Walking by Cycling: A Novel In-Place Locomotion User Interface for Seated Virtual Reality Experiences

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ABSTRACT
We introduce VR Strider, a novel locomotion user interface (LUI) for seated virtual reality (VR) experiences, which maps cycling biomechanics of the user’s legs to virtual walking movements. The core idea is to translate the motion of pedaling on a mini exercise bike to a corresponding walking animation of a virtual avatar while providing audio-based tactile feedback on virtual ground contacts. We conducted an experiment to evaluate the LUI and our novel anchor-turning rotation control method regarding task performance, spatial cognition, VR sickness, sense of presence, usability and comfort in a path-integration task. The results show that VR Strider has a significant positive effect on the participants’ angular and distance estimation, sense of presence and feeling of comfort compared to other established locomotion techniques, such as teleportation and joystick-based navigation. A confirmatory study further indicates the necessity of synchronized avatar animations for virtual vehicles that rely on pedalling.

Author Keywords
Virtual reality, navigation techniques, locomotion user interface, virtual walking

CCS Concepts
•Human-centered computing → Human computer interaction (HCI); •Human computer interaction (HCI) → Interaction techniques; •Interaction paradigms → Virtual reality;

INTRODUCTION
Real walking is usually considered as the most intuitive way of locomotion in real and virtual worlds, and has been found to be more presence-enhancing compared to other forms of locomotion such as flying or joystick-based navigation [46]. Furthermore, walking has been shown to be superior over other techniques for complex spatial tasks [32], cognitive map building [33], and cognitive demands [25]. However, there are limitations of using walking as locomotion user interface (LUI) since it is sometimes impossible to use real walking in immersive virtual environments (VEs) [47]. The main limitation is the size of the tracked area and walking space. For instance, if the VE is larger than the tracked physical space, the user may eventually leave the tracked space while trying to reach distant locations in the VE. A variety of locomotion techniques have been proposed to cope with such physical restrictions, including walking in place [38, 37, 35], redirected walking [31, 40] or omnidirectional treadmills [12, 17]. Currently, the most common locomotion techniques, which can be found in consumer virtual reality (VR) experiences, are teleportation and joystick-based navigation using game controllers [7]. While those LUIs can be used with the supplied input devices of a consumer VR kit like the Oculus Rift or the HTC Vive, they have several drawbacks compared to real walking. Those limitations include a reduced sense of self-motion, limited sense of presence, inferior spatial cognition, or more frequent occurrences of VR sickness symptoms [7].

So far, most LUIs do not satisfy the full range of partly conflicting consumer needs including cost-efficiency, a small form-factor, presence-enhancement, low cause of VR sickness, appropriate for seated experiences, and being multi-purpose for different kinds of virtual locomotion like walking and driving. To fill this gap of current LUIs, we propose the VR Strider, a low-cost and small form-factor LUI that provides an illusion of real walking in VEs for seated experiences. The core idea is to translate motions of a modified mini exercise bike to a synchronized walking animation for a virtual avatar. Moreover, we enhanced the bike machine in such a way that audio-based tactile feedback built into the soles of the pedals simulates virtual ground contacts.

To summarize, the contributions of this paper are as follows:
• construction of a modified mini exercise bike for simulated walking in VR with vibrotactile feedback,
• realistic mappings from cycling to animated walking,
• development of the novel anchor-turning technique for fast and precise rotations,
• a user study to compare established in-place locomotion techniques with VR Strider regarding several metrics (including task performance, spatial cognition, sense of presence etc.) in a path-integration task, and
• a confirmatory study to explore the applicability of VR Strider to other types of virtual locomotion.
Walking is a multisensory activity, which provides humans with visual, proprioceptive, vestibular and kinesthetic cues while moving through the world [41]. While real walking is generally considered as the most natural and intuitive form of locomotion in the real world, its replication in VR remains a challenging task. However, treadmills and pedaling devices are well-suited for supporting locomotion [17], since they prevent users from stepping outside the tracking space while performing walking-like motions. Indeed, preventing displacements in the physical world limits self-motion cues provided by the vestibular sense while using such locomotion devices. Nevertheless, a large number of locomotion interfaces have been developed for use with specific devices, such as treadmills [39, 6], torus treadmills [19], virtual perambulators [19], foot platforms [20], pedaling devices [2, 4] and spheres [26]. In particular, Uniport was the first device built for lower body locomotion and exertion, which operates in a similar fashion to a unicycle [12]. In addition, different bicycle simulators have been implemented for a translation from real to virtual cycling, in full scale [45] or for smaller exercise devices [16]. For instance, Tran et al. [45] examined translation and rotation gains for such devices and reported that redirection can be applied up to an angle of 1.42° without the user noticing. Allison et al. [2] showed that participants significantly overestimated travel distances when they were moving simultaneously in the real and virtual space with a tricycle. When they only pedaled without moving in real space, or when only visual motion cues were provided, the estimation was more accurate. Buttussi et al. [7] compared teleportation, joystick-, and leaning-based navigation techniques in a VR travel task. They concluded that joystick- and leaning-based techniques cause similar levels of VR sickness, while teleportation had no significant impact on the users’ well-being. There was no significant difference for the self-reported sense of presence. Xu et al. [48] compared joystick-based navigation, teleportation and walking-in-place techniques with regards to distance estimation, but could not find any significant differences. Sarupuri et al. [35] further reported similar levels of usability and induced VR sickness between those techniques. Nguyen-Vo et al. [28] compared multiple implementations of leaning techniques with real walking. They could not find any significant differences for task performance between upper-body leaning, full-body leaning and real walking. They concluded that leaning-based techniques can provide enough sensory information for supporting spatial updating, spatial awareness, and efficient locomotion in VR when synchronized with embodied translation feedback. In a similar experiment, Kruijff et al. [23] demonstrated that multisensory input from audio, video and vibrotactile feedback have a positive effect on users’ sense of self-motion and distance traveled. Lastly, Dorado et al. [13] explored homing and path-integration in VR. They reported increased performance of participants with virtual techniques, which match proprioceptive cues from the real world. In their task, treadmills performed significantly better than joysticks.

In summary, the above discussed LUIs try to approximate or replicate natural human locomotion. Teleportation, joysticks, treadmills, leaning and walking-in-place can simulate several aspects of the natural human gait like proprioception, embodiment, a sense of self-motion, low motion sickness, visuals or haptic feedback, but not all of them at once to a convincing degree. Together with the above mentioned end-user restrictions and requirements such as cost-efficiency, physical space requirements and fatigue, it appears reasonable that no in-place technique could to date establish itself as de-facto standard for universal VR locomotion, and therefore teleportation remains as the prevalent VR navigation technique.

**VR STRIDER**

In this section we describe the design and development of the proposed LUI including the device and the locomotion technique that simulates virtual walking in a seated VR experience. Our goal was to provide a LUI that covers as many aspects of the natural human gait as possible, while having the ability to seamlessly switch to different kinds of virtual locomotion.

The device consists of four main components (cf. Figure 1):

1. The base, i.e., a mini exercise bike, that has a fixed position relative to the user’s seat.
2. A freely spinning axis with foot pedals on each side.
3. Electronic parts, which are used for tracking the current axis rotation and the pressure that is applied to each pedal.
4. Two actuators embedded in the soles that provide audio-based tactile feedback.

The base consist of an exercise bike with a small form factor similar to [16]. We modified it with 3D printed pedals with a fixture for tracking markers, a large surface area for the vibrotactile soles and a compartment for the electronics. The circular movement pattern of the user’s legs can be translated into any locomotion movement. As described above, we were particularly interested in replicating real walking, and
Translating Circular to Forward/Backward Movements
The basis for all locomotion techniques that can be employed with the VR Strider hardware is the virtual replication of the circular movement of the user’s feet. As previous studies have shown, full-body avatars have a positive effect on the user’s overall sense of presence [37] and distance estimation [27]. Therefore, our goal is to provide a believable realistic mapping between the user’s posture when using the device to synchronize the user’s proprioceptive cues with the visual feedback. Virtual movement with real bicycles or pedalling devices has previously been used for bicycle simulators [45] and non-animated locomotion [12, 16] using simple tracking techniques like revolution counters or tachometers. As this is fairly imprecise and could not be used to convincingly animate the avatar, we opted to use the reliable tracking system of the HTC Vive with its universal standalone trackers.

To animate the avatar, its torso has to first be aligned with that of the user. The avatar’s feet are then controlled with inverse kinematics (IK) by setting IK targets to the coordinates of the HTC Vive trackers. The movement depends on the rotation of the bike’s axis. To determine the speed at which the real axis (axisR) rotates, we chose to build virtual representations of the pedals and the axis (axisV). To correctly reproduce the current orientation of axisR, the offset from the tracker to the joint between pedal and axisR attachment point needs to be considered; the center of the virtual pedals needs to be offset accordingly by the same vector. In our setup the trackers have an unambiguous orientation relative to axisR, as they can only be mounted in one specific orientation to the pedal. From this information the pose of axisV can be deduced. Its position is the center point between the two virtual pedals, and its orientation is orthogonal to the trackers’ orientations.

To infer a movement, the angle between the current forward direction of axisV and the same value from the last update cycle is calculated. For this, axisV and one pedal are centered on the X-axis in the local object space of the tracking origin. This allows us to find a vector from axisV to the pedal position on a plane in space that is perpendicular to axisV’s axis of rotation. Now, this vector can be compared to the vector of the last update cycle to find a signed angle, which is necessary to determine if axisR is spinning forward or backward. The distance the avatar needs to be moved can be calculated with the formula distance = 2 × \(\pi \times radiusR \times \frac{angle}{360}\).

Animating Virtual Walking
In order to provide a convincing illusion of walking in VR, the implementation needs to be extended in two key areas: the avatar animation adapting to the current movement speed, and separating the tracking of head and feet. In this section, we approximate the human gait cycle as described by Stoeckel et al. [43] by mapping the circular pedal motion to a realistic walking animation. Prior works have explored physics-based character animations [15] and tracking-based IK feet control [11]. However, the translation of circular movement patterns to animated walking is a novel approach.

Humans have a variable gait length, which is directly dependent on the movement speed. Under normal circumstances, the faster a person walks, the longer their step lengths [21]. To replicate this correlation, we found that a two layer animation setup is the optimal choice. The basic concept is to use a generic walking animation for the entire avatar body, and apply IK overrides to the feet. We used generic walking animations from Adobe’s Mixamo service [18] to demonstrate that our setup will work with any animation for rigged humanoid avatars and can therefore be easily implemented into existing projects. A linear interpolation between a set of standing, walking, jogging and running animations was used for upper body, arms and ankles depending on the speed. For the next step, the animation needs to be synchronized to real leg movement and subsequently the current rotation of the bike axis. Instead of playing the animation blend at a certain speed, in each frame the progress of a full revolution of axisV is calculated on a scale of 0 to 1, where 0 refers to a defined default position. That value is then used to manually set the animation to a specific point in its normalized timeline. With this, the avatar animation will match the user’s leg movement as far as having the left foot on the ground when the left pedal is at its lowest point and the same for the right side.

The deficit of generic animations is their predefined gait length and optimization for a specific movement speed. In practice this means that if the calculated speed is not exactly as intended for each individual animation, the forward momentum will not match the gait length of the avatar. This results in the feet sliding over the floor. The linear blending reduces this phenomenon, but it is still easily noticeable. The solution to this problem is to again use IK overrides for the avatar’s feet.

In contrast to the translation from seated user to seated avatar, setting the IK targets directly to the tracker positions is impractical. Feet and head tracking operate in the same reference system, so their relative position to each other is always that of a seated person. As mentioned above, a separation of head and feet tracking is required. It is achieved by introducing a second virtual axis into the scene (axisV2), which copies the configuration of axisV. It is however positioned on ground level directly beneath the avatar and always faces the same direction as the avatar. The feet are then again bound to the virtual pedals by IK targets located at the ankle. This allows us to position the entire tracking space in the VE to align the camera with the standing avatar’s eyes. Hence, the view in the head-mounted display (HMD) is already from the perspective of a standing person of a fixed height.

If those IK targets were to move in the same manner as the pedals of axisV2, the feet’s movements would be described by the red circle in Figure 2 A. To closely match a real gait cycle, axisV2 has to be shifted down so that its center is exactly on ground level (Figure 2 B). Next, the IK target movement has to be limited on the Y-axis. Restricting the Y-value from being lower than ground level prevents the feet from penetrating the ground surface (Figure 2 C). On the resulting half-dome shape, a peak point is defined at maximum step height (Figure 2 D),
We implemented, tested and adjusted multiple turning mechanisms. After a first pilot test of our LUI, we received feedback that

(i) The main idea was to add pressure sensors to the bottom of the feet and detect when the user applies more force to one pedal than the other to allow natural turns while walking. The larger the difference, the sharper the turn. This method enables natural navigation that requires no additional input, similar to real-world walking.

(ii) The gaze-directed solution determines the rotation through a logarithmic function of the view direction. The turning mode is activated when looking to one side and deliberately applying pressure on the same side’s pedal. It ends when the user’s view direction is within a cone of 30° of the avatar’s forward vector. The benefit of this implementation over prior gaze-directed navigation techniques [34, 29] is the ability to look to the side while walking on a straight line, while relieving the hands from all navigation tasks.

(iii) For the hand-directed navigation, a mechanism was implemented that we called anchor-turning. While the trigger is pulled, the wand acts as an anchor for rotations. The world rotates around the user’s head in a similar way to a person sitting on a swivel chair, holding on to a fix point and turning themselves. A user can point at any object or reference point in the scene, and drag it into a different location relative to themselves. For example, pointing at a tree that is 45° to the left of the avatar’s forward direction, and dragging it 45° to the right, rotates the avatar in such a way that the tree is now to the front of the avatar. The calculation is the same as for the rotation of axisY. In the local object space of the avatar, the initial vector from the HMD to the triggering wand is compared to the current, resulting in the signed angle on the X-Z plane in world space. The angle is then inverted to turn the avatar setup in the opposite direction. For a standing avatar, the wand is anchored in the same position in world space, while the initial point keeps its relative position to the avatar and therefore turns with the user. Compared to bimanual [8, 42], gaze- [4] or pointing-based [10] navigation techniques, anchor-turning enables direct and precise single-handed turns while walking. The anchor is defined relative to the user and not the world, allowing for turns of any angle during movement. It is independent from the viewing direction and does not require a surface to point at. Therefore, it is a universal turning technique that can be applied to any seated or room-scale setup. To our best knowledge, this method of turning has neither been implemented, evaluated or published before.

Enhancing the Walking Illusion

After a first pilot test of our LUI, we received feedback that using the VR Strider still induces a feeling of bicycling rather than walking, especially when the virtual feet are not in the view of the user. To address this issue, a simple head-bumping function that uses a sine-wave for the horizontal and vertical movement of the camera was implemented and synchronized to the current rotation of the axis and therefore the animation of the avatar [35]. Furthermore, the avatar was slightly manipulated to lean backwards, bringing the virtual feet into the field of view more often. The angle to which the avatar leaned was dependent on the smoothed speed of the 30 last samples, exactly as the virtual leg radius. The result is a feeling of inertia of the field of view, which is in accordance with the real-world experience when transitioning from standing to walking and vice versa.

Turning Mechanisms

We implemented, tested and adjusted multiple turning mechanisms, which were meant to be used in conjunction or for different use cases. Besides a standard joystick input with a maximum rotational speed of 50°/s, we implemented three additional methods that are (i) purely based on foot pressure, (ii) gaze-directed with foot pressure triggers and (iii) hand-directed only, which are explained in more detail below:

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Sole Haptic Feedback

Previous works have demonstrated the positive effect of multisensory integration of visual, audio and vibrotactile feedback on the users’ sense of presence and distance perception [3, 23]. To explore the applicability of tactile feedback in simulated walking, we implemented a pair of soles that provide audio-based tactile feedback in both feet, in the medial plantar area using a haptic reactor⁷. The soles receive commands from the experiment PC, activate the actuator and reproduce pre-recorded audio files matching the properties of the material the

\[ V_2 = s \times 6 \, \text{mm}^3 \]

https://www.alps.com/prod/info/E/HTML/Haptic

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⁷: 9x10x22.6mm³
user is walking on. For example, we reproduce an amplified audio stream of steps on grass if users walk over a grass surface, simultaneously to the audio feedback on the headphones. The intensity is defined by the walking speed. An Espressif ESP32 microprocessor controls the haptic reactor through an I2S 3W Class D amplifier and also collects pressure values from an array of six force-sensitive resistors (0.5 inches diameter) distributed ergonomically across the sole, transferring pressure data to the computer at a rate of 50Hz over Wi-Fi. The actuator-to-PC latency is approximately 28 ms.

USER STUDY
In this section we describe the user study that we conducted to evaluate the VR Strider LUI. Our hypothesis was that the VR Strider would increase the users’ perception of self-motion, distance estimation and sense of presence compared to other established in-place locomotion techniques. Teleportation and joystick-based navigation were chosen for comparison, as these are among the most commonly used locomotion techniques in consumer solutions and in research [35]. Verifying our hypothesis required a test setup that allowed us to compare these vastly different interaction techniques. Therefore, we chose to design a user study based on a simple path-integration task, i.e., a triangle completion task as previously used for testing navigation performance [44]. Furthermore, we used metrics from similar previous studies that compared teleportation, joystick- and leaning-based approaches in regards to task performance (completion time and number of errors) [7]. This homing task required participants to walk in a triangle pattern. As we provide multiple options for turning in the VE, a small focus group with 5 participants was conducted to find the most usable turning mechanism of the three alternatives described in Section 3. The results indicated that anchor-turning was the preferred method of turning. Participants reportedly found it difficult to consistently apply more pressure to one pedal than the other while pedalling. As the angle error and the distance error in the triangle completion task can be assumed to not be correlated [44, 9], the performance of real head turning can simultaneously be compared with joystick turning and anchor-turning, while evaluating the distance error for teleportation, joysticks and the VR Strider. Thus, it was necessary to disable the other implemented turning mechanisms of the VR Strider setup to have exactly one method of turning per trial.

We expected the VR Strider LUI to cause less VR sickness relative to the joystick condition due to the matching of avatar animation and real leg movement, in combination with a slight head-bumping. We assumed that this would minimize the sensory conflict between visual and proprioceptive systems, which is known to cause VR sickness [24], while supporting the sensation of walking. Furthermore, we expected tactile feedback to be the most significant factor in the users’ ability to estimate distances from the wide range of parameters that can be adjusted for the bike [23], so we separated its usage as a standalone condition. Therefore, we compared Teleportation, Joystick, the bike with tactile feedback Bike FOn and the bike without feedback Bike FOff. Due to the four distinct methods, we chose a within-subject design.

Hence, we assumed the following hypotheses:

- $H_1$: Illusion of walking improves the sense of self-motion. Bike FOn has the highest reported smoothness of movements and lowest difficulty to be accurate in movements.
- $H_2$: Matching leg proprioception and avatar animation reduces sensory conflicts. Bike FOn and Bike FOff cause less VR sickness symptoms than Joystick.
- $H_3$: Cycling is closer to walking than joystick-based navigation. Bike FOn is easier to learn and use than Joystick.
- $H_4$: Tactile feedback improves distance estimation. Bike FOn has a lower distance error than Bike FOff.
- $H_5$: Illusion of walking improves distance estimation. Bike FOn has a higher sense of presence than Teleportation and Joystick.
- $H_6$: Proprioceptive feedback of leg movements improves the user’s sense of presence. Bike FOn has a higher sense of presence than Teleportation and Joystick.
- $H_7$: Anchor-turning is quick and precise. Bike FOn results in similar levels of angular errors as Teleportation.

Participants and Apparatus
20 participants ($M = 30.6, SD = 6.82, 7$ female) took part in the experiment. The mean time per participant was about 60 minutes. Unity3D was used to render the scene on an HTC Vive Pro and a non-swiveling chair to seat the participants within the tracking space for the bike and joystick conditions, and asked them to stand for the teleportation condition. Standing was required to let the participants use their full head and body proprioception for angular estimation as a baseline to test against. Depending on the condition they used an Xbox One Controller or the HTC Vive Wand for input.

Stimuli and Procedure
The experiment started with a demographic and simulator sickness questionnaire (SSQ) [22], followed by a briefing about the nature of the task and the different techniques. Before each condition, the participants were given the chance to experiment with the input device in a test trial and were afterwards asked to perform the given task. In each trial, the participant was positioned at the scene’s center. This position was defined as vertex 1 (V1) of the triangle (cf. Figure 3). V2 was always positioned 10 meters ahead of them and had an arrow marker on top that pointed to V3. After being guided to V2 and V3, participants were then tasked to move back to V1, as precisely as possible. When the participant had arrived at the estimation of V1, they confirmed by pressing a predefined button on the controller or wand. After completing all trials per condition,
the participant filled in the questionnaires described in the following section. After the experiment was finished, participants were asked to state their preferred locomotion technique and what they liked or disliked about it.

The order of the techniques was randomized for each participant, as was the order of the different triangle shape configurations. Initially, we planned to test 3 distance levels between V1 and V2, 3 distance levels between V2 and V3 and 3 angle levels between V2 and V3 like [1] for a total of 27 trials per method condition. We ultimately had to reduce this number after the pilot study because of several reports of strong VR sickness effects during the joystick condition that led to premature aborts of the entire experiment. Based on [44], we used two levels for the distance factor between V2 and V3 (5 and 10 meters), and three levels for the angle between them (60, 90 and 120°). The resulting 6 triangles were then mirrored at random to the left or right to reduce learning effects without increasing the overall number of trials. The markers consist of a semitransparent red cylinder with a height of 10 cm and a radius of 25 cm. This height was meant to make the participant look at the ground when close by to bring the avatar’s body into the field of view. The markers disappeared when stepped on. The ground in the predefined walking area was uniform as we didn’t want to introduce additional cues for orientation in form of textures or vibration patterns, benefiting some conditions more than others. Like [44] and [1], we used salient and non-salient cues as landmarks and reference points for orientation with a ring of unique geometric shapes at a distance of 16 and 22 meters from the center.

Measures
The measures we used to evaluate the techniques are based on a comparative study between teleportation, joystick and leaning for a travel task in VR [7]. This enables an indirect comparison of our technique with their described leaning locomotion technique and extends the performance findings from their travel task by analysing distance and angle estimation. Performance was measured in terms of time to complete the path-integration task, as well as the absolute distance and angle error from V3 back to the starting point V1. The time for the completion of each trial was logged from the first user input to them pressing the assigned confirmation button. Even though the comparison of the required time between instant teleportation, a joystick movement of arbitrary speed and an emulation of walking is unlikely to give insightful results, a difference between the levels of the haptics factor might be observable and was thus considered. The absolute angle error was defined as the unsigned angle between the two vectors originating from the V3, to the starting position V1 and the current position of the user respectively. To make the distance error independent of the angle error, it was not defined as the distance from the user to the starting position as prior studies did [44, 1]. Instead, the difference of the distances from V3 to the starting position V1 and the current position of the user was considered. This reflects the participant’s ability to walk the correct distance after deciding on the direction, independent of the correctness of the chosen direction.

VR sickness was self-reported with the SSQ [22], which consists of 16 items categorized in three subscales (nausea, ocu-lomotor and disorientation). Each item can be rated on a 5-point Likert scale ranging from 0 to 4. The sense of presence was self-reported with the Igroup Presence Questionnaire (IPQ) [36]. It consists of 14 items, categorized in three subscales (spatial presence, involvement and experienced realism) and one item for the “sense of being there”. Each item can be rated on a 7-point Likert scale ranging from 0 to 6. Usability was self-reported with the universal System Usability Scale (SUS) [5]. It consists of 10 items, categorized in two subscales (learnability and usability). Each item can be rated on a 5-point Likert scale ranging from 1 to 5. Additionally, an overall SUS score in a range from 0 to 100 can be calculated from the given answers. Comfort was self-reported with the Device Assessment Questionnaire (DAQ) [14]. It consists of 13 items, of which we adapted items 2, 5 and 6 to be equivalent to the comparative study of [7] and explicitly related to the split of measured performance in distance and rotation (smoothness of movements, difficulty to be accurate in movement and rotations) and added an item to measure leg fatigue. Each item can be rated on a 5-point Likert scale ranging from 1 to 5.

RESULTS
In this section, we summarize the results from the experiment. We had to exclude four participants from the analysis. One of them misunderstood the task and three of them could not finish the session because of feeling slight nausea during the joystick condition. In all three cases the participants stated to generally be susceptible to VR and motion sickness. We included all other trials from the remaining 16 participants in the analysis. Results were normally distributed according to a Shapiro-Wilk test at the 5% level. We analyzed the results with an ANOVA test and Post-hoc Tukey’s multiple comparisons at the 5% significance level with Bonferonni’s correction. Whenever the Mauchly’s test indicated a violation of the assumption of sphericity, the degrees of freedom were corrected using the Greenhouse-Geisser method. For the questionnaires only significant results are reported. The significance codes for figures are as follows: *** ≤ .001, ** ≤ .01 and * ≤ .05.

Completion Time
The results for the completion Time are illustrated in Figure 4(left). The task Time was significantly longer for Bike FOff and Bike FOn in comparison with Teleportation and Joystick, showing that Teleportation (M = 20.9 seconds, SD = 9.79) was the fastest Method. All the resulting details can be found on Table 1. This result is not surprising as teleportation provides a discrete means to cover large distances, whereas VR Strider is a continuous locomotion method.

Distance Error
The results for the Distance Error are illustrated in Figure 4(center). The Distance Error was significantly lower for Bike FOff and Bike FOn in comparison with Teleportation and Joystick, revealing that Bike FOn (M = 1.58 meters, SD = 1.33) was the Method with less Distance Error. All the resulting details can be found on Table 2. This finding confirms hypothesis H3 underlining that the proposed VR Strider LULs is superior regarding distance perception.
Angle Error
The results for the Angle Error are illustrated in Figure 4(right). The Angle Error was significantly lower for Bike FOff, Bike FOn, and Teleportation in comparison with Joystick, revealing that Bike FOn (M = 12.5°, SD = 9.41) was the Method with less Angle Error. All the resulting details can be found on Table 3. This finding confirms hypothesis H2, which underlines that the proposed anchor-turning is superior regarding spatial orientation.

VR Sickness
For the SSQ, we compared the differences from the questionnaire results gathered before and after every Method (POST-PRE). The differences were compared with a Wilcoxon signed-rank test. We found significant differences between the methods; Bike FOff (M = 1.17, SD = 25.1, p = 0.004), Bike FOn (M = -6.54, SD = 27.3, p = 0.003), and Teleportation (M = -7.01, SD = 32.8, p = 0.003) received lower VR sickness scores than Joystick (M = 44.6, SD = 43.6). The SSQ scores are illustrated in Figure 5(left). This finding confirms hypothesis H2, underlining that Bike FOn can be used for longer sessions.

Sense of Presence
For the IPQ, we used a Wilcoxon signed-rank test to compare the differences between Methods. We found significant differences between methods; Bike FOn (M = 62.6, SD = 13.9) presented the highest score, and it is significantly better than Bike FOff (M = 56.7, SD = 14.4, p = 0.018), Teleportation (M = 48.6, SD = 12.0, p = 0.003), and Joystick (M = 36.4, SD = 9.35, p < 0.001). Also, the scores for Bike FOff (p < 0.001) and Teleportation (p = 0.002) were significantly higher than Joystick. Finally, Bike FOff also presented a significantly higher score (p = 0.019) than Teleportation. The IPQ scores are illustrated in Figure 5(center). This finding confirms hypothesis H4, which underlines that leg proprioception has a strong impact on the sense of presence.

Usability
For the usability scale, we compared the questionnaire results with a Wilcoxon signed-rank test. We found significant differences between the methods; showing that Bike FOff (M = 76.4, SD = 14.9, p = 0.004), Bike FOn (M = 73.1, SD = 16.5, p = 0.014), and Teleportation (M = 74.7, SD = 16.0, p = 0.003) produced higher usability scores than Joystick (M = 57.0, SD = 15.0). Thus, according to the data, the usability scores for Bike FOff, Bike FOn, and Teleportation are similar. The SUS scores for the Learnability and Usability components are illustrated in Figure 5(right). This finding confirms hypothesis H5, which underlines that the proposed LUI is easy to learn and use.

Comfort
We analyzed the Likert ratings (1-5) related to comfort (DAQ) with an ordinal logistic regression in order to find differences between Methods. Figure 6 illustrates the distribution of responses for items with significant differences. For the required force, Bike FOff required less effort than Joystick (p = 0.021). For the smoothness of movements, Bike FOff (p < 0.001), Bike FOn (p < 0.001), and Joystick (p = 0.003) produced higher scores than Teleportation. Also Bike FOn was better than Joystick (p = 0.032). For the mental effort, Bike FOff produced a lower score than Joystick (p = 0.016) and Teleportation (p = 0.034). For the difficulty to be accurate in rotations, Bike FOff (p = 0.01), and Bike FOn (p = 0.004) produced lower scores than Joystick. For the difficulty to be accurate in movements, Bike FOff (p = 0.01), and Bike FOn (p = 0.004) produced lower scores than Joystick. For the general comfort of usage, Bike FOff (p < 0.001), Bike FOn (p < 0.001) and Teleportation (p < 0.001) produced higher scores than Joystick. The remaining scores did not present significant differences. This finding confirms hypothesis H1, underlining that Bike FOn improves the sense of self-motion.

Finally, we used a matrix of Pearson/Spearman rank coefficients in order to correlate our demographic data with the dependent variables. We found that older people were faster with the methods Bike FOff (p = 0.002), Bike FOn (p = 0.002) and the Joystick (p = 0.038). There was no correlation with 3D/Games experience. Also, participants with high experience in VR/3D/stereoscopic displays presented significantly lower distance errors for Joystick (p = 0.013) and Teleportation (p = 0.039), and lower angle errors for Joystick (p = 0.013). When asked which of the four tested locomotion devices the users preferred overall, 81.25% stated they liked the VR Strider with enabled tactile feedback the most, citing the ease of usage, the smoothness of movement and the feeling of embodiment as most important benefits. 18.75% preferred the teleportation, with the most common reasoning being the efficiency in travel, and 0% preferred the VR Strider without tactile feedback or the joystick.

DISCUSSION
The results of the study highlight the usability of the VR Strider. Regarding to task performance the proposed LUI
had a positive impact on the participants’ ability to estimate distances and rotations compared to joystick and teleportation. To begin with, we will compare the two Bike conditions.

The results for the tactile feedback condition do not reflect a positive effect on distance estimation. While the mean of the distance error was favorable with feedback enabled (Bike FOn, M = 1.58m, SD = 1.33m versus Bike FOff, M = 2.08m, SD = 1.57m), it did not amount to a statistically significant effect (p = 0.15). Thus, hypothesis H2 could not be validated. We assume that this circumstance is due to the low intensity the haptic actuator provides. This accords with reports from the open-comments section of our questionnaire, with 5 participants wishing for a stronger haptic feedback as it was too subtle while pedalling actively. We plan to solve the problem by using a more powerful surface transducer in our next hardware iteration. On the contrary, the results indicate an effect of tactile feedback on angular estimations (p = 0.044). There was no significant effect for tactile feedback regarding the time to complete the task. The means of these conditions were very close to each other, but the enabled feedback had a slight disadvantage (Bike FOn, M = 31.2 s, SD = 10.8; Bike FOff, M = 28.0 s, SD = 10.3). We attribute this to an increased feeling of embodiment, as we observed participants looking down much more frequently and closely observing their virtual feet, testing slow and fast steps during the experiment. Additionally, we found no significant differences for the self-reported VR sickness, usability or comfort for for the Bike conditions. There was however a significant effect of tactile feedback enabled (M = 62.6, SD = 13.9) versus disabled (M = 56.7, SD = 14.4, p = 0.018) on the sense of presence in the IPQ questionnaire. To summarize, tactile feedback resulted in slightly better orientation and slower walking, but not to a significant margin. The main advantage is an increased sense of presence and sense of embodiment through the feeling of impact that matches the visual representation of the feet touching the ground. Following this observation, we will only discuss the VR Strider with feedback enabled (Bike FOn) when comparing the device with Teleportation and Joystick.

As expected, the instantaneous Teleportation was the fastest technique with Joystick close behind. As previously discussed, the movement speed for the Joystick can be set arbitrarily (to a maximum of 2m/s in our case), making comparisons futile. It is noteworthy however, that participants chose to frequently observe their virtual feet when using the bike and tried different techniques like counting their steps, resulting in an overall slower progression in the task. We also found no significant difference for the distance estimation; in fact, they were almost identical (Teleportation, M = 3.45 m, SD = 2.02; Joystick, M = 3.42 m, SD = 2.10). Bike FOn on the other hand produced significantly lower distance errors (M = 1.58 m, SD = 1.33). The synchronization of proprioception through real leg movements, the visualization and tactile feedback proved to be greatly beneficial to spatial orientation. This is in accordance with prior studies that examined multisensory input and embodied translation cues [28, 23, 47]. While technical attributes like a technique’s accuracy and latency might have confounded the results, we deem them minor factors as the difference between VR Strider and teleport/joystick is enormous (means of 1.58m versus 3.45m/3.42m, p < 0.001).
For the angle error, the Joystick condition was significantly worse than any other condition, while the implemented anchor-turning performed equally as good as real head turning or even slightly better when tactile feedback was enabled. Again, the proprioception of pointing at a reference point and moving it one-to-one with the arm has helped the participants to navigate in the VE. This matches participant comments stating that the anchor-turning feels very natural.

Regarding VR sickness, our hypothesis was confirmed that the joystick would induce the most amount of VR sickness. There is no overlap of the visual input to the vestibular or proprioceptive system, leading to increased incidences of nausea, disorientation and oculomotor related symptoms. We found no significant increases from pre to post SSQ tests for Teleportation or the Bike FOn, meaning that both the pedalling and the anchor-turning do not induce cybersickness and are thus efficient and safe to use. This corresponds with studies that showed an improvement in VR sickness related symptoms when using leaning or teleportation over indirect locomotion techniques [30, 7]. By extension, the Bike FOn causes significantly less VR sickness than leaning techniques [7].

The usability for the Bike FOn and Teleportation conditions were similar. Since the teleportation technique is generally considered to be easy to learn and our device achieved similar results, we can deduce that the translation of circular movement to virtual walking is easy to learn and use. An overall mean SUS score of 73.1 indicates that it can be integrated into a variety of applications for experienced or beginner VR users alike. Sense of presence was reported highest for Bike FOn, again confirming that leg proprioception has a strong impact on the sense of presence. Thus, the attempt to create an illusion of walking in VR while in reality being seated was an overall success. The reported comfort shows the Bike FOn to be superior in the sense of smoothness of movement, required mental effort, difficulty to be accurate in movements and rotations when compared to Joystick and Teleportation. The general comfort of usage was tied between Bike FOn and Teleportation. This is in conformity with the quantitative measurements of the experiment and supports our claim for the general applicability of our device for VR experiences.

Sarupuri et al. [35] compared Walking-In-Place (WIP) to teleportation, Joysticks and TriggerWalking (TW) with respect to usability and VR sickness. They reported similar overall SSQ scores for teleportation, joysticks and WIP, and an SUS score of 69.8 for WIP. TW as a specific implementation of WIP achieved similar results as our teleportation and joystick conditions in a near-identical path integration task. This is conform with other studies that found no significant differences in distance estimation between these techniques [48]. In comparison to WIP, it can be assumed that VR Strider improves distance estimation due to the precise matching of leg proprioception and momentum. It also received higher usability ratings, in particular for leg fatigue. This suggests that a cycling motion is a closer metaphor for walking than WIP.

To summarize, Joystick is not an appropriate method of locomotion for VR experiences. Their usage resulted in high distance and angular estimation errors, and a high amount of VR sickness, while providing a low sense of presence. They lacked in usability and had a low general comfort of usage. Teleportation had an equally low rate of success for distance estimation, but real head turning was vastly superior for angular estimation. It showed less overall occurrences of VR sickness, had a better sense of presence and a higher usability score. The sense of smoothness of movements was unsurprisingly very low, but the general comfort of usage was rated significantly higher than the Joystick. The Bike FOn was the slowest tested locomotion technique, but achieved the best results in distance and angular estimation. VR sickness was comparable to Teleportation, as was the usability. However, regarding sense of presence and comfort it was rated higher than Teleportation. Overall, Bike FOn performed at least as good or better than Teleportation and Joystick in all quantitative and qualitative measures except time.

CONFIRMATORY STUDY

As described above, the VR Strider can also be applied to other forms of virtual movement. As an indicator to see how it could be used as a multi-purpose locomotion device, we conducted a confirmatory study. The goal was to test the switch from a virtual walking to a virtual pedalling experience and vice versa. For this, the pedalling implementation from Section 3 was used and applied to a virtual Go Kart as an example of a direct translation of real to virtual pedalling (see Figure 7).

7 participants were asked to walk up to the Go Kart and enter it via a button press on the wand, drive around a race track and then again exit the vehicle. In the second trial the visual representation of the pedalling was disabled and instead a motor sound was played, even though they still had to peddle to accelerate. The transition was done with a short fade-to-black when entering or leaving the vehicle from either side. With this setup we wanted to test if our device is restricted to walking and pedalling experiences, or to a more broad range of motorized vehicles. The feedback we received was generally in favor of using the manual Go Kart over the motorized version. The consensus was that the manual Go Kart worked really well and that switching from walking to driving and vice versa was a smooth and pleasant transition. Pedalling to accelerate the motorized vehicle however was described as surreal, awkward or even immersion breaking. These reports most likely infer a reduction in sense of presence.
Table 1: Omnibus/Post-hoc and descriptive results for Time.

<table>
<thead>
<tr>
<th>Main Effect</th>
<th>Effect</th>
<th>DFn</th>
<th>DFd</th>
<th>F</th>
<th>p</th>
<th>p&lt;0.05</th>
<th>( \eta^2_p )</th>
<th>( \epsilon )</th>
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<td>12.454</td>
<td>0.000</td>
<td>***</td>
<td>0.454</td>
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<td>.23</td>
<td>0.095</td>
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<tr>
<td>Angle</td>
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<td>0.243</td>
<td>.24</td>
<td>0.091</td>
<td>0.809</td>
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</tr>
</tbody>
</table>

Post-hoc Test for Method (Multiple Comparisons of Means: Tukey)

| Pair                         | Estimate | SE  | t Value | \( Pr(>|t|) \) | p<0.05 |
|------------------------------|----------|-----|---------|-----------------|------|
| Bike FOn - Bike FOff         | 3.22     | 1.50| 2.14    | 0.1415          |      |
| Joystick - Bike FOff         | -5.61    | 1.50| -3.73   | 0.0012          | **   |
| Teleport - Bike FOff         | -7.10    | 1.50| -4.72   | <0.001          | ***  |
| Joystick - Bike FOn          | -8.83    | 1.50| -5.87   | <0.001          | ***  |
| Teleport - Bike FOn          | -10.32   | 1.50| -6.87   | <0.001          | ***  |
| Teleport - Joystick          | -1.49    | 1.50| -0.99   | 0.3753          |      |

Table 2: Omnibus/Post-hoc and descriptive results for Distance Error.

<table>
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<th>Main Effect</th>
<th>Effect</th>
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<th>DFd</th>
<th>F</th>
<th>p</th>
<th>p&lt;0.05</th>
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<tbody>
<tr>
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<td>0.001</td>
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<tr>
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<td>0.002</td>
<td>**</td>
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<td>0.936</td>
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</table>

Post-hoc Test for Method (Multiple Comparisons of Means: Tukey)

| Pair                         | Estimate | SE  | t Value | \( Pr(>|t|) \) | p<0.05 |
|------------------------------|----------|-----|---------|-----------------|------|
| Bike FOn - Bike FOff         | -0.533   | 0.203| -2.63   | 0.044           | *    |
| Joystick - Bike FOn          | 1.008    | 0.203| 4.97    | <0.001          | ***  |
| Teleport - Bike FOn          | -0.219   | 0.203| -1.08   | 0.701           |      |
| Joystick - Bike FOn          | 1.541    | 0.203| 7.60    | <0.001          | ***  |
| Teleport - Bike FOn          | 0.314    | 0.203| 1.55    | 0.409           |      |
| Teleport - Joystick          | -1.227   | 0.203| -6.05   | <0.001          | ***  |

Table 3: Omnibus/Post-hoc and descriptive results for Angle Error.

This unfortunately indicates that VR Strider’s applicability is limited to experiences specifically tailored to walking or vehicles that are powered by pedalling like bicycles, GoKarts, paddle boats or airplanes with manual propellers. This needs to be confirmed in a fully controlled study, but already suggests that the hardware needs to be modified and extended to be useful for a wider range of VR experiences and thus be a universal VR input method.

CONCLUSION AND FUTURE WORK

We presented a novel LUI for VR that proved to be superior to established techniques like joysticks and teleportation in a path-integration task. We contributed the implementation as well as evidence from a user study suggesting that this approach significantly improves the sense of presence and comfort compared to joystick and teleportation. Results also showed that it does not cause more VR sickness than teleportation and is equally as learn- and usable. The provided tactile feedback further increased the users’ sense of presence and embodiment. Anchor-turning proved to be a valid and universal technique for turning in seated or standing VR experiences. The tested implementation of pressure-turning however could not satisfy participants in our pilot study and needs to be iterated on. Even though a smooth transition from virtual standing to virtual seated driving is possible, the applicability of the device is limited to virtual walking and specifically made experiences that have a direct translation of real to virtual pedalling. Other forms of virtual locomotion like motorized vehicles need a different approach as the confirmatory study indicated the necessity of synchronized avatar animations to match proprioception and the virtual representation of legs.

Following our findings in the main study, we would like to further evaluate the positive effect of our realistic cycling-to-walking animation mappings compared to generic animations and naive IK implementations. Another major remaining goal is to improve the implementation of pressure turning and strafing. This could be realized through additional joints on the pedals that enable tilting or swiveling of the feet. To address the challenges of controlling virtual motorized vehicles, we plan to modify the base hardware. The main axis of the bike could be split to make the left and right side independent, with an electronic locking mechanism that enables split and joined rotations. This setup could simulate the behaviour of pedals used for acceleration and braking in cars or yaws in aircrafts and helicopters. Building and testing the required hardware remains as a target for future work.

The implementation’s source code is available on GitHub\(^2\).
REFERENCES


