RedirectedStepper: Exploring Walking-In-Place Locomotion in VR Using a Mini Stepper for Ascents

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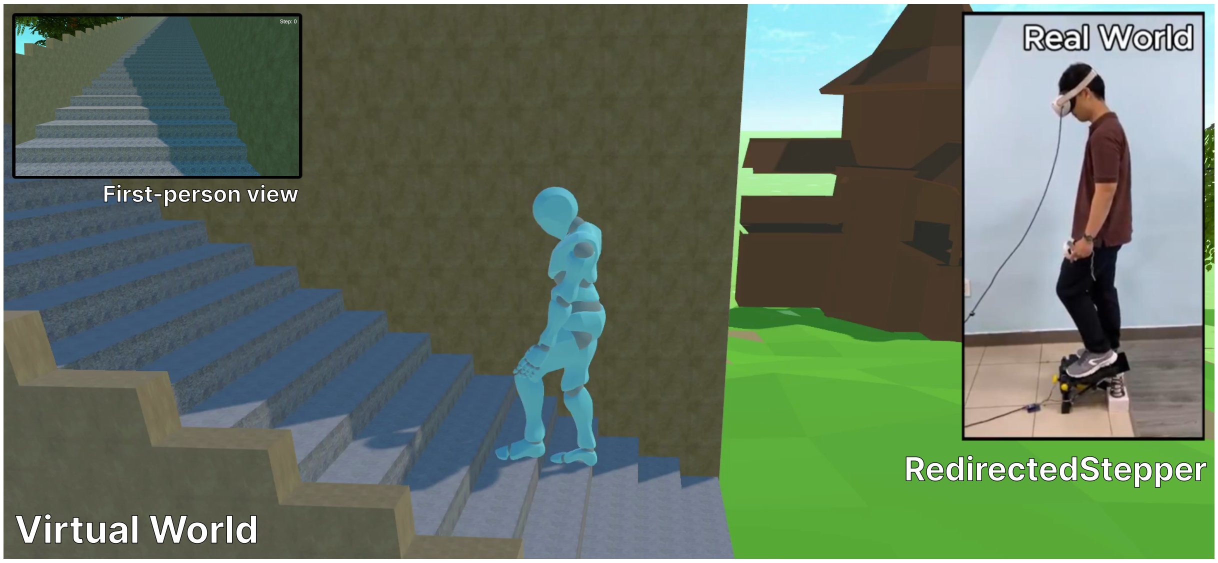

Figure 1: A user stepping on our proposed RedirectedStepper device in the real world (top-right) to ascend a stair in virtual reality (VR) (left). The VR scene, captured from a side-view camera, provides an illustrative overview of the humanoid avatar's pose on the stairs. The user actually sees the virtual environment from the first-person view of the avatar.

ABSTRACT

Walking on inclined surfaces is common in some Virtual Reality (VR) scenarios, for instance, when moving between floors of a building, climbing a tower, or ascending a virtual mountain. Existing approaches enabling realistic walking experiences in such settings typically require the user to use bulky walking-in-place hardware or to walk in a physical area. Addressing this challenge, we present RedirectedStepper, a locomotion technique leveraging a novel device based on a mini exercise stepper to provide realistic VR staircase walking experiences by alternating the tilt of the two stepper pedals. RedirectedStepper employs a new exponential mapping function to visually morph the user's real foot motion to a corresponding curved path in the virtual environment (VE).

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Combining this stepper and the visual mapping function provides an in-place locomotion technique allowing users to virtually ascend an infinite staircase or slope while walking-in-place (WIP). We conducted three within-subject user studies (n=36) comparing RedirectedStepper with a WIP locomotion technique using the Kinect. Our studies indicate that RedirectedStepper improves the users' sense of realism in walking on staircases in VR. Based on a set of design implications derived from the user studies, we developed SnowRun, a VR exergame application, demonstrating the use of the RedirectedStepper concept.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; *HCI design and evaluation methods*; **User studies**; **Usability testing**; Laboratory experiments; **Empirical studies in HCI**; **Interaction techniques**; Mixed / augmented reality; **Virtual reality**; *Haptic devices*; **Interaction devices**; Empirical studies in interaction design;

KEYWORDS

Virtual Reality, Usability, Experience, Haptic Feedback, Study, Height Change, Stair

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1 INTRODUCTION

Physical walking provides realistic experiences for Virtual Reality (VR) users to move in VR environments [15]. Such walking does not cause motion sickness due to the user's proprioceptive cues being aligned with the visual stimuli presented in the virtual environment (VE). This congruence between physical movement and virtual feedback enhances a user's sense of presence; the feeling of being physically located within the VR space [64].

In the physical world, walking occurs not just as level walking on flat ground, it is also used in various forms of uneven terrain and slopes, for example, climbing stairs, walking down a slope, or crossing hilly mountain tracks. A range of studies investigated ascent and descent behavior characteristics [36]. Yet studies combining such models with VE are scarce because natural locomotion on inclined surfaces in VR is challenging. VEs are capable of depicting a variety of flat surface (level walking) and inclined surface (ascent or descent) scenarios, but ascending, descending, and walking on level surfaces differ significantly in terms of the biomechanics needed [2]. Therefore, an ideal method for realistic walking experiences must provide tailored mapping schemes between physical and virtual movement. That is, a one-fits-all mapping does not seem feasible. At the same time, creating a physical play area matching the extent and slope of the VE is costly or even infeasible (e.g., a VE depicting a mountain or a gigantic tower), and the VE would be limited by the play area. To mitigate such problems, VR research has seen several studies proposing alternative techniques enabling users to travel in a limited space, including walking-in-place (WIP) [19, 44, 73, 77], seated-based walking [16, 24] where the user remains stationary, or redirected walking [29, 53] where the user walks on a modified trajectory.

Realistic VR locomotion on inclined surfaces, e.g., ascending or descending staircases to transition between floors or walking up a hill, remains a challenge. Yet, such surfaces are common in our daily lives. Therefore, the development of walking techniques for such scenarios is an important component of research on the navigation of inclined surfaces in VR, essentially making VR more applicable to simulate different terrains and environments by offering realistic navigation experiences.

Locomotion in commercial VR systems commonly relies on teleportation, which instantly transfers the user from one position to another, but lacks both the realistic kinetic and haptic experience of walking [5, 9]. To address this absence, researchers have explored approaches to provide haptic feedback and presented mapping techniques to enhance height perception during physical walking on flat surfaces [3, 39, 46, 59]. Yet, such methods often limit the design of VEs and restrict user locomotion. External devices providing proprioceptive feedback (active or passive haptics) have become promising alternatives. While early efforts employed bulky and difficult-to-deploy actuators [30, 31], recent approaches offer compact devices supporting single-step height changes [57]. Using a haptic suit with low-pressure pneumatic gel muscle (PGM) actuators, which synchronize force sensation with visual information, has also been tested for stair-climbing [48].

To keep hardware requirements low and without relying on haptic suits, we propose the RedirectedStepper system, which employs an instrumented version of a simple and inexpensive mini exercise stepper to provide the force sensation of walking on inclined surfaces in VR. Prior research has exploited mini exercise steppers as in-place locomotion devices for walking on flat surfaces or for CAVE environments [43, 76]. Going beyond such uses, our system explores the possibility of using a stepper to enhance the user experience when walking on inclined surfaces in VR. Here, the term inclined surfaces refers to a staircase or inclined terrain. Encapsulated in a compact form factor, the mini exercise stepper employed in the RedirectedStepper allows the user to alternate the heights of its two pedals by changing their tilt angles, enabling the user to jog in place. To provide the user with the illusion that their feet are climbing up stairs, RedirectedStepper leverages the visual dominance phenomenon [11], mitigating the angular difference between the pedals' tilts and the actual staircase step. Specifically, we propose a mapping method to visually morph the user's foot motion trajectories in VR. The mapping method utilizes an exponential function to remap the vertical motion of the real foot into a corresponding curved path for the virtual foot during stepping actions. Notably, the novelty of our proposed function lies in its capability to create ascending leg postures more consistent between the user's legs in the real world and their virtual counterparts in VR. To generate appropriate visual feedback, the virtual viewpoint is adjusted proportionally to the real foot's movement. To evaluate the usability of RedirectedStepper, we conducted three within-subject user studies with 12 different participants (n=12) in each, for a total of 36 participants (n=36), comparing the proposed technique with an established in-place walking method based on a depth-sensing camera in three walking scenarios: a straight staircase, a spiral staircase, and a hill slope. The results from these three studies indicate that RedirectedStepper has the potential to make walking up stairs in VR feel more realistic. In addition, we also derived a set of three design implications for effectively supporting VR ascent on inclined surfaces with RedirectedStepper. Based on these implications, we developed SnowRun, an exert game that leverages RedirectedStepper as the input device. SnowRun exemplifies the realization of our design implications in a jogging game scenario. We conducted an exploratory user study with eight participants to gather their qualitative feedback regarding their experience when playing SnowRun. Overall, the participants' feedback indicates the promising effectiveness of our design on users' perception and physical effort in playing the game using RedirectedStepper.

In summary, this paper presents the design and implementation of our cost-effective system for simulated walking on inclined surfaces in VR based upon a novel mini exercise stepper. We also contribute a remapping scheme to visually morph the user's foot motion trajectory onto the stepper, thereby creating the illusion of stepping on a surface with a different height level in VR. Further, we contribute our findings from empirical user studies with three different inclined surfaces to evaluate our newly developed RedirectedStepper technique. Finally, we demonstrate an implementation of the design considerations derived from the user studies in SnowRun, a VR exergame.

2 RELATED WORK

This section presents an overview of systems that support VR locomotion on inclined surfaces. We review studies on factors influencing the user experience during traversal of inclined surfaces in VR and examine methods for mapping users' foot and head trajectories between virtual and real worlds, facilitating physical walking in VR environments.

2.1 Human Factors for Ascent and Descent

The motions, forces, and movements at the major joints of the lower limbs of a person ascending and descending stairs have long been studied [2]. The movements produced when ascending and descending staircases were clearly greater than during level walking and authors found that "descending movements produce the largest movements" [2]. Lu et al. [41] found that under good visibility conditions, "landing has a positive effect on speed" for ascending but a negative effect for descending. Ghiani et al. studied where people look when walking up and down a familiar staircase [26] and found that participants looked further ahead when ascending than when descending. That is, participants fixated on closer steps when descending. For escalator walking, Lai et al. [37] showed that descending escalators greatly decreased gait performance and walking confidence. We believe these human factor findings from physical staircase walking are relevant when it comes to supporting VR locomotion on inclined surfaces. That is, a device supporting gait performance during ascent might not support descent equally well. Also, visual cues that help ascending users might provide less help for descending users.

2.2 Locomotion Approaches for VR Navigation

Providing a realistic navigation experience is an important part of immersive Virtual Reality (VR) environments [65]. Multiple techniques have been explored to enable VR navigation through locomotion, such as teleportation, continuous artificial locomotion (CAL) (using joysticks or gestures to continuously move through the environment), or physical walking. Teleportation can help users quickly reach a destination in VR but introduces less spatial immersion than CAL or physical walking [8, 35] or even leads to spatial disorientation [4]. CAL techniques offer continuity in virtual worlds [40], increasing the sense of spatial presence compared to teleportation [35]. However, techniques using controllers reduce presence and immersion [10, 12, 40] and can cause motion sickness due to sensory mismatch [38]. Alternatively, CAL techniques using arm swing, hand/finger gestures [23] or head orientation [74] were not perceived as natural ways for locomotion in VR. The most straightforward approach to physical walking is Real-Walking [6, 45, 67], which allows users to walk naturally within a tracked area. Despite maintaining a high level of presence and causing less motion sickness [50, 67], this approach is limited by the size of the tracked area. Techniques, such as Redirected Walking [50, 54, 68] can potentially enable users to walk infinitely in a bounded physical space to explore a much larger VR environment but may cause disorientation [40]. Alternative approaches leverage mechanical hardware systems [13, 18] to enable users to move within large VEs without the need for sizeable physical spaces, which can provide a realistic walking experience, and avoid motion sickness. Yet, these approaches suffer from high cost and low usability due to bulky form factors.

2.3 Techniques for Navigating Inclined Surfaces in VR

An early approach to providing haptic sensations for walking on stairs in VR was the Gait Master [31]. This complex system employed a treadmill platform and was impractical to set up for end-users. Similar approaches include the CirculaFloor [30], which utilizes an underfoot robotic system consisting of several tiles. Each tile can change its height corresponding to each step the user is walking in VR. While it supports both horizontal and vertical movement, there is a noticeable latency for the system to actuate a tile to the desired height level, disrupting the user's walking experience. Later research utilized smaller devices or even no additional devices to enable stair ascent by walking in VR. The Level-Ups system [57], for instance, used motorized stilts that offer a more intuitive experience. They adjust the height as the user walks, simulating stair steps. However, similar to the CirculaFloor, Level-Ups cannot replicate continuous stairs and make walking on flat ground awkward due to their weight.

Mini-exercise steppers similar to those used in our work have also been utilized as input interfaces for VR in the past. Wiegand and Brook [76] modified the stepper's damper to maintain the user's effort within a range that is conducive to walking on a flat surface. Matthies et al. [43] leveraged a stepper for an immersive gaming experience in VR or CAVE environments. Still, they did not comprehensively investigate the usability and the effect on the user experience of this approach within the context of terrains. Similarly, the rehabilitation support system based on a stepper developed by Hamano et al. [27] also lacks a thorough user study to inform the usability of this approach for travel on inclined surfaces. Moreover, mapping techniques between the real foot's motion trajectory on the device to the stepping motion on virtual stairs have either not been explored or were not clearly reported in these studies. This calls for further work into how users perceive their stepping foot motion in VR using steppers.

Instead of creating hardware that simulates a physical staircase, congruent visuo-haptic feedback can also be leveraged to increase the sense of touching a surface that users are walking on. For example, by presenting a haptic sensation created by small bumps [3, 46] or fluffy mats [75] together with an appropriate virtual scene, users can experience a convincing perception of ascending stairs. However, these approaches require physical objects to be placed exactly at the right location under the user's feet, inevitably restricting the design of the virtual world and the user's locomotion within it.

Recently, a promising method yielding force sensations through a pneumatic gel muscle was proposed by Okumura et al. [48]. This method generates motion illusions by presenting a force sensation through artificial muscles that promote muscular activities. However, this requires a device to be worn on the users' bodies to experience the expected force. In addition, this approach did not address the issue that physical space is frequently limited.

2.4 User Experience Factors in Navigating Inclined Surfaces in VR

It is known that humans can process multiple sensory inputs and take a weighted average of these sensory signals [22]. Yet, when physical cues are lacking during the climb of a virtual staircase, users tend to overemphasize their physical actions more than usual [59]. On the other hand, improving suitable sensory input modalities in a VE can increase the sense of presence of objects in the environment [20, 25]. In addition, Wang et al. [75] pointed out through their experiments that when the disparity in height between the toe and heel increases, it results in pronounced tactile feedback; consequently, users can experience a more intense sensation of walking uphill. In addition, Okumura et al. [48] demonstrated that activating muscles through force feedback can induce the perception of stair-climbing.

2.5 Virtual-real Environment Remapping for Locomotion in VR

Remapping a user's real-world foot movement and rendering it in the VE is a generally viable approach to redirect users' behavior in the physical world so that they feel like they can realistically move around within and interact with the VE [1]. Cheng et al. [17] developed a system where users ascend a physical staircase and are then returned to the ground level by a lifter. Their system manipulates the lifter's movement to produce undetectable motion to generate this illusion. However, the user needs to move in a specific path to reach the lifter and staircase, limiting the design of the VE. Another approach focused on motion remapping techniques [39, 46, 59], exploring several functions to map users' walking motion on a horizontally flat surface to stair-ascending or -descending motions. It adjusts the virtual user's feet to match the timing of their real steps touching a flat floor in the real world. All these approaches share a common remapping mechanism which aims to adjust the vertical position of the virtual swing foot in VR so that it will step on the next stair when the physical correspondence touches the floor. This results in the two physical feet positions being at the same height when the user is actually stepping up or down a virtual stair step in VR. Consequently, the peak of the real foot's trajectory would be mapped to a mid-way point on the virtual foot's trajectory, rather than to the next stair step's level. Such postures of the users in the real world are inconsistent with actual stair ascending or descending postures, where one foot is typically at a higher position than the other. In this work, we aim to ensure that the user's foot positions in the physical world correspond more accurately with their virtual counterparts, creating more realistic stair-ascending postures. Specifically, when the user's foot is at the peak position of a pedal, the virtual corresponding foot must also simultaneously step onto the next stair, resulting in one foot at a higher position than the other, both in the real and virtual environment. Additionally, we also rely on the finding that by synchronizing the force sensation with visual information, we can match the motor and perceived sensations at the muscle-activity level, enhancing the sense of climbing stairs [48].

Inspired by a range of techniques for navigating inclined surfaces in VR, we propose using a mini exercise stepper. We identified above a need for a better understanding of how users perceive their stepping foot motion with a remapped mini stepper. Based on such an understanding, we anticipate that such steppers will enhance the user experience when navigating inclined surfaces in VR. In our research, we investigate this change experimentally. Since movement remapping for locomotion in VR plays a key role in our setup, we specifically investigate the reported real-virtual mismatch. Table 1 provides an overview comparison between the aforementioned prior work and RedirectedStepper.

3 REDIRECTEDSTEPPER

This section presents the design and development of our proposed system, RedirectedStepper, including the hardware and in-house instrumentation of the stepper device and the mapping technique for virtual foot and viewpoint manipulation.

3.1 RedirectedStepper Device

The hardware of RedirectedStepper is an instrumented version of a mini exercise stepper device, comprising two main components (see Figure 2). The first component is the mini stepper with two pedals where the user stands and performs jogging-in-place by alternately pressing down the pedals. The second component is a pair of Inertial Measurement Unit (IMU) sensors that capture the acceleration of the pedals' movement, which is then used to calculate the pedal angle. The IMU sensors are wired to an ESP32 module [1], which receives the acceleration data, calculates the pedal angles, and forwards them to a computer for further processing.

During our initial iterative testing, we modified the original mini exercise stepper to enhance both the user experience and device safety. We replaced the original pedals of the mini stepper with two

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[1] https://docs.espressif.com/projects/esp-idf/en/stable/esp32/get-started/index.html

	Space Usage	Real Motion	Haptics	Evaluation VE
WIP [19, 44, 73, 77]	in-place	vertical stepping	flat plane	flat terrain
Level-Ups [57]	several m^2	N/A	active	single stair step
Daram [39]	several m^2	horizontal walking	flat plane	staircase
Nagao et al. [46]	several m^2	horizontal walking	passive	staircase
Seo et al. [59]	several m^2	horizontal walking	flat plane	staircase
RedirectedStepper	in-place	vertical stepping	dynamic	staircase, slope

Table 1: Comparison of different stepping methods.

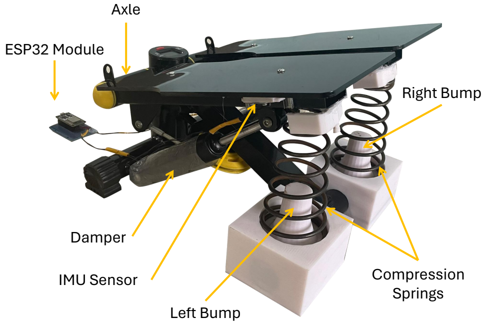

Figure 2: The in-house design, RedirectedStepper, is a mini stepper sized 44 x 40 x 23 cm with a total weight of 7.4 kg. The figure also shows the IMU sensor attached to the device and the ESP32 Module used to transfer the data to the computer.

larger mica sheets, each measuring 34 x 17 cm. The purpose was to expand the foot placement area, which, based on our preliminary experiments, led to an increased sense of safety. Users quickly adapted to the device when they could see their actual foot position in the real world. However, when wearing a VR headset, they often felt uncertain about stepping due to the inability to see their feet's positions. In addition, the original, narrow pedals gave users the impression that their feet were on the edge of a small object, unlike stepping on a stair surface. By using larger pedals, we were able to mitigate these issues.

In the original design of the mini exercise device, a foot was noticeably inclined upward when in the lowest position. During our internal studies, users reported an unexpected sensation in their ankles that led to a reduction in realism while engaging in virtual stair climbing. To avoid this sensation of an incline, we thus incorporated a 15 cm high support beneath each pedal to prevent it from descending too far.

Initially, the mini exercise stepper was designed so that the user pushes one pedal down to lift the other one. However, adding a support prevents the pedal from moving down too far. Consequently, we incorporated a pair of compression springs (Constant $k = 2858N/m$) beneath the pedals. These springs assist in lifting the pedals when users raise their feet. Therefore, in addition to the mini stepper's dampers, the pedals' compression springs provide extra resistance against the user's downward force. This design aims to mirror the experience of climbing real stairs.

The angles of each pedal relative to the ground serve as input data for our mapping function. Various methods to measure the attitude angle exist, such as using a geomagnetic or acceleration sensor. Accelerometers are generally favored for inclination measurement due to their high resolution, widespread use, and superior accuracy compared to geomagnetic sensors [70]. Thus, we used an IMU MPU6050 module[2] positioned underneath each pedal. The tilt angles were calculated using the formula:

$$\alpha = \arctan\left(\frac{AZ}{\sqrt{AX^2 + AY^2}}\right)$$

where AX, AY, and AZ are the acceleration readings on the X, Y, and Z axes, respectively, obtained from the IMU sensor [70]. IMU sensors are susceptible to noise during data acquisition due to external disturbances, such as vibrations [51]. Therefore, the tilt angles need to be filtered before use. Common filters like Low/High Pass or Band Pass ones differentiate noise from real measurement data based on an apriori known frequency [42]. However, the noise from an IMU sensor lacks a stable and distinctive frequency. The general purpose Kalman Filter (KF) estimates the system's state based on previous observations [34]. Consequently, we used it for sensor reading purposes as described by Ma'arif et al. [42].

In order, the equations of each stage were defined as follows:

Predict: Project the state variance ahead:

$$P_t^- = P_{t-1} + Q$$

Update (Correct): Calculate Kalman gain K_t, correct state θ_t, and update state variance P_t:

$$K_t = \frac{P_t^-}{P_t^- + R}$$

$$P_t = (1 - K_t) * P_t^-$$

$$\theta_t = \theta_{t-1} + K_t * (\alpha_t - \theta_{t-1})$$

where α_t is the tilt angle calculated from the sensor data, θ_t is the estimated state or corrected tilt angle, P_t is the state variance of the KF process, R is the measurement constant, and Q is the process variance constant. Empirically, we selected parameters for the Kalman filter on the tilt angle as follows: $P_0 = 0.01; R = 4; Q = 0.035$.

The ESP32 module rapidly sends real-time left and right pedal angle data to the Unity application over WiFi using the UDP protocol (approximately 80-85 packets/second).

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[2] https://invensense.tdk.com/products/motion-tracking/6-axis/mpu-6050/

3.2 Virtual Mapping Technique

The tilt angle (θ) received from the ESP32 module is used to compute the height of the pedal's back end. This height is the distance between the pedal's back end to the horizontal plane through the pedal's axle and is represented as h_{Real}. Given that the pedal has a distance l between the axle and the end, this conversion simply uses the formula: $h_{Real} = \max(0, l \cdot \sin(\theta))$. Yet, when jogging on the stepper's pedals, the foot motion trajectory is nearly a vertical path, which does not resemble a foot's actual motion when stepping up a stair. In such a motion, one typically lifts one's foot first a bit more than the height of the next staircase step, then moves the foot forward and finally puts it down on the step's surface. This procedure helps avoid collisions of the toes with the stairs, which would happen if the foot is moved in a straight path. Thus, with RedirectedStepper, we need to map the vertical straight path of the actual foot to a visually curved one in VR.

As our remapping goal is different from earlier works [39, 46, 59] in terms of the alignment between the user's real and virtual foot, the remapping functions used in these works are not directly applicable to RedirectedStepper. Therefore, we propose the following novel functions to translate the user's real foot trajectory walking on the stepper's pedals to the virtual one ascending a stair in VR.

$$\Delta h_F = \tau \cdot h_{Real}$$

$$\tau = \frac{H}{H_{Real}}$$

$$\Delta d_F = \Delta h_F^c \cdot \frac{D}{H^c}$$

where the exponent $c > 1$ is a pre-defined constant for the curve of the virtual step rising's path, D and H represent the virtual tread and rise of a step, and H_{Real} is the maximum height of the pedal's end, which corresponds to the maximum tilt angle θ. Δh_F and Δd_F are the horizontal and vertical translations of the virtual foot. The trajectories of the real and virtual feet are depicted in Figure 3. If (and only if) $\Delta h_F \geq H$, we can determine when the foot has finished the trajectory. In our implementation, we set H_{Real} to be at 97% of the maximum pedal's end because of the small fluctuation of the tilt angle θ received from the ESP32 module.

To determine the value of c, we conducted a pilot with a small group of five participants. During the pilot, they experienced the movement and were asked to vote on which value of c provided the smoothest movement of the virtual foot. After conducting this pilot, we determined that a value of $c = 3$ resulted in the virtual foot mapping curve most preferred by the participants. Specifically, with a smaller value of c (such as $c = 1$), the virtual foot unrealistically passed through stair objects, whereas a larger value of $c = 5$ resulted in a robotic-like movement, where the foot lifted upward before moving forward. Figure 3 depicts different exemplary virtual trajectories of the users' feet corresponding to three values of c. We chose to use $c = 3$ in our implementation. Figure 5 shows representative data motion collected during our studies.

Analogous to the foot position mapping, the viewpoint mapping methods of earlier works [39, 46, 59] are not suitable for the in-place technique as they rely on the horizontal translation of the real head. In addition, linear viewpoint movement produces less vection than stair movement does, resulting in less motion sickness [21], which has been empirically demonstrated to be not significantly different from a periodic up and down motion [46]. Consequently, we map the viewpoint manipulation linearly. Specifically, the vertical and horizontal translations of the virtual viewpoint are linearly mapped with the height of the pedal's end (h_{Real}). A trajectory is considered completed, if and only if the rise of the virtual viewpoint is greater than or equal to the height of the virtual step, and the viewpoint is updated only after that footstep is completed.

The height of the pedal's end h_{Real} can be considered equal to the step height. Therefore, our virtual mapping method could be utilized by any in-place technique that relies solely on the foot height as input data for spatial mapping in inclined surface contexts. Such techniques can then employ our equations to manipulate both the virtual foot and viewpoint. Figure 4 depicts the different states of the user's physical foot on RedirectedStepper's hardware and its virtual correspondence in VR.

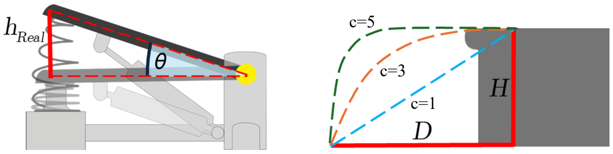

Figure 3: The illustration of maximum angle θ (left) and the trajectories of the virtual foot (right) with three different values for c (1, 3, and 5)

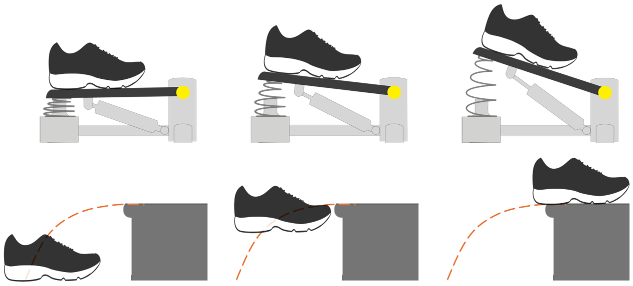

Figure 4: A visualization of the real (first row) and corresponding virtual (second row) foot trajectories, illustrating the following scenarios: (left column) the real foot at the lowest position of the pedal, corresponding to the virtual foot at the base of the staircase; (middle column) the real foot at a midpoint in its trajectory, with the virtual foot lifted in the air, approaching the staircase; and (right column) the real foot at the highest position of the pedal, with the virtual foot placed on the staircase. The position and orientation of the virtual foot in the middle and highest positions were remapped to enhance the realism of the foot's movement during the staircase ascent.

4 EVALUATION METHODOLOGY

To assess the proposed technique, we empirically conducted three within-subject user studies. In each study, we compared our new

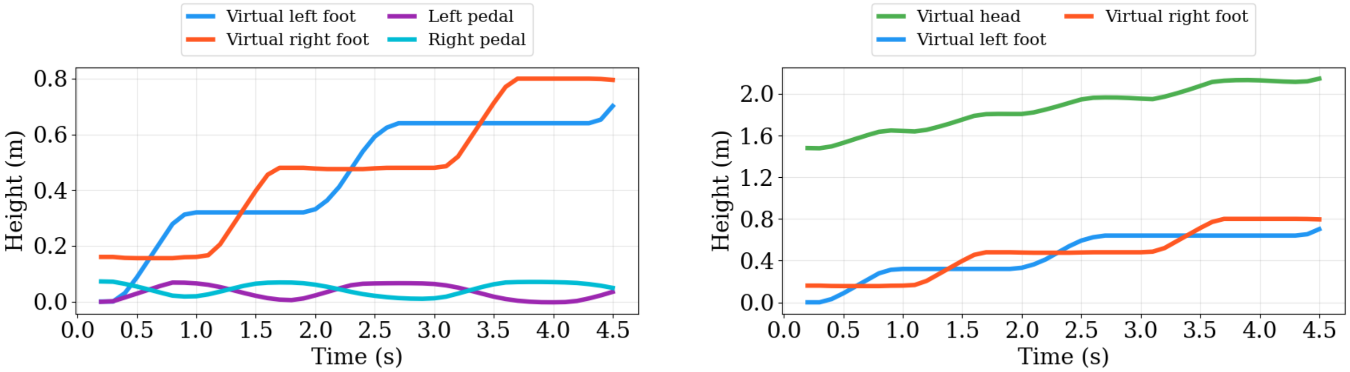

Figure 5: A representative sample from our studies. The left graph shows how the real pedal motion is mapped to virtual foot motion, while the right graph shows also the mapping for the virtual head motion.

technique to a standard WIP technique that uses a motion capture device [61, 78, 79]. This section presents the apparatus, experimental procedure, and measures for the studies.

4.1 Apparatus

In our studies, we utilized an Oculus Quest 2[3] head-mounted display (HMD) to immerse participants in our experimental VEs. These environments were designed and rendered using Unity3D. For the baseline, we adopted a modified version of the standard WIP method since WIP is the closest locomotion method to RedirectedStepper in terms of physical foot motion requirements and compatibility with constrained spatial settings, i.e., both RedirectedStepper and WIP allow the user to remain at the same place. Alternative locomotion methods based on redirected walking [39, 46, 59] necessitate larger physical spaces to facilitate redirected walking, making them less suitable for comparison with RedirectedStepper. Additionally, CAL techniques are not directly comparable due to their differing physical foot motion demands. To implement the baseline technique, we used an Azure Kinect[4] as the motion capture device for the standard WIP technique. Specifically, we employed the Azure Kinect Body Tracking SDK[5] to track the movement of the feet. We then processed the body tracking data to compute the foot's distance from the ground, which we defined as the foot height. Ultimately, we mapped the foot height to the movements of both the viewpoint and the virtual foot using our proposed virtual mapping technique. Namely, the foot height computed from the body tracking data was used as h_{Real} in our equations. To capture the whole body of the user, the Azure Kinect was positioned at a distance of 2 meters. Figure 6 illustrates the two interaction techniques used in the user studies.

4.2 Experimental Procedure

Upon arrival, participants were given a study information sheet. After that, they signed a consent form and provided demographic details. Participants were then familiarized with RedirectedStepper and the Oculus Quest 2 HMD. Each such familiarization session lasted about two minutes. Each participant only took part in one of the three studies. All participants were from the metropolitan area where the research team was located and recruited through emails or snowball sampling. All our studies investigated two experimental conditions: our proposed technique (RedirectedStepper) and the established WIP technique using the Azure Kinect (Kinect). Participants experienced both conditions across separate sessions, counterbalanced between participants. Within each session, participants engaged with one condition and were given a maximum of 10 minutes to ascend to a designated location, which entailed taking 500 steps to reach and finish the task. After each such session, participants answered a questionnaire described below. Upon finishing all sessions, they participated in a semi-structured interview. Interviews were audio-recorded for transcription purposes. For safety, the experiment was conducted under the surveillance of an experimenter and a safety guard. If necessary, participants could use the wall beside the device as support. To mirror the physical setup, each VE in our experimental studies included a wall to provide feedback corresponding to the real environment.

4.3 Measures and Statistical Analysis

We recorded multiple observations to evaluate the techniques, including task performance, questionnaires, and semi-structured interviews. For task performance, we recorded participants' time to finish the task, the number of their steps, and their pace in each study. We also captured participants' movements, including their feet and head 6DoF poses in the study environments.

To investigate participants' experiences, we used three questionnaires. The first was the Simulator Sickness Questionnaire (SSQ) [55] that consists of 16 items, each rated on a 4-point scale ranging from 0 (None) to 3 (Severe). The second was the Igroup Presence Questionnaire (IPQ) [58]. The IPQ assesses the sense of presence and consists of 14 items and has four subscales: Spatial Presence (SP), Involvement (INV), Experienced Realism (REAL), and General Presence (GP), or the "sense of being there." Each IPQ item is rated on a 7-point Likert-like scale ranging from -3 to 3. The third was a Usability Questionnaire (UQ). This questionnaire comprises 30

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[3] https://www.meta.com/quest/products/quest-2
[4] https://learn.microsoft.com/en-us/azure/kinect-dk
[5] https://learn.microsoft.com/en-us/azure/kinect-dk/body-sdk-download

(a) RedirectedStepper

(b) Kinect

Figure 6: Real-world view of the two experimental conditions: A participant ascending a virtual stair using RedirectedStepper (top row) and the Kinect (bottom row).

items and is an extended version of a questionnaire used in previous work [9], which in turn built on questions from several questionnaires [7, 14]. The UQ has ten dimensions categorized into four groups: Ease of Use, Ease of Learning, Satisfaction, and Usability. The Ease of Use has five dimensions: Feeling of Frustration (FT) probing the users' emotional response to any frustration or annoyance they experience while using an interaction method, Feeling of Being Overwhelmed (OV) investigating how overwhelmed users feel when interacting with the technique, Feeling of Tiredness (TI) targeting the mental or physical fatigue users experience during or after using a method, Required Effort (RE) as the cognitive or physical effort needed to perform tasks using the technique, and Difficulty of Operating (DIO) looking at how straightforward it is for users to operate the method. There is one dimension for Ease of Learning: Difficulty of Understanding the technique (DIU) checks how easy it is for users to comprehend the technique. The Satisfaction has two categories: Feeling of Enjoyment (EN) targets the users' emotional satisfaction while using the method and Intention to Use (ITU) investigates whether users express a desire to continue using the technique in the future. Finally, there are two dimensions of Usability: Feeling of Being in Control (IC) probes the users' perception of control over the technique, and Realism (RL), which looks at how closely movement aligns with users' expectations and real-world scenarios. Each item in the questionnaire is rated on a 7-point Likert-like scale ranging from 0 to 6. Note that the IPQ's REAL measure assesses how real the VE feels to the user, while the UQ's RL targets movement realism, focusing on how the movement in the VE feels to the user.

Besides descriptive statistics of participants' rating scores on the questionnaires and their performance, we conducted significance tests using Generalized Linear Models (GLM) in R [52] to validate if there were statistically significant differences between the two techniques. The significance level was set at 5% ($\alpha = .05$) and odds ratios (OR) were considered as indices of effect size. An odds ratio measures how strongly an outcome is associated with an exposure: very small ($OR < 1.68$), small ($1.68 \leq OR < 3.47$), medium ($3.47 \leq OR < 6.71$), and large ($OR \geq 6.71$) [28, 69].

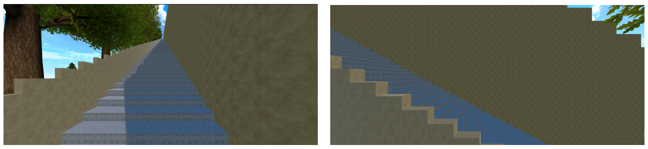
To gain a deeper understanding of the participants' experience, we conducted a 15-minute semi-structured interview after each participant had finished the experimental sessions for both conditions to gather participants' qualitative feedback. The interview, which took place in a separate room, was audio recorded and transcribed afterward.

5 EMPIRICAL STUDIES

To comprehensively investigate the effects of RedirectedStepper on users across various contexts, we conducted three studies. Each study involved a unique VE with an inclined surface: (Study 1) a straight staircase as a standard terraced surface, (Study 2) a spiral staircase as a terraced surface with a directional shift, and (Study 3) a continuously sloped hill as an inclined surface.

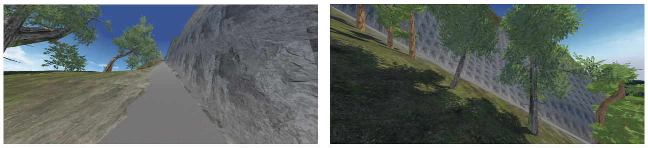
5.1 Study 1: Straight Staircase

We investigated the users' experience and behavior for climbing a straight virtual stair using RedirectedStepper and Kinect. In this study, participants were asked to climb a straight staircase. Each



(a) Straight Staircase VE used in Study 1.

(b) Spiral Staircase VE used in Study 2.



(c) Straight Slope VE used in Study 3.

Figure 7: The three alternative VEs used in Studies 1 (a) straight staircase, 2 (b) spiral staircase, and 3 (c) straight slope, as seen by the user in the first-person view (left column) and from the side (a and c) or top view (b) (right column).

stair step had a rise of 16 cm and a tread depth of 30 cm (see Figure 7a). This staircase configuration adheres to the construction regulations of the participants' country regarding standard stair dimensions.

5.1.1 Participants. We recruited 12 participants (*M* = 21.0, *SD* = 3.49; 5 females and 7 males) (P01-P12). This quantity is similar to the sample size in previous research [29, 32, 46, 71]. Of these, eight had never used VR before. Each participant spent approximately 60 minutes on the whole study. On average, the participants weighed 56.75 kg (*SD* = 8.96) and were 163.25 cm (*SD* = 8.51) tall. Four participants had experienced VR before. All participants had normal or corrected-to-normal vision.

5.1.2 Results.

Task Performance. In the first condition, ten participants completed the staircase task successfully, while two could not finish the task within 10 minutes. In the second condition, nine participants managed to complete the task within the required period, whereas three did not. Despite participants taking more time to perform the task at a slower pace and with a lower number of steps (see the supplementary material), there were no significant differences in the task performance in terms of time (*p* = .79), participants' pace (*p* = .89), and their number of steps (*p* = .91) between the two techniques.

Questionnaire. Regarding the SSQ rating scores, there were no significant differences between the two conditions, except for Sweating. Participants reported experiencing more sweating when performing the task with the RedirectedStepper (*t* = 2.21, *p* = .038, *OR* = 2.30). In addition, we observed no significant differences in rating scores for the IPQ's subscales: GP (*p* = .78), SP (*p* = .80), REAL (*p* = .95), and INV (*p* = .70) between the two conditions. The results of the UQ showed significant differences in three dimensions: OV (*t* = 2.10, *p* = .048, *OR* = 2.22), RE (*t* = 2.15, *p* = .043, *OR* = 2.26), and DIU (*t* = 2.32, *p* = .03, *OR* = 2.38). Figure 8 and Figure 9 illustrate the ranges of IPQ and UQ rating scores for both techniques, respectively.

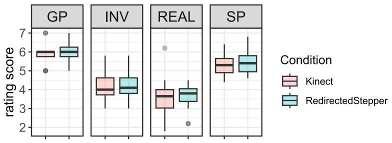


Figure 8: Boxplot visualization of the IPQ ratings for both conditions in Study 1.

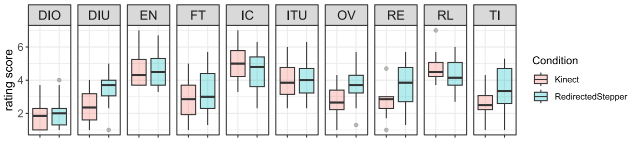


Figure 9: Boxplot visualization of the UQ ratings for both conditions in Study 1.

Qualitative feedback. Our analysis of post-experiment interviews revealed four primary issues regarding RedirectedStepper.

Attention to maintain balance: We observed that participants reportedly felt a sense of insecurity as they paid more attention than usual to maintaining balance: Participant (P) 03 noted, *"I find the [RedirectedStepper] technique quite difficult because I had trouble balancing… When I stood on it, I only looked in one direction. If I had turned around, I would have lost my balance and fallen easily."* P12 added, *"As for the [RedirectedStepper] technique, I didn't look down much because… I felt like I needed to be more balanced, so I didn't often bend down… I just looked straight ahead."*

Unusual experience: Several participants identified subtle factors related to the design of the proposed device as unusual. Specifically, the force feedback was heavily concentrated on the heel, which deviated from the experience of climbing actual stairs. P09 reported, *"This tiredness was mainly felt in the ankles… It could be because that area was impacted by the springs. … So I feel the tiredness in the ankles while climbing stairs, which normally makes me feel tired in the thighs and knees, but not so much in the ankles."* Some participants also reported that the higher end of the inclined pedal reduced the realism of the experience with the device when performing the tasks: P01 stated, *"I didn't feel [walking in the scene] much like with [RedirectedStepper]. I just lifted my heels. I also lifted my whole feet but I didn't feel that it was much like climbing up stairs."*

Realistic experience from force exertion: The minimal effort required to move the body in the Kinect condition reportedly led to a less realistic experience compared to that with RedirectedStepper. When using the RedirectedStepper, participants had to exert force on the moving foot, reflecting the actual physical effort required to climb stairs. P12 reported, *"… I felt like the [RedirectedStepper]* *technique was more realistic. My steps looked more natural than they did with the previous technique [Kinect] . . . I felt like I had actually climbed the stairs because I pushed my foot down."* P05 also shared, *"When I pushed down hard with my foot, it moved easily. . . it felt like walking up stairs. It's like pushing all the way down made me complete the entire step . . . I felt like it was more realistic. It used just the right amount of force, like when I was walking upstairs."*

Sense of height difference between feet: In both conditions, participants could distinctly perceive the difference in elevation between their feet. The act of stair climbing on a flat surface using the Kinect was perceived as less realistic, whereas our proposed RedirectedStepper provided a more life-like experience. P09 asserted, *"The feeling of [RedirectedStepper] is more natural because my foot kind of lifts up, it's real. But compared to the flat surface [Kinect], it's too fake, like pretending. But this one, on the pedal, it feels a bit more like walking . . . It's like the feeling of lifting your foot and then stepping to go up the stairs, it's more similar on the pedal [RedirectedStepper]. Well, on the flat surface [Kinect], I pretend to step, and it feels like I'm walking on a flat surface, not climbing stairs."*

5.2 Study 2: Spiral Staircase

As users responded positively to the more realistic stepping with RedirectedStepper, Study 1 demonstrated the potential of our locomotion technique for ascending straight staircases. To further investigate if this potential of the RedirectedStepper would persist in a different scenario, we conducted a second study involving the ascent of a spiral staircase. During the training phase for this study, participants were instructed to raise their feet beyond the pedal's maximum height. Essentially, their foot was lifted higher than the pedal's peak height to create brief intervals during which the foot was not in contact with the pedal. For this study, participants were asked to ascend a spiral staircase, with a rise and tread of 16 cm and 30 cm, respectively (see Figure 7b). The steps were uniformly arranged within a circle with a diameter of 13.6 m.

5.2.1 Participants. This study involved new 12 participants (*M* = 20.42, *SD* = 1.62; 2 female and 10 male) (P13-P24), who did not take part in the first study. Of these, 10 participants had never used VR before. The average study time per participant was approximately 60 minutes. The participants had an average weight of 58.82 kg (*SD* = 10.79) and an average height of 166.09 cm (*SD* = 8.07). Two participants had experienced VR before. All participants had normal or corrected-to-normal vision.

5.2.2 Results.

Task Performance. All 12 participants completed the staircase task with RedirectedStepper, whereas only eleven participants accomplished the task within the allocated time with the Kinect. There were no significant differences in the task time (p = .35), pace (p = .68) or the number of steps (p = .23) for participants between the two conditions. Yet, on average, participants still spent less time and took fewer steps at a faster pace with the Kinect (see the supplemental material).

Questionnaires. Similar to Study 1, there was no significant difference between the two conditions in rating scores on the SSQ except for Sweating (t = 3.53, p = .002, OR = 3.24). We also observed no significant differences in IPQ rating scores for the IPQ: GP (p = .38), SP (p = .51), REAL (p = .61), and INV (p = .59) between two conditions. The results of the UQ showed significant differences in rating scores for five dimensions: TI (t = 2.13, p = .045, OR = 2.25), OV (t = 3.20, p = .004, OR = 3.02), RE (t = 3.47, p = .002, OR = 3.20), DIO (t = 2.43, p = .023, OR = 2.46), and DIU (t = 2.37, p = .027, OR = 2.42). The ranges of IPQ and UQ rating scores for both techniques are shown in Figure 10 and Figure 11, respectively. Please refer to the supplemental material for further information on rating scores for the questionnaires and their analysis results.

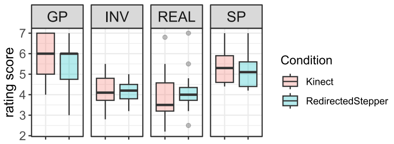


Figure 10: Boxplot visualization of IPQ ratings for both conditions in Study 2.

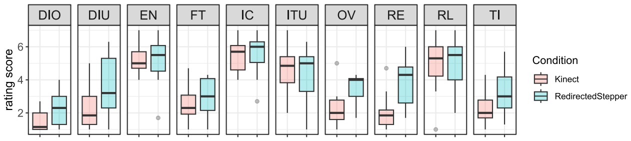


Figure 11: Boxplot visualization of UQ ratings for both conditions in Study 2.

Qualitative feedback. In line with Study 1, the points of *Attention to maintaining balance* and *Realistic experience from force exertion* were also observed in this study. Instability issues, such as imbalance caused by head rotation, initially restricted the user experience. However, these problems gradually faded as participants adapted to RedirectedStepper. In addition, participants suggested that RedirectedStepper slightly improved the realism of the experience due to the force exerted on their feet. The interviews revealed three additional noteworthy points:

Unique experience of standing on elevated ground: Interestingly, participants found RedirectedStepper to provide a unique experience, or at the very least, a more realistic simulation of stair climbing due to standing on elevated ground, compared to the WIP technique on flat ground with the Kinect. P19 reported, *"The [RedirectedStepper] technique is more fun. It's kind of more challenging. . . stepping onto that platform [RedirectedStepper] which is higher [compared to the ground], makes me more cautious. . . When playing the [RedirectedStepper] game, I focused on the real step. . . I was afraid of falling, so I just focused on how I stepped, whether I lifted my foot or not, whether I fell or stepped incorrectly."* P20 added to this *"[With RedirectedStepper], I tried walking while looking back to see how it felt. . . It felt very real. Because when you walk [on the stairs] while looking back, you lose your balance. It's like applying real-life knowledge to VR. . . It's so realistic that if you don't focus on your steps, you'll fall, just like in real life."*

With prolonged use RedirectedStepper is not preferred: Although RedirectedStepper was found to provide a more realistic experience in the evaluated scenario, participants favored the WIP technique for continuous use over a longer period. This preference was primarily due to the increased tiredness induced by RedirectedStepper. Specifically, participants opted for RedirectedStepper in scenarios with fewer stair steps and chose the Kinect for longer staircases, as it required less physical exertion. P16 stated, *"By the sensation, I would prefer [RedirectedStepper]. I like the sensation it brings. The [Kinect] is more suitable for longer use, such as 20 minutes or more."* P20 added, *"For this scene [500-step staircase], I prefer the [Kinect], because it is safer. . . If I go a short distance, I find [RedirectedStepper] to be more reasonable. Since it's just a short distance, I don't need to focus too much."* Interestingly, participants clarified that they would hesitate to climb a high staircase.

Surprising fact about ascending a spiral staircase: All participants reported no discomfort while ascending the spiral staircase in the forward direction. This paradox, when pointed out during the interview, surprised all participants due to their ability to ascend the staircase seamlessly while maintaining a straight direction in the real world. P16 reported, *"I know it [the stair] is spiral, but I didn't notice it was spiral when I was climbing."* P15 asserted, *". . . Although, naturally, we must climb spiral stairs with changes in direction. With each step, it changes the direction slightly, but in the experience, I walked straight forward [on RedirectedStepper]. However, that was reasonable, there was no problem. . . for both [systems, Kinect & RedirectedStepper]."*

5.3 Study 3: Straight Slope

The preceding two studies evaluated the potential of RedirectedStepper in the context of staircases with discrete height levels. We expanded this investigation to explore the effect of our technique on walking up a hill slope, where the height changes continuously, i.e., not step-wise. The hill slope in this study formed a 30-degree angle with the horizontal plane, 212.5 m long, corresponding to 500 steps (see Figure 7c). To adapt the visual feedback, the virtual feet were rotated and tilted upward in the VE as they made contact with the slope.

5.3.1 *Participants.*

Using similar methods as in the two previous user studies, we recruited twelve new participants (M = 20.33, SD = 1.55; 4 female and 8 male) (P25-P36). Of these, 10 participants had never used VR before. Each participant spent approximately 60 minutes in the study. On average, the participants weighed 66.42 kg (SD = 8.87) and were 168.92 cm (SD = 8.33) tall. Two participants had experienced VR before. All participants had normal or corrected-to-normal vision.

5.3.2 *Results.*

Task Performance. All 12 participants completed the slope task within 10 minutes in both conditions. Like Studies 1 and 2, participants spent more time completing the task at a slower pace and more steps with RedirectedStepper than with the Kinect (see the supplemental material). However, there were no significant differences in the task time (p = .50), pace (p = .25), and number of steps (p = .33) between the two conditions.

Figure 12: Boxplot visualization of IPQ ratings for both conditions in Study 3.

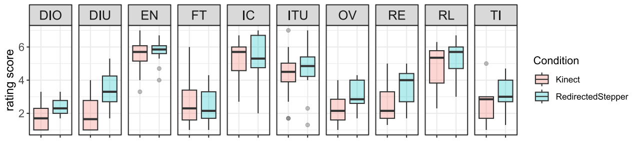


Figure 13: Boxplot visualization of UQ ratings for both conditions in Study 3.

Questionnaire. We observed no significant differences in the rating scores for the SSQ between two conditions, except for three symptoms: Fatigue (t = 2.94, p = .008, OR = 2.83), Increased salivation (t = 2.38, p = .027, OR = 2.42), and Sweating (t = 2.55, p = .018, OR = 2.55). In addition, there were no significant differences in rating scores for the IPQ's subscales: GP (p = .45), SP (p = .97), REAL (p = .61), and REAL (p = .53) between the conditions. The analysis results for the UQ rating scores showed significant differences in four dimensions: OV (t = 2.09, p = .049, OR = 2.22), RE (t = 2.33, p = .029, OR = 2.39), DIO (t = 2.14, p = .044, OR = 2.25), and DIU (t = 3.19, p = .004, OR = 3.01). Figure 12 and Figure 13 respectively present the ranges of IPQ and UQ rating scores for both conditions.

Qualitative feedback. Two findings emerged from this study, both of which align with the two previous ones: *Attention to maintaining balance* and *Realistic experience from force exertion*. The post-experiment interview revealed another interesting point.

Unusual inclined direction of pedals: Several participants reported the experience of ascending a slope using RedirectedStepper, which features two downward pedals, to be unrealistic. They stated that walking on flat ground provided a more authentic experience than using RedirectedStepper. P27 asserted for RedirectedStepper, *"In the scene, the slope was very steep but . . . my actual feeling was that I leaned forward . . . Climbing without the stepper [Kinect] was better because at least it was flat."* In addition, P31 commented, *"For slope climbing, [RedirectedStepper] was to go down . . . It looked like my brain realized I went up but in reality, my body went down . . . this is opposite. However, in the [Kinect] experience, it was more reasonable because I walked on the flat so it was not too different."*

Despite the experience provided by RedirectedStepper to be perceived to be less realistic by several participants, most of participants believed in ascending the slope using RedirectedStepper, due to the force exertion and visual representation. P25 stated, *"I found that the [RedirectedStepper] technique made me feel like . . . climbing on the slope. . . Once I got used to that machine, I thought it would be very similar to slope climbing. At first, I thought that when walking on a slope, my toes had to point up, but when I reflected about it. . . it* *looked really like when I stood on my tiptoes to continue going up the slope."* P35 added, *"At first, I was confused as to why I was going uphill but it [RedirectedStepper] tilted in the opposite direction. I felt like it was a bit weird. But I felt that the tilt made me lean forward more realistically than standing on the flat . . . [However when you climbed, did you realize anything strange?]. Hmm, No."*

6 DISCUSSION

6.1 Usability and User Experience

The results of the post-experiment interviews highlighted the challenge of simultaneously wearing a VR headset and stepping on the RedirectedStepper. This challenge was significantly reflected in the higher rating scores for the Difficulty in Understanding and Difficulty in Operating dimensions in the UQ. In addition, unlike walking on a flat surface, the walking mechanism of RedirectedStepper was unfamiliar to all participants. This issue gradually diminished as participants became more accustomed to learning and operating the device. Consequently, a more extensive training session might be necessary to familiarize users with the device before they start using it.

Maintaining balance on the device was perceived to be challenging and sometimes even required participants to pay more attention than anticipated. As a result, this might redirect their focus away from the VEs to the real world and reduce their feeling of presence in VEs. The results of the IPQ showed that there were no significant differences in the level of presence perceived by participants between the conditions. This indicates that this challenge did not significantly degrade participants' experience with RedirectedStepper. In addition, it can be seen that the challenge could be mitigated after participants experienced and practiced with the device for a while. This is also reflected in the lack of significant difference in rating scores for the Feeling of Frustration, Enjoyment, and In Control of the UQ between the two conditions.

Our findings highlight force exertion as a key element influencing the induction of a realistic ascending stair experience in participants within the VEs assisted by the force feedback afforded by the device and proprioception. The levels and sources of force exertion differ substantially between the two conditions. While the force exertion with RedirectedStepper originates from the pedals, the WIP experience on the flat ground receives force from the interaction with the ground. This indicates that the pedals provide users with a more natural and intuitive sense of foot and body movement in the VEs. In addition, the forces required to push on the pedals induce a sense of body weight when stepping on stairs.

It is noticeable that the realism of the ascending stair experience has multiple dimensions, i.e., not only force and proprioceptive realism but also movement visual realism plays a role. Results from the UQ rating scores reveal that there are no significant observed differences in perceiving the visual realism of the movement of ascending stairs. Participant interviews affirm the contribution of force exertion to the realism of ascending stairs. To some degree, the combination of both the evaluation using the questionnaire and interviews supports the contribution of the movement techniques to the feeling of realism in ascending stairs. This practice also aligns with recent recommendations on combining measurement techniques to evaluate psychological concepts, such as presence [63, 72].

Due to the mechanism below the pedals, our in-house design RedirectedStepper required higher physical effort than using Kinect. This higher effort caused increased sweating in all three studies and increased fidelity and salivation in Study 2. These effects are also visible in the longer task-performing time, slower pace, and fewer steps participants took across all three studies. Although RedirectedStepper does not facilitate rapid movement, it aligns better with real-world navigation of inclined surfaces. For example, navigating terrains with varying elevations demands higher effort and more time compared to traversing flat surfaces.

The Kinect was preferred by participants for ascending staircases, particularly long ones, because of the lower physical effort required. As it involves only walking on flat ground, the Kinect offers a comfortable experience with minimal effort, allowing users to enjoy the view and engage in other activities in the VEs. Our proposed device was better suited for providing *a realistic experience* when ascending staircases. This was supported by the higher rating scores for the Feeling of Being Overwhelmed and Required Effort in all three studies and the Feeling of Tiredness in Study 2. Notably, there were no significant differences in rating scores for all other dimensions of the UQ, including the Feeling of Frustration, Enjoyment, Intention To Use, In Control, and Realism between the two techniques. These findings highlight the usability of the system and its capability to provide a satisfactory experience, as well as induce realistic experiences of ascending stairs in VR users. Moreover, they suggest a strong potential for the usage of the system in exertion games in VR as well as training and exercise purposes.

6.2 Disparity Between Visual and Proprioceptive Channels

In Study 3, and in contrast to Studies 1 and 2, participants seemed to report more concerns about the experience of ascending the slope, likely influenced by the inclined direction of the stepper's pedals. We attribute this to the design of the stepper and the difference in the visualization of the avatar's foot in Study 3, where the avatar's feet were tilted more upward than in Studies 1 and 2. This might have led to larger disparities between the visual and proprioceptive cues that participants perceived on their toes in Study 3.

Furthermore, qualitative data from Study 3 indicated that RedirectedStepper influenced the direction of the toes to the incline. This observation suggests that RedirectedStepper might provide a more authentic experience for descending a hill slope, rather than ascending. As a result, further investigation into the device's operation might be necessary to accurately simulate the sensation of descent for such scenarios. Addressing this issue could enhance the usability of the proposed approach, making it a more comprehensive locomotion technique for scenarios involving changes in height.

6.3 Design Implications

Based on the insights gained from our studies, we derived a set of three *design implications* (DCs), for incorporating mini exercise steppers to facilitate physical in-place ascending inclined surfaces in VR. First, (DC1) using an exercise stepper is more suitable for enhancing the experience of stepping up onto surfaces with discrete height levels in VR, such as staircases, rather than walking on continuously sloped terrains like hill slopes. Second, (DC2) suitable visual guiding cues in VR should be provided to keep them aware of the positioning of their feet on the pedals, to help users maintain their balance safely on the device. Third, (DC3) as using an exercise stepper can require noticeable physical effort from users, VR environments should incorporate appropriate designs to reduce experiences that could be perceived as tiring, especially in prolonged usage scenarios.

6.4 Limitations

While the three user studies offered multiple insights into the effect of RedirectedStepper on users' perceptions, they also revealed certain limitations that need to be investigated in future work. First, with the current implementation, the stiffness of the compression spring may be perceived differently by individuals, mainly depending on their body weight. The average weight of participants in our study was 65 kg. We observed that participants with weights around this average value or higher did not complain much about the effort they had to spend on pushing the pedal. Conversely, female participants with an average weight of approximately 50 kg reported experiencing physical exhaustion during the task. We believe that this issue can be addressed in the future by integrating springs with adjustable stiffness [33, 56, 66], which would enable a dynamic system configuration tailored to an individual user's weight, enhancing usability and reducing physical strain. Future systems might thus need to explore adaptive designs for this component.

Second, as mentioned earlier, instead of solely focusing on stair ascent scenarios, additional studies might be necessary to examine systems similar to RedirectedStepper for descending a hill slope or potentially even a staircase. Additionally, Study 2 only examined one curvature for the spiral staircase. Future studies should consider exploring the effect of different curvatures on the perceived realism when walking on stairs with RedirectedStepper. Likewise, to enable users to walk on inclined surfaces, further hardware instrumentation and mapping methods will need to be explored. Moreover, in our studies, participants walked on predefined navigation paths, which did not provide insights into how the RedirectedStepper system would be perceived in cases where users can freely control their movement direction. Such experimental settings should be explored in the future to evaluate the usability of the system more comprehensively.

Additionally, although we explored the use of RedirectedStepper for ascending inclined surfaces in this paper, it might be possible to exploit the device for walking on flat surfaces in VR. We might consider adopting the mapping approach employed by Freiwald et al. [24] in VR STRIDER. This system maps the circular motion trajectories of two feet of a user cycling on two pedals of a mini exercise bike to corresponding forward/backward movements of his/her avatar's legs in VR. Notably, both VR STRIDER and RedirectedStepper share a key characteristic where the user's feet alternate between a fixed peak and lowest position during movement. Given this similarity, the mapping function employed in VR STRIDER could be adapted and optimized for RedirectedStepper, enabling locomotion on virtual flat surfaces and enhancing the system's versatility for VEs with varying surface inclinations.

Also, the participant population in the study was relatively young with low to medium weight and height. Future research should thus examine RedirectedStepper with a broader range of age groups and more diverse physical characteristics. Concurrently, as walking-in-place, especially when using RedirectedStepper, can lead to user fatigue, future research should consider this issue in evaluations with different age groups.

In addition, although the remapping functions proposed by Nagao et al. [46], Seo et al. [59] and Lim et al. [39] are different from ours in terms of the foot trajectories to be mapped, they could be potentially modified to replace the existing virtual vertical translation method in RedirectedStepper while keeping our horizontal translation mapping unchanged. We leave exploring this aspect also as future work.

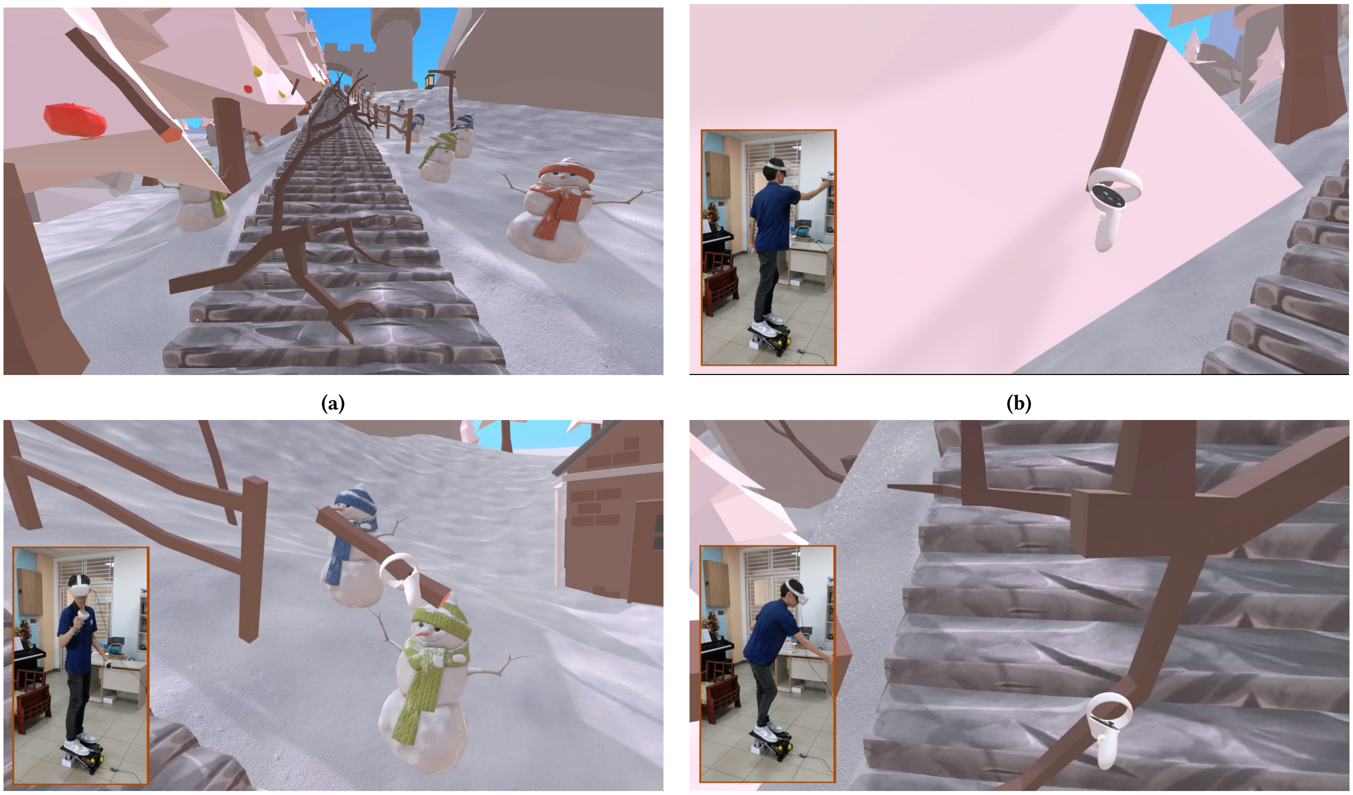
Finally, each participant was limited to experiencing only a single inclined surface condition. As a result, they may not have been able to fully perceive the effectiveness of the proposed remapping function during ascent across various terrains. Future research should adopt a within-subject design, wherein each participant engages with RedirectedStepper across multiple inclined surface conditions. Such an approach would provide more comprehensive comparative data, enabling a deeper understanding of the effects of the proposed remapping function across diverse environmental contexts.

7 EXEMPLARY APPLICATION: SNOWRUN GAME

To exemplify how the outcomes of our work can be implemented in a specific context, and building on the design implications gathered from the user studies, we designed and developed a VR exergame application called SnowRun (see Figure 14). Conceptually, SnowRun requires players to ascend a straight stair (DC1) to climb a snowy mountain as quickly as possible. During the run, the players should perform certain side activities, designed either as missions or reward items. For example, the player can earn more points by picking up objects during their run (see Figure 14b), throwing wooden sticks at snowmen standing beside the running track (see Figure 14c), or removing obstacles from the path (see Figure 14d). By engaging in these activities, the player can take short rests, reducing the need for continuous walking on the stepper (DC3).

We conducted a preliminary user study with SnowRun to gather users' qualitative feedback on their experience when playing the game with RedirectedStepper. We recruited eight university students as participants ($M = 22.25$, $SD = 2.87$, 6 males and 2 females) to try SnowRun. The participants had an average weight of 67.5 kg ($SD = 14.14$) and a height of 167.75 cm ($SD = 8.99$). Among them, 1 male and 1 female participant had participated in one of the previous studies. Each participant had at least 15 minutes to familiarize themselves with RedirectedStepper before starting the game. Afterward, they participated in an interview to share their experiences.

On average, each participant spent 643 ($SD = 139$) seconds, i.e., more than 10 minutes, playing the game. Most feedback from participants focused on the difficulty of completing the mission of



(a) (b) (c) (d)

Figure 14: SnowRun game, including (a) an overview of the game scene, and activities to be performed during the run, such as (b) picking up sticks, (c) throwing sticks at snowmen, and (d) removing obstacles.

throwing sticks at the snowmen, indicating that stepping on the device did not cause any discomfort or, at the very least, not enough to be noticeable. All participants noted that the need to maintain balance did not distract them as they focused on the game's activities. While standing on the device, all users could turn sideways to retrieve objects from a tree, throw sticks at snowmen, and bend down to pick up obstacles. Participants shared that they were aware of their balance during these actions but did not express any safety concerns. We argue that the combination of the mission objective to be completed (here: reaching the end of the stair as quickly as possible) and different activities along the way effectively distracted users from the concerns of standing on the device's pedals. Also, some participants noted that while using the RedirectedStepper required physical effort the waiting time between stages provided an opportunity to rest. One participant even suggested adding a button to allow players to extend their rest if desired. These brief breaks helped players sustain their energy for longer gameplay sessions. These comments confirm our choice to realize the design implications from the previous studies in SnowRun. As exergames have been employed for exercise training, testing, and rehabilitation [47, 49, 60, 62], Snowrun could be repurposed for these applications. Although this evaluation is a preliminary study with a relatively small sample size, it demonstrates the potential for incorporating the design implications outlined in the previous section and utilizing our system for physical exercise and training purposes.

7.1 Conclusion and Outlook

This paper presents multiple studies and insights targeting realistic experiences in VR when navigating inclined surfaces. The inclined surface studies here involved a staircase and inclined terrains. For this purpose, we introduce RedirectedStepper, an in-place locomotion system combining a mini exercise stepper with a novel visual remapping method to create an illusion of stepping up, which leverages the tilt-based pedals of the device. Different from prior work, our system employs a remapping function tailored for the stepper device which enables consistent ascending postures between the user's legs in the real world and their virtual correspondences in the VE. We compared our system to a baseline locomotion technique tracking the user's body movements using a Kinect within three different scenarios with inclined surfaces: a straight staircase, a spiral staircase, and a hill slope. The results of the studies illustrate the promising ability of our proposed interaction approach to enhance the sense of realism in stepping up stairs in VR. Still, we also observed some limitations for walking on inclined surfaces in VR, like a hill slope. Further, our study of SnowRun, a VR exergame application, demonstrated that a mission-driven gamification approach, implementing short rests as game challenges or reward collection activities, can unobtrusively help reduce users' tiredness when walking on the device.

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