Virtual climbing: An immersive upslope walking system using passive haptics

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Abstract  Background  In virtual environments (VEs), users can explore a large virtual scene through the viewpoint operation of a head-mounted display (HMD) and movement gains combined with redirected walking technology. The existing redirection methods and viewpoint operations are effective in the horizontal direction; however, they cannot help participants experience immersion in the vertical direction. To improve the immersion of upslope walking, this study presents a virtual climbing system based on passive haptics.  Methods  This virtual climbing system uses the tactile feedback provided by sponges, a commonly used flexible material, to simulate the tactile sense of a user's soles. In addition, the visual stimulus of the HMD, the tactile feedback of the flexible material, and the operation of the user's walking in a VE combined with redirection technology are all adopted to enhance the user's perception in a VE. In the experiments, a physical space with a hard-flat floor and three types of sponges with thicknesses of 3, 5, and 8cm were utilized.  Results  We recruited 40 volunteers to conduct these experiments, and the results showed that a thicker flexible material increases the difficulty for users to roam and walk within a certain range.  Conclusion  The virtual climbing system can enhance users' perception of upslope walking in a VE.

Keywords  Virtual reality; Redirected walking; Passive haptic; Flexible material

1 Introduction

Many related studies on virtual reality (VR) have realized users' walking in virtual environments (VEs), such as through redirected walking technology (RDW)[i-4], which enables users to roam in VEs. However, existing studies mainly focus on the horizontal direction, and there are few relevant studies on enhancing the vertical height experience in VEs. A virtual scene is the mapping of a real physical space. Real physical space and the users' movement in real space are all three-dimensional and not limited to a two-dimensional plane. Therefore, research on the enhancement of the vertical height experience of virtual scenes is of great significance.

Currently, VR technologies mainly focus on human visual perception; however, human perception is...
composed of visual, auditory, tactile, and other senses. A passive tactile sense is obtained when external objects contact an individual. Azmandian et al. proposed tactile retargeting, which enables a single physical object to provide passive tactile feedback to multiple virtual objects[3]. Therefore, we can combine the passive tactile sense with visual perception and enhance the immersion of upslope and downslope walking in a VE. This method provides a simple and effective way to improve user experience.

To improve the immersion of upslope walking, this study presents a virtual climbing system that uses passive haptics with which to obtain and enhance a user's spatial perception of movement in the vertical direction of the VE, and establishes a safe and effective virtual roaming system that enables users to obtain the perception of upslope walking in VEs. Using the passive tactile sense, our virtual climbing system enables users to walk on virtual slopes when their feet tread on flexible material, and then improve the users' immersion in VEs. In addition, combined with the RDW technology, multiple users who walk on sponges can achieve the goal of infinite walking in virtual scenes.

The main contributions of our work are as follows:

1. We first present a virtual climbing system, which can significantly enhance the user's immersion in upslope walking in a VE without using additional equipment. By wearing HMDs the users can safely and flexibly experience an upward movement in a VE.

2. We use sponges to provide users with tactile feedback, such that users can obtain a passive tactile sense and obtain an enhanced perception of vertical movement in virtual scenes. Compared with the method of setting small bumps[5], user movement is safer and more flexible.

3. In our virtual climbing system, users do not need to understand the details of the HMD and other devices. They can explore all kinds of virtual scenes with upslopes simply, and have better visual enjoyment and immersed senses.

2 Related works

In a VE, the movement of users is simpler and more efficient than in a real space[6]. Usually, only a simple and small physical scene is used to realize the roaming of a large-scale VE. Razzaque et al. proposed the redirected walking method, which first adopted three types of gains (translation gain, rotation gain, and curvature gain) and other methods to perform viewpoint manipulation to change the user's perceptual experience in the horizontal direction[7]. When the user interacts with objects in the scene, such as touching, bumping, interacting with other users, shaking hands[8], and talking, the corresponding tactile feedback will bring a strong experience to the user[8-9], which is also very important for VR applications. Therefore, in recent years, many researchers have attempted to combine the sense of touch and hearing with the common use of visual feedback to enhance the spatial perception of users.

To date, most VR roaming systems focus on immersion on horizontal ground, such as Dong's multi-user redirected walking[10-11], which uses the transform gain and rotation gain of horizontal ground to realize the redirection and collision avoidance of multiple users. However, this technology does not explore the perception of the vertical direction in a VE or address perceptions other than visual perception. They proposed a recovery algorithm, adjusted the relative position and direction of multiple users, and made the physical space and virtual space consistent. Finally, the handshake was completed in both the virtual and physical spaces. The recovery algorithm improves user satisfaction in terms of system availability. Nagao et al. built a simple and safe system to simulate stairs walking in a virtual environment[5] and obtained the perception of the vertical direction. This system uses the passive tactile sensation generated by users stepping on small bumps attached to the flat floor in real space to obtain a strong sense of ascending and
descending. It also analyzes and explores the shape of small bumps. However, in the process of walking, the system requires the users to step on the pre-set small bumps; otherwise, the perception brought by passive touch will not be realized. Meanwhile, the application of the system is relatively single, which makes it impossible for multiple users to walk simultaneously. In addition, the small bumps are made of hard material, which will cause a certain risk to the users when they are walking with the HMD. Iwata et al. presented a locomotion interface to create a sense of walking on an uneven surface\[12\]. However, it requires exclusive equipment, and users can only walk within a certain range. In addition, March-and-Reach presented by Lai et al. cannot allow users to move more freely\[13\]. Matsumoto et al. focused on energy consumption while walking uphill and downhill\[14\]. Walking uphill takes three times as much energy as walking on flat ground, whereas, walking downhill takes only half as much energy. They improve the feeling of walking uphill and downhill using translation gains.

Computer-controlled stilts\[15\] attempted to sense the vertical direction. By changing the height of the stilts, users can realize the rise and fall in VE with no discomfort; thus, vertical experience perception can be obtained. However, owing to the heavy weight of stilts, users wearing HMD cannot walk naturally on flat ground and there is a possibility that they might get hurt.

Therefore, there is still no perfect solution for immersion in the vertical direction. Our work attempts to provide users with passive tactile sensations by walking on flexible materials that are placed on the horizontal ground to enhance the perception of VE vertical space. Meanwhile, the different densities of flexible materials can make users walk more freely and flexibly.

3 Upslope walking system using passive haptics

3.1 Concept

This virtual climbing system aims to enable users to obtain a strong sense of upslope easily and effectively by walking on flexible materials without complicated physical hardware equipment. The virtual climbing system includes the following ideas:

First, by allowing users to walk on a flexible material placed on flat ground, a passive tactile sensation is obtained to simulate upslope walking, thereby providing an immersive experience of the slope.

The second is to combine visual perception and passive haptics. While users are walking on a flexible material to gain passive tactile sensation, the RDW technology and the user's viewpoint are used to manipulate the character changes in the virtual scene\[16-17\], such that the users can obtain a more realistic upslope experience.

This virtual climbing system does not require a real sloped ground and uses the passive touch feedback of a flexible material to simulate walking on slopes. Combined with the RDW technology, users can use this virtual climbing system to roam all types of virtual scenes.

3.2 Tactile feedback

With the advantages of low cost and good effect, passive tactile stimulation can enhance the immersive experience through feedback to the users. When walking on the upslope, the angle of ankle dorsiflexion changes dynamically. As the slope angle increases, the ankle angle continues to increase, which corresponds to the slope angle. Previous studies have shown that when a person walks on a slope with an angle of $\pm12^\circ$, his body cannot maintain a flat walking posture, and this change will occur between $\pm6^\circ$ and $\pm12^\circ$\[18\]. It is an important method for our system to change the users' walking posture by simulating the
slope of a real scene, thereby simulating the upslope walking experience (Figure 1).

Figure 2 shows the gait diagram of a person during walking. The left and right feet were symmetrical. In this study, our work mainly focuses on three stages, as shown in Figure 2a, b, and c. Gait 1: one foot is fully on the ground, and the other heel just touches the ground; Gait 2: both feet are on the ground; Gait 3: one foot is on the ground, and the other toe is about to leave the ground. In the uphill process, the foot has the greatest contact with the ground in Gait 2, which also means that the tactile feedback is strongest in Gait 2. When the users reach Gait 2, the virtual climbing system should provide users with sufficient tactile feedback such that they can acquire a strong upslope walking experience.

![Figure 1](image1.png)

**Figure 1** Tactile feedback of walking on sponges: (a) the user wears HMD and walks on the flexible material in the physical space; (b) the user walks up and down the slope in VE.

![Figure 2](image2.png)

**Figure 2** Human gaits while walking. We mainly focus on three states (a), (b), (c).

The tactile stimulation of the slope gradient in the VE is provided to the soles of the user's feet. The slope formed by the height difference between the toe and the heel, which is felt by users walking on the flexible material of the real physical space is an important reference feature for walking upslope. Figure 3 shows the gait of the users stepping on the flexible material in the virtual scene and real world, respectively.

![Figure 3](image3.png)

**Figure 3** User’s gait in virtual scene and real world: (a) cross section of the user’s foot on a flexible material; (b) user’s gait diagram in a real scene.

We exploit the easy deformation of flexible material and the physical characteristics of human walking; thus, when users walk, there is a certain difference in height between the toe and heel of each foot, as well as angle that forms between the foot and the ground, which is the tactile feedback of users’ upslope walking in our system.

### 3.3 Visual feedback

In a virtual scene, we manipulate users’ viewpoints to enhance users’ experiences. Marchal proposed a method that manipulates viewpoints of users to effectively enhance the experience of walking up and down. For walking up and down slopes, a simple and effective way to manipulate the viewpoint is to move the viewpoint linearly along the slope, as shown in Figure 4.
The height of the viewpoint in VE can be expressed as:

\[ H'_v = H'_{v-1} + \Delta x \times \tan \alpha \]

where \( H'_v \) is the height of the current time in the VE, \( H'_{v-1} \) is the height of the last moment in the VE, \( \Delta x \) is the distance traveled in the real scene, and \( \alpha \) is the slope of the ramp.

This method can better show the viewpoint changes during the entire walking process; however, in the actual walking process, we need to pay more attention to the moments of local changes. In the process of walking, the viewpoint changes along the ramp. There were slight fluctuations at each step, and the fluctuation cycle was consistent with the walking cycle. The change in viewpoint is shown in Figure 5.

The improved height of the viewpoint is expressed as:

\[ H'_v = H'_{v-1} + \Delta x \times \tan \alpha + \sin \left( \frac{\Delta x}{L} \pi \right) \]

where \( L \) is the step length.

The comparison of the two viewpoint operations is shown in Figure 6.

There is a difference between the energy consumption of people walking on flat ground and slopes\(^{29} \). When going up on a slope with a gradient of 0.1, the energy consumption is approximately three times that of walking on flat ground. Based on this and considering the actual physical experience, we adopt a simple method to enable users to obtain good visual feedback: the walking distance in a real scene is \( \Delta x \); when VE is on an upslope, the walking step in VE \( \Delta x = 0.6 \Delta x \).

In addition, we need to consider when the state of VE will change; for example, during walking on an upslope, the user is about to walk toward a steeper or gentler slope. To ensure the user's sense of experience, we need to ensure when the user is at the state switching point in the VE, or when the user is at the edge of the flexible material in the real scene. In Figure 7, the distance between the user's position and the edge of the flexible material is \( S \). In VE, the distance between the user position and the state switching point is \( S \) in the real scene.

The viewpoint operation can be calculated as:
3.4 Upslope walking based on multi-user redirection

In traditional horizontal redirected roaming, the user's walking experience in any direction is consistent. However, users' experience of roaming on the hillside should change with the slope. To adapt to the constant change in slope, we use the circular course.

In this study, real circular lanes were designed with multiple groups of the same material and different thicknesses. The radius of the circular lane exceeds 7.5m; thus, users can walk up freely and infinitely in a virtual scene.

To avoid collisions caused by the difference in the walking speed of users, different paths of virtual scenes, switching ramps, and other factors for multiple users sharing the same physical space, this study adopts a multi-user redirected walking method to the virtual climbing system, which includes the following solutions.

3.4.1 Upslope walking based on multi-user redirection

To enable users to climb indefinitely in the virtual environment, users will walk on circular lanes made of flexible materials in the physical space (Figure 8). For the different thickness of the flexible materials can lead to different uphill experiences, we set some lanes of different thickness in the physical space to simulate the ramp of different slope. However ramps in virtual space are straight but lanes in physical space are circular. So they needs to be constantly redirected to stay in the middle of a certain lane as possible as he can when the users climb on a slope of a certain grade, until the user needs to change ramps in virtual space.

In the process of applying the algorithm, the radius of the arc used by the curvature gain is 7.5m; thus, the maximum angle that can be rotated for each step is calculated as follows:

$$\text{maxAngle} = v \times \frac{\Delta \text{time}}{(2 \times \pi \times 7.5) \times 360}$$

where $v$ is the speed of the user, and $\Delta \text{time}$ is the time taken for each step.

To keep the users as far as possible from the two boundaries of the ring, the virtual climbing system calculates and monitors the distance between the user and the middle point of the ring, where $\Delta l$ is calculated as follows:

$$\Delta l = \frac{(l_{\text{inside}} + l_{\text{outside}}) \times 2 - l}{2}$$

where $l$ is the distance between the user and the center of the circle, $l_{\text{inside}}$ is the radius of the inner circle of the circle lane where the user is located, and $l_{\text{outside}}$ is the radius of the outer circle of the circular lane where
we verify that the passive haptics provided by the sponge we used can indeed bring users an
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Preliminary research on us
ore than a meter away from him
the system will request the slower user to pause for a
When a
and the angle is consistent with the tangent direction of the arc at that point
the user's direction moving counterclockwise is set in the
When the user is
If a user
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Collision reset
For the second type of collision
due to the short reaction
the user behind will be guided to
two types of collisions can occur
the faster user from
Collision avoidance
When multiple users share the same physical space, two types of collisions can occur: the faster user from
behind hitting the slower user in front and the user hitting other users while switching lanes.
In order to avoid the first type of collision as much as possible, when the distance between two users in
the same lane is less than a certain value and the user behind is faster, the user behind will be guided to
another adjacent lane of the same thickness. For the second type of collision, due to the short reaction
distance, we will adopt the collision reset method.
Collision reset
The reset mechanism is used to reset the movement status of the user when the user is about to cross
physical borders or cannot avoid collisions with other users.
As shown in Figure 9, the two situations need to be reset. If the user crosses the lane by mistake, the
user's direction of motion will be reset to the tangent direction of the arc at that point. If a user
collides with another user while changing lanes, the slower users will be suspended for a while.
When the user crosses the original lane, the user's direction of motion is set to the tangent
direction of the arc at that point. When the user is
about to collide head-on with other users, the user's direction moving counterclockwise is set in the
clockwise direction, and the angle is consistent with the tangent direction of the arc at that point. When a
collision is sent to the user while crossing the lane, the system will request the slower user to pause for a
few seconds until the faster user is more than a meter away from him.

4 Preliminary research on user experience
In this section, we verify that the passive haptics provided by the sponge we used can indeed bring users an
uphill experience. Here, we assume that the thicker the sponge, the stronger the feeling of going uphill. Through the passive tactile-based uphill experience simulated in our system, we researched the user's sense of experience and realism. In the experiment, in addition to the uphill experiment, we also performed the downhill experiment together (simply swapping the start and end). We asked participants to walk on flexible materials of different thicknesses to obtain passive haptics to simulate the experience of uphill and downhill. In addition, we detected changes in the heart rate intensity of participants during this process and obtained preliminary experimental results.

4.1 Method

4.1.1 Participants

In the preliminary experiment of users' experience, we recruited 18 participants (14 males and 4 females) from the laboratory. The youngest was 22 years old, and the oldest was 27 years old; the average age of the participants was 24.1 years old. All participants had normal or corrected vision, and none had heart disease. Six participants experienced head-mounted VR devices before the experiment. In the experiment, 8 participants wore glasses to conduct the experiment.

4.1.2 Hardware

Our experimental space is shown in Figure 10, and the space size was 3m×4m. Participants wore an HTC Vive HMD with a visual field refresh rate of 90Hz, and visual field resolution of 1080×1200. To display the virtual scene, we used a computer with a Core Intel i7-8700 processor, 16GB memory, and an NVIDIA GeForce GTX 1070 graphics card. The virtual environments were rendered using the Unity3D engine version 2018.2.4f1. During the experiment, participants wore a heart rate detector on their wrists to obtain heart rate data.

In the experiment, the virtual scene we used was a part of the hillside, with trees and flowers on both sides as a reference, which can also enhance the users' experience. To provide participants with tactile feedback, sponge was used as a flexible material and laid flat on a flat floor. The participants walked on the sponge to simulate the experience of uphill and downhill. We used sponges of three different thicknesses: 3cm, 5cm, and 8cm. Simultaneously, we used walking on a hard texture board as an experimental control.

4.1.3 Materials

To check whether our VE technology will cause discomfort to users, we used the 16 simulator disease questionnaire (SSQ)\(^\text{(2)}\). To assess the users' sense of presence, we used a 10-item IPQ questionnaire\(^\text{(2)}\).

4.1.4 Procedure

In our initial experiment, we evaluated the experience of users and realism in two cases of tactile feedback (walking on the surface of the sponge as a flexible material) and no tactile feedback (walking on a hard and flat ground).

In the experiment, each participant completed two rounds of experiments; each round needed to complete two sets of experiments (uphill and downhill). In each group of experiments, participants walked
on a hard floor and three sponges of different thicknesses. This was repeated once. Before the experiment started, the participants wore all the equipment and were taken to one end of the experimental site. After the participants got used to the VE scene, they began walking along the ramp in the VE until they reached the end of the ramp. In the experiment, we tested and recorded the heart rate intensity of participants after each round of experiment. Between each round of experiment, the participants rested for 2 min, and between the two groups, the participants rested for 5 min. After two rounds of experiments in each group, users filled out the SSQ and IPQ questionnaires.

4.2 Result

4.2.1 Scene of experience

Upon completion of the experiment, 288 (2×4×2×18) questionnaires were administered. Figure 11 shows the subjective scores of participants walking on flat ground and sponges of different thicknesses for up and downhill experiences. A score of 0 indicates no uphill or downhill experience, and a score of 5 indicates a strong uphill or downhill experience. We obtained the average of the scores of participants in each group of experiments as the result. According to the results shown in Figure 11, both 5 cm and 8 cm sponges can give participants a strong uphill experience, whereas the 3 cm sponge brings a weaker uphill experience, and some participants even gave lower scores than they gave for walking on hard floors. Meanwhile, we found that according to the subjective scores of participants, the flexible materials we set have passive tactile sensations, and cannot bring users a sense of downhill experience (the scores are mainly concentrated in 0 and 1). We also conducted a data significance analysis. For uphill, F>F crit, and p<0.01, we can conclude that sponges of different thicknesses have a more significant impact on the uphill experience. However, for downhill, F=2.64<F crit=2.72, we can conclude that sponges of different thicknesses have almost no effect on the downhill experience, and are maintained at a low score, indicating that the tactile feedback we set did not properly simulate the downhill experience.

4.2.2 Heart rate intensity

We collected 288 sets of heart-rate intensity data. In the case of the differences in the heart rate of different participants, we used the heart rate of walking on the hard floor as a reference, calculated the difference between the heart rate of each volunteer on the sponges with different thicknesses and the hard floor, and compared 18 participants. The difference between the participants was averaged. Figure 12 shows the experimental results of the heart rate intensity of participants. We conducted a data significance analysis. For heart rate intensity, F=3.78>F crit=2.94. This shows that sponges of different thicknesses have a more significant impact on the heart rate of the participants.

4.2.3 Simulator sickness and safety

During the experiment, the participants were accompanied by two participants to ensure their
safety. After the experiment, none of the participants experienced any discomfort nor collided or fell during the experiment.

4.2.4 Discussion

Figure 11 shows the scores for walking on hard floors and sponges with different thicknesses. We can see that in the uphill walk, the 5cm and 8cm sponge scores were higher, which is in line with our expectations. As the thickness of the sponge increases, the tactile feedback on the soles of the feet becomes stronger during the experiment; thus, the participants' experience of going uphill during the VE roaming process will be more significant. However, we made two important findings. The score of the hard floor was higher than that of the 3cm thick sponge, which was somewhat unexpected. After the experiments, we learned that there are two reasons for this "anomaly".

While haptic feedback was used to obtain an uphill experience, we also have viewpoint operations. Although participants did not receive tactile feedback, such as walking on a sponge, they received visual feedback from the operation viewpoint, creating an uphill experience.

While considering the tactile feedback brought by the sponge, we also need to consider the softness of the sponge itself. Meanwhile, we refer to the elastic deformation formula: 

\[ F = \frac{1}{2} kx^2 \]

The elastic range of a 3cm sponge is inherently small, and the force that can be generated is also very small. Therefore, what the user feels is not the force generated by the deformation of the sponge, but its soft and easy-to-step characteristics. Therefore, users' experience of going uphill is not strong. In Experiment 1, we will further explain the abnormality of the 3cm sponge. Through the experiment, the results of the heart rate intensity of participants can also be seen. When walking on sponges with a thickness of 5cm and 8cm, the heart rate intensity has a more significant change compared to walking on a hard board, indicating that in the experiment, it causes more difficulties or pressure, more likely to cause participants to feel "tired," and thus get a higher score. However, this is related to the individual differences of each participant. During data processing, we found that, for several participants, walking on sponges of different thicknesses did not cause changes in heart rate intensity.

In addition, we found that the worst point is that our starting point for setting sponges of different thicknesses to provide feedback and tactile sensation has not been confirmed in the downhill experiment. Only scores of the 3cm thick sponge scores was close to that of hard floors, whereas sponges of 5cm and 8cm thick had low scores. Consequently, we consider the possible reasons that are consistent with the low score of the 3cm sponge in the uphill experiment. The softness of a 3cm sponge is greater than the force it can provide. For the 5cm and 8cm sponges, because of their large thickness, the force it provides dominates their soft nature; thus, we obtained results that were not in line with expectations.

Despite the abnormality, the results of the preliminary study met our expectations. The force generated by the deformation of the flexible material acts on the soles of the user's feet, allowing the user to obtain tactile feedback, thereby enhancing the user's experience of climbing. This view is especially applicable to 5cm and 8cm thick sponges.

5 Experiment 1: Influence of flexible material thickness on VE slope

In the preliminary research, the experimental results show that the haptic feedback we set does not have a good effect on the downhill experience; however, it can provide users with a strong uphill experience. In this section, we consider the relationship between flexible materials with different thicknesses and
gradients in a virtual scene.

5.1 Method

5.1.1 Participants

In this experiment, we recruited 22 volunteers, aged 22 to 27, with an average participant age of 23.9 years, including four females. All the volunteers had normal or corrected vision. Nine volunteers reported experience with HMD. None of the volunteers had prior knowledge of the experiment.

5.1.2 Hardware

The space size of this experiment was 5m×4m. The HMD and PC used were consistent with those in our preliminary study. In this experiment, we used three types of sponges with thicknesses of 3cm, 5cm, and 8cm. Our virtual scene contains three mountain roads with different slopes, as shown in Figure 13, which are 10°, 20°, and 25°, respectively. To measure the height difference between the user's heel and toe during the experiment, we used a gradienter in angle measurement with an accuracy of 0.1°. We fixed the gradienter on the user's upper body and adjusted the position of the level. When the volunteer stood on the horizontal ground, the level value was 0°.

5.1.3 Materials

In Experiment 1, in addition to the SSQ used in the preliminary study, we also added the IPQ questionnaire to evaluate the corresponding relationship between flexible materials with different thicknesses and different slopes in the VE from the subjective sensation of users. In addition, we used the data measured by the level during the walking process of the user to support and analyze the conclusions of the user. To reduce errors in the experiment, we took the average value of three frames before and after the critical gait point as our experimental data.

5.1.4 Procedure

In Experiment 1, we tested the users' experience of virtual roaming with different slopes on sponges of different thicknesses. Each volunteer completed 12 small experiments in each round, which were divided into four groups. Users should walk upslope at three slopes (10°, 20°, and 25°) on four types of ground materials (hard flat ground, 3cm sponge, 5cm sponge, and 8cm sponge). Before the experiment, the volunteers were led to one starting point of the walking area. After the users got used to the virtual scene, they started walking until they reached the end of the ramp in the virtual scene. For each small experiment, we measured four key points in the gait: the angle between the ball of the foot and the ground. After each small experiment, the volunteers took a two-minute break. When the volunteer finished an experiment, he/she filled in the IPQ questionnaire, and when the volunteer finished all four experiments, the SSQ questionnaire was completed.
5.2 Result

After this experiment, we collected 22 SSQ and 88 IPQ questionnaires. We calculated the experience of using sponges of different thicknesses and walking on different slope ramps in the VE. A score of 0 indicates an awful experience, and a score of 5 indicates a very good experience. We averaged the scores of participants in each group of experiments as the result. Among them, we measured 22×12 sets of level data.

5.2.1 Sponges of different thicknesses on different slopes

As shown in Figure 14, the performance of the 3cm sponges on each slope was poor, which is also consistent with our preliminary study. The sponge with a thickness of 5cm performed well on all three slopes, especially on the ramp with a slope of 20°, which gives users a strong sense of experience. The 8cm sponge performed better on ramps with higher slopes than those with lower slopes.

Figure 15 shows the degree of the level measured by the users when walking under sponges of different thicknesses and represents the degree of the user's foot and plane at several key moments in the walking process.

We conducted a significance test on the data to verify whether the sponges with different thicknesses would have a significant difference in the angle of the composition of the soles of the feet and the ground at different critical gait points. We found that for the key point of gait 1, the difference in sponge thickness did not have a significant effect on the angle we needed to measure (F=0.34<F crit=3.74, P=0.71). Similar results were obtained for gait 3; sponge thickness did not have a significant effect (F=2.60<F crit=3.73, P=0.11). However, we found that sponge thickness had a very significant influence on gait 2 (F=53.0>F crit=3.73, P≤0.01).

5.2.2 Simulator sickness and safety

The volunteers experienced no discomfort during or shortly after the experiment, and no collisions or falls occurred during the experiment.

5.3 Discussion

From our experimental results, sponges of different thicknesses have no significant effect on key points 1 and 3 of the gaits; however, they have a more significant impact on key point 2. Regarding the key points we selected, key point 1 is the angle formed when the user's heel just touches the sponge behind the heel in the process of walking, and key point 3 is the angle when the user's toe is completely touching the ground, but the heel is about to leave the ground. There was no direct correlation between the two and the thickness of the sponge. Key point 2 is the angle formed when the user's heel lands completely, and the toe just
touches the sponge, which is significantly related to the thickness of the sponge. When the thickness of the sponge is larger, the height difference between the toe and heel will be larger, forming strong tactile feedback; thus, users can obtain a stronger sense of experience. In the process of walking, the gait is constantly reciprocating, and tactile feedback mainly comes from the time when the heel touches the ground to when the toe leaves the ground, namely, the key points of gaits 1 and 2. During the transition from 1 to 2, we provide users with sufficient tactile feedback to enhance the users' upslope experience. As shown in Figure 15, when the thickness of the sponge is 5cm, the angle of formation is between 7 and 12, and when the thickness of the sponge is 8cm, the angle of formation is between 9 and 14. They are both greater than 6°, which generates sufficient tactile feedback to users, allowing them to obtain a strong upslope experience, which is consistent with what we mentioned earlier.

6 Experiment 2: Study of the effect of upslope walking system based on multi-user redirection

6.1 Method

To make better use of the upslope walking experience brought by flexible materials of different thicknesses, we designed and tested a redirection walking method suitable for infinite upslope walking. It is necessary to perform many experiments and test many parameters to verify the validity of RDW algorithms, which is impractical for live-user research. Therefore, the simulation method is common in research on RDW[22-24].

In our system, the physical space consists of two rings formed by concentric circles with radii of 7.5m, 8.5m and 9.5m. The inner and outer belts corresponded to sponges with thicknesses of 5cm and 8cm, respectively, which simulate different slopes of the uphill. Users walk and are redirected around the circles. Each user uses a different VE, which includes a 300-meter-long slope with random alternating steep and gentle slopes. It should be considered that the speed between users may not be the same during the real uphill process. In the experiment, each user's speed was set at random to a constant between 0.7 and 1.1.

To test the performance of the redirection method with different numbers of users, we set up three experiments with different numbers of users. At the beginning of each experiment, each user was evenly distributed in the inner ring lane of the physical space.

During the roaming process, any two users in the same circuit lane with a distance of less than 1m was recorded as a collision. Each experiment was repeated 30 times.

6.2 Result

To test the effectiveness of our redirection method for obstacle avoidance and improvement of the roaming experience, we compared the collision times using the collision avoidance algorithm and without using the collision avoidance algorithm. Meanwhile, we also studied the influence of the number of users.

As shown in Figure 16 compared with the algorithm without collision avoidance, when the number of users increases, the motion behavior of users in the physical space becomes more complex, and the number of collisions will also increase accordingly. However, our approach can still significantly reduce the probability of collisions, which enables users to have a more immersive upslope experience.

To evaluate the normality of the dependent variables, a Kolmogorov-Smirnov test was conducted. Because the experimental results were not normal, they were analyzed using nonparametric techniques. We
adopted three evaluation parameters: mean, median, and interquartile range. The Mann-Whitney U test was used for post hoc multiple comparison tests. A significance value of $\alpha=0.05$, was used for all tests. P-values for post hoc multiple comparison tests were adjusted using the Bonferroni method.

The analysis of the number of collisions for different conditions showed a significant difference between the two RDW strategies. This effect was observed for the 8-user condition compared by our algorithm to the algorithm without collision avoidance ($U=86.0, p=0.001$) and the 6-user condition compared by our algorithm to the algorithm without collision avoidance ($U=214.5, p=0.005$). However, for the 4-user condition, $p>0.05$. This is because the physical space is sufficiently large for four users to keep the number of collisions at a very low level.

7 Conclusion

We used sponges, a commonly used flexible material, to provide passive haptics to simulate upslope and downslope walking in a VE. When a user walks on a flexible material, the deformation of the sole and material constitutes a slope corresponding to the uphill slope in the VE. The virtual climbing system, using HMD to bring visual stimulation to users, combined with the tactile feedback of flexible materials, can provide users with a strong upslope experience.

In our experiment, the flexible material was uniform; thus, users could walk more freely and safely in all directions. Our preliminary research confirmed that the passive tactile sensation of flexible materials can provide immersive experiences of upslope walking. In Experiment 1, we studied the relationship between the thickness of the flexible material and the slope of the VE. The experimental results show that, to a certain extent, when the thickness of the flexible material increases, the user's upslope experience will be enhanced. In the simulation experiment of Experiment 2, RDW was introduced, and the situation of walking on slopes in the case of multiple users was considered. By setting the collision avoidance priority, the virtual climbing system can enhance users' immersive experience of upslope walking.

However, our system had some limitations. First, our system does not produce a good experience for downhill, which is the major shortcoming of our system. Second, because the users can walk freely in all directions, our virtual climbing system cannot precisely control the speed and direction of users walking. When the user changes the state artificially, such as changing the direction during upslope walking, we need some time to guide the users to leave the flexible material area. During this shifting time, the user may have a poor experience. In the future, we will consider the arrangement of flexible materials, using materials of different thicknesses to bring different levels of experience, and staggering the use of materials of different thicknesses, such that users have more flexibility in changing VEs.

Declaration of competing interest

We declare that we have no conflict of interest.

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