping onto steps) and unnaturalness (i.e., how unnatural the user felt the jumping experience was compared to his/her expectations before the jump) of these techniques, we conducted a user study letting users actually perform jumps where specific combinations of the two viewpoint-manipulation methods were applied. The results showed that the participants gave positive scores in terms of both reality and naturalness in most of the conditions when jumping onto steps with heights of 0.2–0.8 m. Based on the results and the subsequent

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978-1-6654-9617-9/22/$31.00 ©2022 IEEE
DOI 10.1109/VR51125.2022.00084

analysis, we prepared several key guidelines for presenting a natural step-up jumping experience in VR applications with our technique.

2 Related Work

2.1 Vertical Locomotion in VR

Vertical locomotion in VR is usually achieved using controllers, such as teleportation methods (e.g., Point & Teleport [3]). Despite their high applicability, these methods provide less of a subjective sense of presence compared to ones using actual physical movements [31].

As for methods using physical body movements, many have examined viewpoint manipulation during walking to achieve vertical locomotion in VR. Examples include methods that provide the sensation of walking on uneven terrain [18], slopes [19], or stairs [28] through viewpoint manipulation. These methods also permit vertical locomotion with a common VR setup, but they require a certain distance of horizontal movements, requiring a larger physical space.

In addition to viewpoint manipulation, several methods combine haptic cues from objects placed in physical space. Hu et al. showed that when a slope is placed in reality, the perceived inclination can be increased or decreased simply using viewpoint manipulation [8]. Cheng et al. introduced a lifter device that creates an illusion of elevation by generating reverse and imperceptible motion [4]. As an attempt with a simpler setup, Nagao et al. explored providing the sensation of ascending/descending stairs by placing bumps in the physical space to present passive haptic feedback to the user's soles [20]. These studies could provide a realistic sensation of ascending/descending, but they limited the flexible use of the physical space because special devices or objects had to be placed in it.

In related work, researchers have also considered using shape-changing interfaces of a physical floor to achieve vertical locomotion in VR. More specifically, several studies have developed systems that generate various terrains and objects that can be stood upon or leaned against. These systems were achieved by mechanisms using inflatable bags that rise from the floor [29,30] or a dynamic pin-array floor [9]. These mechanisms will considerably extend the variety of possible actions, including vertical locomotion in VR, but the clear limitation is the high cost of their installation.

Another approach is to employ wearable devices for providing ascending/descending sensory feedback. Schmidt et al. developed a shoe-based device equipped with a lift table underneath the soles to provide the sensation of ascending a step [27]. This approach is advantageous in not requiring any device or object to be placed in the physical space, but it does require the user to wear special weighted devices through the experience.

As described above, researchers have proposed various methods to achieve vertical locomotion using actual body movements, but none of them has achieved this with instantaneous movements or without using external devices or objects.

2.2 Locomotion with Jumping motions

There are two main use cases of jumping motion in VR. One is to trigger a specific spatial translation such as teleportation (e.g., [2,14,35]). Although they could expand the variety of actions, their purpose was different from ours: They used jumps as gesture commands, without focusing on simulating the entire jumping action in VR. The other approach is to map the entire jumping motion between reality and VR, including the work by Kim et al. [13] and Kang et al. [11], which simulated jumping under low-gravity environments. These methods extended the actual jumping by pulling the user from above with a cable, and they also investigated jumping to different heights by manipulating the viewpoint in the VR space. Those studies are closely related to ours, but the difference is that they focused on the special situation of a low-gravity environment, which thus requires a large-scale external setup.

Redirected Jumping (RDJ) is a method that applies gains to the actual jumping motion as a way of visually manipulating VR jumping experiences using only a common VR setup. Hayashi et al. investigated the detection threshold of gains (the range of gains that is not noticed by the user) for the distance, height, and rotation of a jump [7]. Jung et al. investigated the detection threshold of gains for curvature manipulation [10]. Havlík et al. introduced an application using RDJ that adopts gains outside the detection threshold for distance manipulation [6]. In response to these studies, Li et al. studied the interaction effect between the gains for distance and height, and they found that as one gain becomes larger, the other becomes less noticeable [16]. Li et al. also found that gain manipulation becomes more easily noticed in more complex VR environments [17]. As shown above, researchers have been actively working on RDJ in recent years, and they are investigating various kinds of extensions. However, this concept of RDJ has not yet been applied to achieving the experience of ascending/descending jumps. We thus explore this experience by building on the RDJ concept.

3 PseudoJumpOn

We propose PseudoJumpOn, a novel vertical locomotion technique that allows the user to experience jumping onto higher places in VR by applying a set of viewpoint-manipulation methods to the physical jumping motion on a physical floor. Since the action of jumping onto higher places is highly compatible with full-body VR experiences such as games and fitness, we expect our technique to provide casually used vertical locomotion interaction in many VR applications. In the following, we describe the design and implementation of our technique.

3.1 Principle and Approach

PseudoJumpOn focuses on the ascending jump motion with two-legged stepping, out of various possible jumping motions. We chose it as one of the simpler and probably safer jumping motions for our initial step. In addition, this study does not cover descending jump motions. One reason is that ascending jump would be a more frequent motion (descending jump would not necessarily require a jumping motion). Another reason is that implementing descending jumps where the virtual peak point comes before the real one would require a different algorithm from ascending jumps (see Section 6 for details).

The design of PseudoJumpOn is based on three main principles: (i) minimizing physical efforts and risks during takeoff and at landing; (ii) implementing the system without external sensors or objects; and (iii) aiming for a high subjective sense of reality and significant naturalness during manipulation.

Considering principle (i), the timing of takeoff and landing should be exactly the same in reality and VR to avoid giving users any misunderstanding of their body states relative to the ground. Given the above and principle (ii), we consider employing viewpoint manipulations like RDJ (or haptic retargeting [1], assuming the landing point is the target that gives the haptic cue), which can be achieved using a common VR setup. More specifically, we consider emulating the two characteristics of the ascending jump motions in contrast to jumping on a floor: the differences in height and duration between ascent and descent. Accordingly, we propose two corresponding viewpoint-manipulation methods as follows.

1. **Gain manipulation**: applying a larger gain for ascent than for descent during jump motion, creating a difference in height between the ascent and descent in VR (note: *gain* refers to the ratio of the mapped amount of movement in VR to that in reality) .

2. **Peak shifting**: delaying the peak timing of the jump, creating a difference in time between ascent and descent in VR.

The gain manipulation is based on the work by Kim et al. [13] and the RDJ concept [7, 10]. Among previous works, Hayashi et

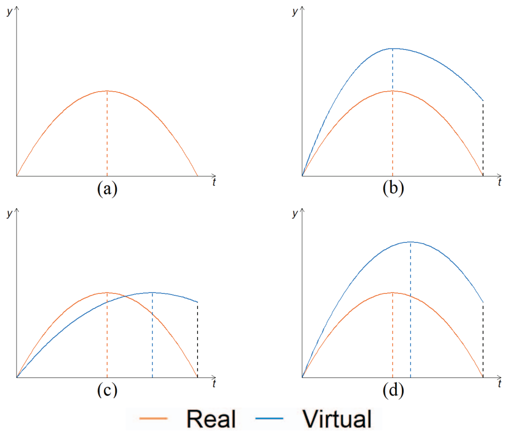

Figure 2: Changes in the user's height with (a) no manipulation, (b) gain manipulation, (c) peak shifting, and (d) both. The peak height in reality and the landing height in VR are the same for all four figures.

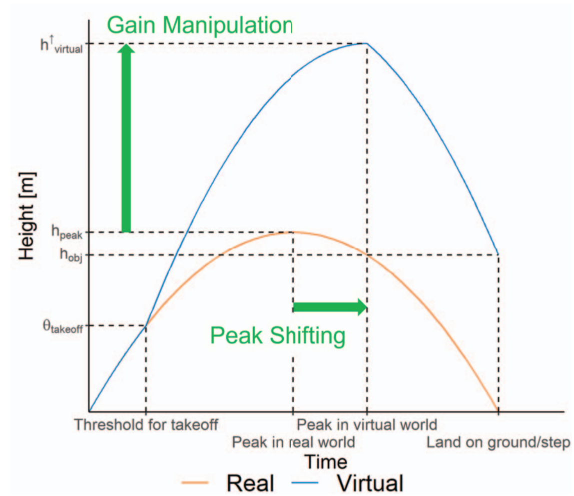

Figure 3: Theoretical position changes with gain manipulation and peak shifting applied.

al. [7] reported that users are particularly insensitive to height manipulation, which might be true even if the ascent and descent gains are individually set. Thus, we believe that subjective reality and naturalness could be maintained at least within the user's unnoticeable gain range (principle (iii)). In addition, larger gains enable VR jumps with smaller physical jumps, which will increase the safety at landing (principle (i)). Fig. 2(b) shows an example of temporal changes in the user's jumping height under the gain manipulation (for the y-axis, the head height at the start of the jump is set to zero) , showing that the descent height is lower than ascent height in VR by applying smaller gain during descent.

The peak shifting partially resembles the concept of the study by Cheng et al. [4], who demonstrated how the somatic sensations of ascending and descending are confused when riding on a lifter. The peak shifting also focuses on users confusing them during jumping, and thus the detection and consequent negative perceptions (e.g., subjective unnaturalness) of the manipulation could be mitigated (principle (iii)). Fig. 2(c) shows an example of temporal changes in the user's jump height with the peak shifting, showing the trajectory in VR (blue) looks stretched horizontally from that in reality (orange). Both have the same peak height, but the time until reaching the peak point and the landing height are different.

Fig. 2(d) shows changes in the user's height when both gain manipulation and peak shifting are applied. In the figure, the difference in the gains (i.e., velocity) between ascent and descent is mitigated compared to Fig. 2(b), while showing a higher peak height compared to Fig. 2(c). Thus we expect the trajectory will become more realistic when both methods are applied compared to when either of them is applied.

3.2 Algorithm

Fig. 3 shows an overview of the gain manipulation and peak shifting algorithms, where we additionally considered jump detection. Note that both algorithms are based on the assumption that the system knows the height of the jumping target at the moment the user starts jumping. For the implementation of the algorithms, from the safety perspective, we adopted an all-in-one VR headset (Oculus Quest 2 [5]) that can perform 6-DoF tracking by itself without interference by cables of the head mounted display (HMD) at landing.

3.2.1 Jump Detection

For the detection of jumping motion, we defined the user's body activity into five states: standing, ready, ascending, descending, and landing, as in the RDJ study [7]. Among them, we refer to the ascending and descending states as "jumping," during which gain manipulation and peak shifting are applied.

Unlike the original RDJ work [7] with an HTC Vive setup, our implementation with Oculus Quest 2 is unable to obtain the positions of the user's waist and feet. Therefore, we redesigned the jumping detection algorithm based only on the head (HMD) position. Since the obtained head position fluctuates even when the user only looks around, we have made some adjustments to prevent the false detection of jumps. To be specific, we recalibrated the threshold height for jump detection $\theta_{takeoff}$ as 0.11 m (originally 0.03 m [7]), which indicates the increase in the user's head height from the "standing" state before transitioning to the "ascending" state. We confirmed that the system with this setting could considerably prevent false jump detection (at least in the user study described later) without wearing any additional markers.

3.2.2 Gain Manipulation

Gain manipulation is applied to the amount of the user's movement in the height direction at each frame, as in RDJ [7], and the algorithm is based on the work by Kim et al. [13]. They used the following equation to calculate the descending gain $g_v^{\downarrow}$ as a function of the ascending gain $g_v^{\uparrow}$, the peak height of the physical jump h_{peak}, and the height of the jumping target h_{obj}.

$$g_v^{\downarrow} = \frac{g_v^{\uparrow} h_{peak} - h_{obj}}{h_{peak}} \tag{1}$$

However, this equation does not consider the difference in descent time between real and virtual, i.e., it cannot accommodate peak shifting. We thus modified it as follows:

$$g_v^{\downarrow} = \frac{h_{virtual}^{\uparrow} - h_{obj}}{h_{remain}} \tag{2}$$

Here, h_{remain} is the height of the user's head in reality at the moment when the user reaches the peak in VR, and $h_{virtual}^{\uparrow}$ is the peak height of the jump in VR, which is calculated by the following equation.

$$h_{virtual}^{\uparrow} = \theta_{takeoff} + (h_{peak} - \theta_{takeoff}) \times g_v^{\uparrow} \tag{3}$$

For example, when the user physically jumps 0.21 m in height (i.e., $h_{peak} = h_{remain} = 0.21$ m) to ride a 0.40-m step (i.e., $h_{obj} = 0.40$

m) under the ascending gain $g_v^{\uparrow}$ =5.0 (note: threshold for jump detection is set at $\theta_{takeoff}$ =0.11m), the peak height in VR ($h_{virtual}^{\uparrow}$) is calculated as 0.61 m (Equation 3) and the descending gain ($g_v^{\downarrow}$) is calculated as 1.0 (Equation 2).

3.2.3 Peak Shifting

To represent how much the peak point is delayed in VR, we defined the variable peak shift (ps) using the following equation.

$$ps = \frac{t_{virtual}^{\uparrow} - t_{physical}^{\uparrow}}{t_{physical}^{\uparrow}} \quad (4)$$

Here, $t_{virtual}^{\uparrow}$ is the ascent time in VR, and $t_{physical}^{\uparrow}$ is that in reality. The peak shift ps indicates the magnitude of the delay in time to reach the peak point in VR compared to that in reality, represented as a ratio of the original time, ideally ranging from 0 to 1.0. When $ps = 1.0$, which is the theoretical maximum, the ascent time in VR is twice as long as that in reality, meaning that the user reaches the peak point in VR at the moment of landing in reality. Note that the actual jump trajectory is slightly different from this theory (i.e., the user is still in descent in reality when he/she reaches the peak in VR) because we need to consider the time lag between the start of the jump and its detection. However, for simplicity, we regard a peak shift of 1.0 as the maximum value in this study.

In the software, we implemented peak shifting so that the frequency of the frame updates in VR is $1/(ps+1)$ times the original (72 Hz). For example, when the peak shift is set at $ps = 1.2$, the modified frequency of the frame updates is 60 Hz. The user's physical height at each frame obtained from the HMD is recorded in a queue, and it is dequeued and applied at the modified frequency of the frame updates (i.e., $72/(ps+1)$ Hz) in VR, resulting in the peak timing in VR occurring $ps+1$ times later than that in reality.

4 User Study

4.1 Overview

We conducted a user study to evaluate PseudoJumpOn. Our main purposes here were to investigate the users' general perception of the jumping experience with our approach and to derive guidelines for the use of the two techniques by understanding the user's perception, such as the subjective sense of reality and naturalness during jumps under the applied viewpoint manipulation. In the experiment, participants made jumps under the condition of applying a combination of the two manipulation methods, and then they answered questions. The study design of the experiment was officially approved by our university's ethics committee.

4.2 Experimental Design

4.2.1 Independent Variables

The experiment was a three-factor within-participant design with the following independent variables: ascending gain ($g_h^{\uparrow}$ = 1.0, 2.0, 3.0, 4.0, 5.0), peak shift (ps = 0, 0.2, 0.5, 1.0), and step height (0.2 m, 0.4 m, 0.6 m, 0.8 m). Regarding the ascending gain, Kim et al. [13] included values both inside and outside the detection threshold. Referring to this, we set the ascending gains at 1.0 to 5.0 at 1.0 intervals, where the upper detection threshold in the prior RDJ work (2.16) [7] was within the range. For the peak shift, we chose 0.2 and 0.5, in addition to the theoretical minimum and maximum of 0 and 1.0. A peak shift of 0.5 was the condition under which the virtual peak point appears halfway between 0 and 1.0 in time. A peak shift of 0.2 was the condition under which the descent is approximately half of the ascent (peak) in height, when only peak shifting is applied. The step height refers to the height of the target that participants jump onto, and we adopted this since the effect of our techniques would depend on it. Based on people's average capability of vertical jumps, we set the conditions containing both possibly reachable heights (0.2 m, 0.4 m) and unreachable heights (0.6 m, 0.8 m) in reality.

4.2.2 Dependent Variables

For the subjective measurements, unlike most studies concerning viewpoint manipulation such as RDW and RDJ, we did not investigate the detection threshold because the participants obviously knew that there were no physical steps in reality. Instead, to examine how much our technique satisfied principle (iii) (mentioned in subsection 3.1), we created our original questionnaire about the subjective sense of reality and unnaturalness on a 7-point Likert scale (we employed original questionnaire because we wanted to understand the user's perception at every single trial and authorized metrics e.g., SUS PQ [32] did not meet this purpose). The sense of reality was to measure how much the participants felt that they had jumped onto actual steps in each trial. The unnaturalness was measured by asking how much the participants felt the jumping experience in each trial was different from what they expected before the jump. In addition to these original questions, we obtained the participants' physical efforts and motion sickness by the Simulator Sickness Questionnaire (SSQ) [12], filled out before the experiment, after half of the trials (40 trials), and after all of the trials (80 trials).

For the objective measurements, we recorded the change in the participant's head (HMD) position at 72 Hz during the trials, which was used to calculate the jumping height. In addition, as a safety-related measure at landing, we recorded a maximum deviation distance of the participant's head in the front-back direction for three seconds after landing (we defined this as "staggering").

4.3 Participants

Twenty university students (13 males, 7 females, mean age: 20.5 ($SD = 1.28$)) participated in the experiment. As for their VR experiences, two had more than five experiences, nine had fewer than five experiences, and the rest had no experience. Each participant was paid for their participation (approx. 30 USD) in accordance with university regulations.

4.4 Apparatus

Fig. 4 shows the experimental setup. Participants wore an HMD (Oculus Quest 2) and held a controller in their right hand for use in answering questions. The experimenter held the left-hand controller to control the experiment program. The HMD provided images at 72 Hz, at a resolution of 1832×1920 per eye. We used Unity (ver. 2019.3.6) for software implementation. We performed the experiment in a 2.25 m×3.00 m (height: 2.50 m) play area and covered the floor with a gym mat for the participants' safety. However, the mat was hard enough to avoid affecting the participants' perception. To prevent COVID-19 infection, each participant wore a disposable VR mask, and a replaceable silicon cover was attached to the HMD. The devices used in the experiment (e.g., silicon cover, controllers, PC) were disinfected before and after the experiment. Both the experimenter and the participant wore masks, and they kept apart at a sufficiently safe distance during the experiment.

Fig. 5 shows the virtual environment used in the experiment. The design of the environment was mostly align with that in the experiment by Hayashi et al. [7] so that we could relate the results to theirs. We used an environment with a floor and a wall. We drew grid lines at intervals of 0.5 m on the floor and the wall. The wall had infinite height and was displayed on the left side of the participants at a 10-m distance. The position of the participant's controller (i.e., position of right hand) was displayed with a white, 10-cm-diameter ball. Other parts of the participant's body (e.g., left hand, feet) were not shown in the environment. The starting point of the jump was indicated by a pink, 0.5-m-diameter circle on the floor. As the jumping target, we placed a white cube with a base area of 1 m square so that the center of the step was 1 m ahead of the starting point of the jump. This means that the distance between the participants and the step was 0.5 m, which was thought that they could comfortably make jumps.

4.5 Procedure

We first explained our purpose and gave an overview of the experiment to the participants, and we asked them to sign an informed consent form. After that, participants filled out a pre-SSQ questionnaire. We then explained the procedure of the experiment and how to use the controller. After the explanation, the participant wore the HMD.

We then guided participants to the initial position of the jump in front of a desk, placed in the area as a reference, and started the practice phase. In this phase, we initially showed them the four step heights (0.2, 0.4, 0.6, 0.8 m) but then asked them to jump to white markers shown on the floor at the same horizontal position as the steps, rather than actual steps. Gain manipulation and peak shifting were not applied during this phase. After each jump, the questions about reality and unnaturalness were displayed on their view as in the experiment phase. We carefully explained the meaning of the questions and how to answer them. Then, the participants were asked to slowly move backward to the initial position until touching the desk, and after touching it, move one step forward to avoid hitting it in the next trial. The practice trials could be repeated until the participants understood the procedure.

In the experiment phase, we randomly presented combinations of ascending gain, peak shift, and step height as described earlier. We instructed participants to jump as high as possible using two-legged jumping to reach the step; this instruction was given because insufficient jump height sometimes lead to false jump detection in the preliminary study. However, we did not instruct participants where to look during the trials.

Each experiment trial included the following steps. First, the experimenter confirmed that no obstacle was in the path of the participant's jump, and then the experimenter pressed the button on his/her controller to start the trial. After the virtual environment for the trial was shown to them, the participants could make jumps at their own timing. After the participants made a landing, a question form window asking them about the jump's reality and unnaturalness was shown, and they answered the questions using their controllers. The exact questions are as follows. 1) Reality: "How much did you feel like you actually jumped onto the higher place ?" (1 = Not at all, 7 = Very much); 2) Unnaturalness: "How different was your current jumping experience from what you had in mind before the jump?" (1 = Very similar, 7 = Totally different). After answering the questions, the virtual step slowly sank to the ground to let participants move back to the initial position to get ready for the next trial. The next trial started when participants pressed the button on their controller.

After half of the trials were completed, participants removed the HMD and filled out the SSQ, and then they took a break for about five minutes. After the participants completed all of the trials, they filled out the SSQ again. In addition, they were asked to answer our original questionnaire, administered through a Google Form, about their criteria for choosing answers to the questions about reality and unnaturalness, how they thought the system presented the ascending jump experience, and their overall impressions. The entire experiment took about 1 to 1.5 hours per participant, including breaks, and it was recorded by a video camera with the participants' consent.

4.6 Results

We excluded the data of 41 out of the 1600 trials (2.56%) due to tracking errors. The Shapiro-Wilk test revealed that the obtained data for reality, unnaturalness, and staggering were not normally distributed ($p < .01$ for each). Thus we used an Aligned-Rank Transform (ART) [34] to allow the use of parametric methods and performed repeated measures ANOVA testing of the three within-subject effects of step height, ascending gain, and peak shift. Since the contrast tests with ART sometimes lead to incorrect results, we instead used a Wilcoxon signed-rank test with Holm adjustment (to the original data) for the post-hoc analysis. For the one-factorial analysis (on the SSQ scores and the jumped height), we used a Friedman test.

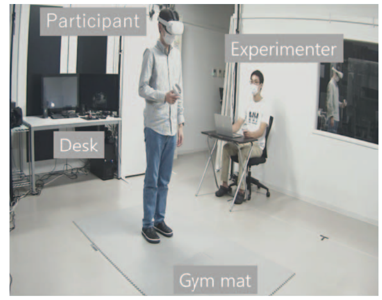

Figure 4: Experimental setup.

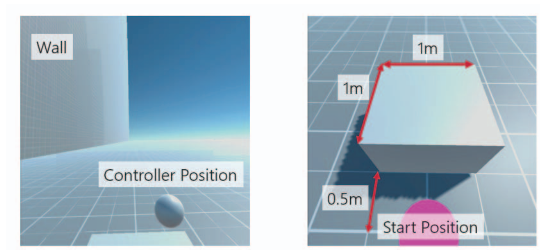

Figure 5: Participant view in the experiment (presented step height: 0.4 m). Left: forward view, right: downward view.

4.6.1 Subjective Measures

We first observed the correlation between the scores of reality and unnaturalness and found a significant but quite weak negative correlation between them ($r = -0.28,\ p < .01$). Accordingly, we analyzed these two measures independently as follows.

Subjective reality. Fig. 6 left shows the mean score of subjective reality at each step height colored by ascending gain and peak shift. The error bars (in these graphs and hereafter) indicate the standard error. We can see that all of the plots in Fig. 6 have more than the neutral score (4 out of 7). A three-way RM-ANOVA with ART did not find any main effect ($p > .05$), although the score at 0.2 m was lower than the others (0.2 m: 4.4, 0.4 m: 5.0, 0.6 m: 5.1, 0.8 m: 5.0, no significant difference).

Subjective unnaturalness. Fig. 6 right shows the mean score of subjective unnaturalness at each step colored by ascending gain and peak shift. We can see that all of the plots in Fig. 6 have less than the neutral score (4 out of 7). A three-way RM-ANOVA with ART only revealed a main effect on step height ($F(3,57) = 11.02,\ p < .01,\ \eta_p^2 = .37$). Pairwise comparison revealed that the participants perceived significantly higher unnaturalness in the 0.8 m condition compared to the others ($p < .05$ for each).

Simulator sickness. Table 1 shows the mean and standard deviation of the SSQ score before the experiment, after 40 trials, and after 80 trials. A Friedman test revealed a significant difference between them ($\chi^2(2) = 28.96,\ p < .01$), and pairwise comparisons revealed that the score before the experiment was significantly lower compared to the others ($p < .01$ for each). From the comments, some participants complained of fatigue, but no one reported other symptoms such as nausea during or after the experiment.

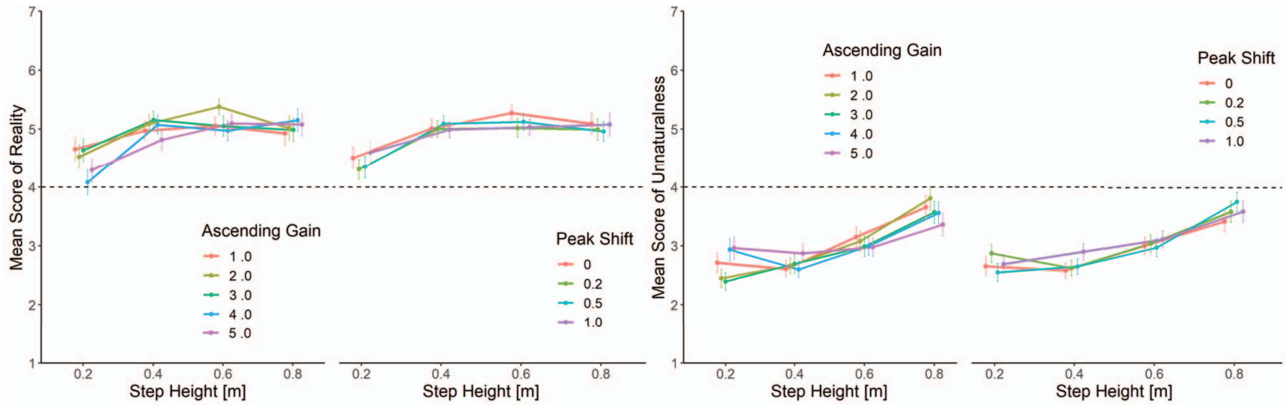

Figure 6: Mean scores of subjective reality (left) and unnaturalness (right) at each step height, ascending gain, and peak shift.

Table 1: SSQ score.

	Mean	SD
Before experiment	3.37	4.99
After 40 trials	19.8	13.2
After 80 trials	25.1	17.4

4.6.2 Objective Measurements

Fig. 7 shows the mean jumped height (in the physical space) and the staggering (i.e., maximum deviation distance of the participant's head in the front-back direction for three seconds after landing) for each step height. Regarding the jumped height, the mean height for all conditions was 23.0 cm (SD =8.5 cm). A Friedman test revealed that step height significantly influenced jumped height ($\chi^2(3) = 734.7,\ p < .01$). As for the staggering, a three-way RM-ANOVA with ART revealed a main effect on step height ($F(3,57) = 3.69,\ p < .05,\ \eta_p^2 = .16$) and an interaction effect between ascending gain and peak shift ($F(12,228) = 2.65,\ p < .01,\ \eta_p^2 = .12$). Pairwise comparison revealed that the staggering at a step height of 0.8 m was significantly larger than that of 0.2 m ($p < .05$). No other main effect or interaction effect was found ($p > .05$).

4.6.3 Comments

When asked about their criteria for answering the reality question, many of the participants' answers focused on the step height. Nine said that as the steps became higher they felt higher reality, but one, on the contrary, said that as the steps became lower she felt higher reality. Another participant commented that it did not feel real at the beginning until he grew accustomed to the trials. Regarding the criteria for answering the unnaturalness question, six participants said they felt higher unnaturalness as the step height was higher, unlike the criteria for reality. There were also some comments referring to the viewpoint manipulations during the jump, such as feeling unnaturalness when they reached a step, even though the jumping height was not considered so high, or when their viewpoints were raised higher than they had imagined.

When asked to guess the mechanism for the ascending jump experience, many participants commented that the system might have changed the distance and/or speed of the viewpoint during the jump, referring to a phenomenon close to gain manipulation. In addition, several participants mistakenly speculated that the mechanism might be a change in the position of the window displayed for answering the questions after the jump (note: the window was placed at a constant height from the ground). No participant mentioned the peak shifting or related factors such as manipulation of the ascending and descending times.

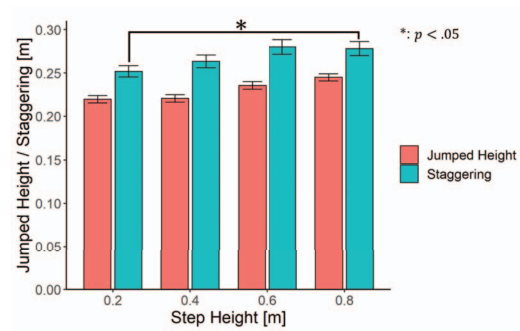

Figure 7: Mean jumped height and staggering for each step height.

5 Discussion

5.1 Overall Results

The results show that the participants gave positive (more than neutral) scores in terms of subjective sense of reality and unnaturalness in most conditions, even though they knew that there were no physical steps placed in the space. This suggests that the experience of an ascending jump with our techniques was generally realistic with low unnaturalness under any of the tested conditions of gain manipulation and peak shifting. Some of the participants' comments on their general impression also support this, such as "I did not feel uncomfortable in general" and "It was amazing to feel as if the step-up jumping experience was happening in reality". We previously expected that excessively high ascending gains (beyond the detection threshold) or peak shifts would result in lower reality or high unnaturalness, but in fact the participants seemed to be quite insensitive to (i.e., tolerant of) the viewpoint manipulations during a jump. One reason for this would be due to the nature of jumping behavior itself, such as small movement distance and duration of the motion, as Hayashi et al. also suggested [7]. Applying a larger threshold height to the jump detection than done in their work would lead to an even smaller duration of manipulation, which might also be a reason for the participants' reactions.

Based on these results, our method can be practically applied as a casual vertical locomotion in a variety of VR scenarios, including even the experience of jumping onto a commonly unreachable step (0.6 m, 0.8 m). For example, many games use stairs or a lifter to move around in a terrain with height differences, but introducing step-up jumping using our method will enable more manipulative and detailed user actions. In terms of exercises, our method can also be applied to jumping squats on a step (Fig. 1 right), which is an exercise to strengthen the muscles of the lower body.

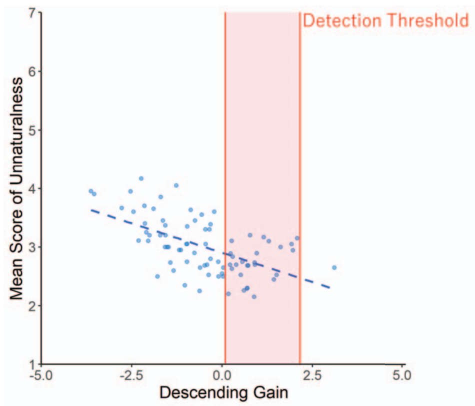

Figure 8: Mean scores of unnaturalness plotted against mean descending gain in each condition. Red area denotes the detection threshold in vertical direction reported by Hayashi et al. [7]

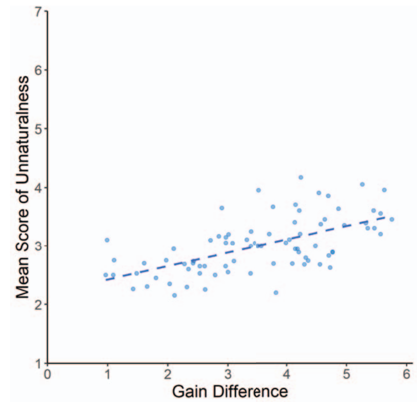

Figure 9: Mean scores of unnaturalness plotted against the mean gain difference in each condition.

5.2 Subjective Reality

We found that neither step height, ascending gain, nor peak shift significantly affected the reality score and the score was more than neutral in all conditions, indicating that the step-up jumping experience was generally realistic. However, we also found a weak tendency for the reality score at 0.2 m step height to be slightly lower. We can infer the reason for this from the participants' comments that they felt higher reality when the step was higher. This suggests that they rated the reality score mainly depending on their view after they jumped onto the steps, rather than during the jump. This consideration could explain the results showing that the participants felt their jump was somehow realistic even in an unrealistic jumping situation, such as a higher step height than people can normally jump or a larger ascending gain that exceeds the detection threshold.

5.3 Subjective Unnaturalness

We found that the step height significantly affected the unnaturalness score in that higher steps caused higher unnaturalness. Relatedly, one participant said that he felt unnatural when he successfully jumped onto a step even though the jumped height did not feel high enough to reach it. This indicates that the unnatural viewpoint transition while jumping would partially affect the unnaturalness score.

Focusing on the unnaturalness scores related to the ascending gain at each step height in Fig. 6 right, we could observe a notable tendency between ascending gain and step height (with no significant difference). At the lowest step height (0.2 m), the higher ascending gains (4.0, 5.0) gave higher unnaturalness while lower ones (1.0, 2.0, 3.0) gave lower unnaturalness. On the other hand, at the highest step height (0.8 m), the inverse results, respectively, were obtained, suggesting that jumping too high or too low relative to the step height might lead to higher unnaturalness. Accordingly, we speculate that the participants might have judged the unnaturalness score based on the expectation that they could reach the step with a "moderate" jumping height before the jump, regardless of whether they were physically capable of doing it. This implies that the unnaturalness might be mitigated by presenting a jump with a moderate height compared to the step height.

Another perspective involves the descending gain. Kim et al. [13] showed that the subjective sense of presence becomes lower particularly when the descending gain is outside the detection threshold, which might also be applicable to our study. Fig. 8 shows the mean descending gain and unnaturalness score in each experimental condition (i.e., each combination of step height, ascending gain, and peak shift). From this figure, we can see that there are plots where the descending gain was outside the detection threshold (mostly below it), and their unnaturalness scores seemed to be higher. We performed a correlation analysis and showed a significant negative correlation between them ($r = -0.57,\ p < .01$). This indicates that the results mainly align with the study by Kim et al. [13] and that the descending gain should be adjusted to within the detection threshold to mitigate unnaturalness.

To further examine the subjective unnaturalness related to the gain manipulation, we also focused on the difference between the ascending gain and the descending gain (we call this *gain difference*, also Δg_v), calculated by the following equation.

$$\Delta g_v = |g_v^{\uparrow} - g_v^{\downarrow}| \tag{5}$$

Here, the smaller gain difference indicates that the trajectory is closer to the real physical phenomenon. Fig. 9 shows the mean gain difference and unnaturalness score in each experimental condition. We then performed a correlation analysis, which showed a significant positive correlation between them ($r = 0.61,\ p < .01$). This observation suggests that reducing the gain difference would lead to lower unnaturalness. As a way to reduce the gain difference, peak shifting would be inherently effective because it manipulates the landing height without changing the gain difference.

5.4 Simulator Sickness

We found that the SSQ score increased with the number of trials. The main reason for this would be the "fatigue" and "sweating" items in the SSQ. Although no participants complained of serious symptoms such as nausea during and after the experiment, practical applications should consider avoiding repetitive use of jumps due to the risk of fatigue. Note that we also examined the effect of the repetitive jumps (leading to fatigue) on the subjective reality and unnaturalness by comparing the mean scores for each between the first and second half of the trials, but found no significant difference in the scores ($p = 0.28$ and $p = 0.74$, respectively) for both of them.

5.5 Gender

Several RDW studies have shown that the user's gender affects the perception of viewpoint manipulation [21, 22, 33]. Although we did not include participants' gender in the experiment design as an independent variable thus the number of female and male participants was not equal, we additionally analyzed its effect. We performed four-way RM-ANOVAs with ART for subjective reality and unnaturalness, testing the effects of gender, step height, ascending gain, and peak shift. The results revealed a main effect of gender ($F(1,18) = 10.03,\ p < .01,\ \eta_p^2 = .36$) for subjective reality, showing that female participants perceived significantly lower subjective reality than male participants. The results also revealed an interaction effect between gender and step height ($F(3,54) = 3.21,\ p < .05,\ \eta_p^2 = .15$) for subjective unnaturalness, showing that female participants perceived significantly higher subjective unnaturalness than male participants in the 0.4, 0.6, and 0.8 m conditions ($p < .01$ for each). No other main effect or interaction effect was found for either reality or unnaturalness ($p > .05$).

Interestingly, these results suggest that the female participants perceived lower reality and higher unnaturalness than the male participants, which is inconsistent with the previous results that female participants are less sensitive to viewpoint manipulation (during walking) than males [21, 22, 33]. The reason for the males' higher reality is unclear, but their higher sensitivity to viewpoint manipulation might positively affect the sense of reality. As for the females' higher unnaturalness, it might be due to the gender difference in physical capability. A Mann-Whitney U test revealed that the jumped height by female participants (M =21.8 cm, SD =7.9 cm) was significantly lower ($p < .01$) than that of male participants (M =23.7 cm, SD =8.7 cm). Lower jumping height leads to smaller descending gain (see Equation 2 and Equation 3), possibly resulting in higher unnaturalness for female participants.

5.6 Safety

We did not observe any accident such as stumbling or falling in the experiment, and no participant expressed any safety concern. Meanwhile, the tracked position data showed that higher virtual steps caused higher physical jumped height and larger staggering. However, we are optimistic about this because the jumped height and staggering increased by only approximately 10%, despite the step height increasing by four times (0.2 m to 0.8 m) in VR (see Fig. 7). Therefore, we believe that the system could present jumping experiences safely enough within the range of the conditions we tested in the experiment, although we have to consider the instability of landing as the steps become higher in practical use.

5.7 Usage Recommendations

Based on the above discussion, recommendations for utilizing our techniques in practical VR applications can be summarized as follows:

- The users are generally insensitive to (tolerant of) viewpoint manipulations while jumping, and thus the ascending jump experience can be presented with reasonably high reality and low unnaturalness even with certain changes in the gain and peak shifting conditions;
- The user's sense of reality might be provided mainly by presenting the view of reaching the step after jumping, rather than that during jumping.
- The user's perceived unnaturalness would be lowered by choosing "moderate" ascending gain that reaches the step height and possibly utilizing peak shifting to reduce the gain difference between ascent and descent;
- Repetitive use of jumps should be avoided due to simulator sickness, especially user fatigue;
- As the step height in VR increases, the jumping height in reality and consequent staggering at landing would increase gradually, an effect that should be considered in applications; and
- Females tend to perceive lower reality and higher unnaturalness in visually manipulated step-jumping experience compared to males, which might also be considered in applications.

6 Limitations and Future Work

Although this study gained an understanding of the user perception of our PseudoJumpOn system and guidelines for its use, it still has some limitations.

First, this study does not investigate the effects of possible external factors. For example, some studies have shown the complexity of how the virtual environment affects the sensitivity to viewpoint manipulation in RDW [15, 24] and RDJ [17]. This effect might also be seen in the ascending jump motions. Self-representation of the user in VR has also been investigated in several studies in RDW [15, 23, 26] and RDJ [17], which would be worth exploring for ascending jump motions. In addition, our experiment did not have enough number of participants to evaluate possible between-participant effects (e.g., user's gender, physical capability) that might affect the experience. Consequently, conducting a study with more participants and a different variety of these factors would be another beneficial future work. Similarly, we tested only one trial for each experimental condition per participant considering their fatigue, which could also be a limitation for this study.

Second, our method requires a higher threshold for jump detection than the previous work [7]. This did not lead to an increase in the jump detection error in the experiment, but might have some negative effect on the subjective jumping experience. To improve this, the threshold could be reduced by using the acceleration of the user's head and/or machine-learning-based methods.

Third, this study focused on ascending jump motions, without considering the descending jump motions. While our implementation of the peak shifting for ascending jump motions depends on the user's past positions, it would require the user's future positions to apply it to the descending jump motions where the virtual peak point comes before the real one. Consequently, our future work will explore predicting or replicating the future positions to achieve forward peak shifting during descending jump motions. In addition, we need to carefully examine the user's physical risks for descending jump motions, since the user may reach the physical floor before being prepared for landing. Furthermore, we did not consider jump motions except for two-legged jumping. Future work will explore other kinds of jumps, such as one-legged jumps or repetitive jumps.

Finally, our current implementation must know the height of the user's jumping target to calculate the descending gain. This implies that the system might not be usable in situations involving multiple targets within the range where the user can make a jump. One solution for this would be to simply avoid placing multiple steps of different heights where ascending jump motions are used in the virtual environment. Another solution is to predict the jumping target by building a prediction algorithm based on the initial velocity and its direction of the jump. Building such prediction algorithm and general adaptation would be a promising future work.

7 Conclusion

We proposed PseudoJumpOn, a novel vertical locomotion technique that allows the user to experience jumping onto a higher place using a common VR setup. We designed and implemented two viewpoint manipulation methods of gain manipulation and peak shifting, and then we conducted a user study to understand the user's perception of them. The results showed that the users generally perceived an reasonably high sense of reality with low unnaturalness, even with certain changes in the gain (including those that exceed the user detection threshold) and peak shifting conditions. The subsequent analysis derived several findings, such as the ability to lower unnaturalness by using moderate ascending gain that reaches the step height and possibly applying peak shifting to reduce the gain difference between ascent and descent. Future work will explore building algorithms for predicting jumping targets from user motions and adaptively applying viewpoint manipulations for more general use and better jumping experiences.

Acknowledgments

This work was supported in part by JSPS Grants KAKENHI (19KK0258).

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