From Street to Simulator: Assessing Cyclist Movement Consistency Between Virtual and Real-World Environments

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Abstract

Virtual reality (VR) is increasingly used for cycling research, yet the fidelity of these simulations remains under-validated. We introduce a publicly available dataset of synchronized, full-body inertial measurement unit (IMU) data and egocentric video from 11 participants cycling matched 1.4 km routes in Vienna and a VR simulator. Initial analyses indicate that core cycling biomechanics are well-replicated in VR. However, significant differences emerge in upper-body motion and emotional responses. Participants exhibited greater torso rotation in VR and reported lower enjoyment compared to outdoor cycling. The dataset provides a benchmark resource for validating simulator designs and investigating embodied locomotion in VR. To facilitate research and benchmarking, the dataset and analysis tools are shared at: street2simulator.de.

CCS Concepts

• **Human-centered computing** → **Empirical studies in ubiquitous and mobile computing**; **Empirical studies in HCI**.

Keywords

Cycling Simulation, Movement Analysis, Comparative Dataset

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1 Introduction

VR cycling simulators provide a safe and controlled environment for research in urban mobility, health, and road safety. However, the extent to which these simulators replicate the nuanced physical experience of real-world cycling is largely unknown. A critical barrier to advancing simulator design and validating findings has been the lack of publicly available, high-frequency motion data comparing cyclist behavior across matched real and virtual environments.

This paper introduces a new dataset to address this gap. We present synchronized, full-body IMU recordings and video from cyclists on an identical route in both the real world and a VR simulation. We provide a brief, illustrative analysis to demonstrate the dataset's utility for investigating three central questions:

Consistency and movement characteristics: Do limb movements (pedaling rhythm, balance adjustments, coordination patterns) differ between VR and real-life cycling, and if so, when?

Immersion and simulator sickness: Do abrupt head or torso movements in VR correlate with higher reported simulator sickness symptoms? Do emotional experiences (enjoyment, frustration) differ between VR and real cycling?

Gaze behavior and visual attention: Do head movement patterns differ systematically between VR and real-world cycling? Are differences in visual attention strategies associated with subjective ratings of immersion?

2 Method

Eleven participants (9 male, 2 female; mean age = 24.4, SD = 3.7, mean height = 174.2 cm, SD = 8.5, mean weight = 68.9 kg, SD = 10.3) were recruited from a university community. All participants were regular cyclists and provided written informed consent. The study was reviewed and approved by the ethics committee of the University of Siegen under the reference number LS_ER_03_2023. Participants completed two cycling sessions: first in VR, followed by real-world cycling along a matched 1.4 km urban route in Vienna. The order of sessions was not counterbalanced. After each session, participants completed questionnaires, including the Simulator Sickness Questionnaire (SSQ) and ratings of their emotional experience (e.g., enjoyment, frustration). Data from one male participant was excluded due to technical issues, resulting in a dataset comprising 10 complete trials.

VR Simulator and Route Design The real-world cycling was conducted in Vienna, featuring realistic conditions such as curves, tramlines, and varying pavement textures. The virtual environment replicated this route using a Unity3D-based simulator equipped with a smart direct-drive trainer and a ±5° motion platform for lateral tilt. Previous research demonstrated that as little as one degree of tilt in the direction of travel enhances realism and presence without significantly increasing simulator sickness [4]. The virtual route

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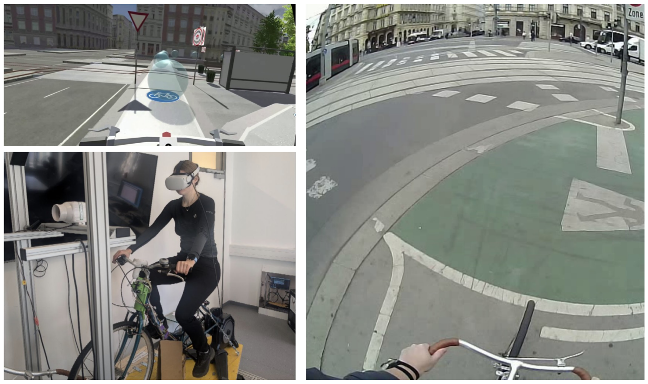

Figure 1: Our dataset comprises cycling motion data for the same route in VR (left) and in the real world (right). Participants wore 6 body-worn IMUs and an egocentric camera.

included landmarks and static obstacles, but did not incorporate dynamic traffic or pedestrians. Participants used two similar bicycles in the VR and real-world sessions, maintaining consistent seating and handlebar adjustments to ensure comparable conditions.

Data Collection and Structure We used a wearable IMU system adapted from prior equestrian research [3], capturing tri-axial acceleration and gyroscopic data at 120 Hz (±8g range). Six IMUs were placed strategically : head (mounted in VR headset and helmet), torso, forearms, and thighs. Data synchronization (within 10 ms) was managed via a Raspberry Pi carried by participants. Egocentric video was recorded at 30 fps using a head-mounted camera for the real-world session and simulation capture for VR. Data synchronization was validated post-collection through event-based alignment (e.g., initial pedaling movements).

The dataset includes synchronized raw tri-axial IMU data (120 Hz), egocentric video (30 fps), participant demographics, and questionnaire responses. In total, this comprises 20 cycling trials and 109 sensor streams (accounting for minor technical issues). Sessions averaged 153 seconds (SD = 27) in VR and 354 seconds (SD = 54) outdoors, reflecting natural variations due to traffic and environmental conditions. IMU data were consistently sampled at 120 Hz and synchronized with millisecond-level precision through centralized timestamping managed by the Raspberry Pi. Egocentric video accompanied each trial at 30 frames per second. Raw IMU data were converted to scalar magnitude signals for preliminary analysis, preserving movement intensity information for comparison across conditions. All data was collected during one week during non-rush hour traffic.

3 Evaluation

To demonstrate the dataset's utility, we performed preliminary analyses assessing technical integrity, movement fidelity, emotional response, and visual attention. Statistical analyses were primarily conducted using t-tests, acknowledging minor deviations from normality, yet considered sufficient for exploratory purposes.

For downstream analyses, we computed the Euclidean norm of each sensor's acceleration and angular velocity, reducing each tri-axial stream to a single representative signal. This transformation

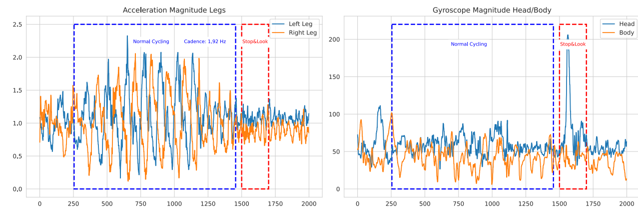

Figure 2: Clear pedaling rhythm visible in the data with an intersection and looking for traffic

preserves essential movement characteristics while simplifying comparisons. As visualized in Figure 2, inspection of these signals revealed clear periodic patterns linked to pedaling cycles, as well as characteristic movements related to balance and gaze.

Movement Consistency and Coordination A primary goal was to examine whether full-body movement patterns during cycling differ systematically between immersive VR and real-world conditions. We hypothesized that motion in VR might exhibit greater regularity due to the fixed setup. To test this, we analyzed time-series IMU data from the arms, legs, torso, and head, focusing on rhythm, coordination, and abrupt changes in motion.

We first assessed pedaling rhythm by analyzing the acceleration magnitude from the thigh-mounted IMUs. Peak detection indicated periodic motion corresponding to pedaling cycles in both conditions, as visualized in Figure 2. A statistical comparison of inter-peak intervals revealed significantly lower variance in the real-world condition ($p < 0.01$), suggesting more consistent pedaling cadence outdoors. The frequency of the pedaling was not significantly different between conditions (p: 0.115).

To examine limb coordination, we computed the cross-correlation coefficients between the left and right leg IMU signals to quantify bilateral synchronization. Contrary to our initial expectations, there was no significant difference (p: 0.813) in the average temporal alignment between limbs. Nevertheless, outdoor cycling showed slightly lower variation in limb synchronization, suggesting a more stable bilateral pedaling pattern in real-world conditions.

Upper-body motion was analyzed using data from the forearm and torso-mounted IMUs, focusing on both translational acceleration and rotational movement. While no significant differences (p: 0.842) were found in the acceleration variability of the upper body between VR and real-world conditions, significant differences ($p < 0.01$) emerged in rotational motion patterns. Specifically, the variability of upper-body gyroscopic rotation was higher in the VR condition compared to outdoor cycling. The torso rotation signal exhibited a lower standard deviation in the real-world condition ($p < 0.05$), indicating more stable control. These findings suggest that although overall body sway remained similar across conditions, participants experienced greater rotational instability in VR, potentially reflecting subtle balance adaptations or sensorimotor mismatches induced by the virtual environment.

Overall, results indicate that VR cycling successfully reproduces many fundamental motor patterns of real-world cycling, but subtle differences occur in upper-body rotational control. Although limb synchronization was largely comparable across conditions and appeared to be more influenced by individual differences than by the environment itself, participants exhibited greater variability in torso rotation during VR cycling. This increased rotational instability may reflect adaptations to the virtual environment's visual-vestibular constraints or the fixed base of the simulator. These findings highlight the importance of high-resolution motion data in detecting fine-grained movement differences and support the use of this dataset for evaluating the fidelity and embodied realism of immersive locomotion simulations.

Simulator Sickness and Emotional Response To better understand how body motion in VR influences user experience, we examined the relationship between sensor-derived movement patterns and subjective reports of simulator sickness and emotional engagement. Participants completed a structured post-simulator questionnaire rating their symptoms across dimensions of nausea, dizziness, eyestrain, headache, fatigue, sweating, difficulty focusing, and disorientation, using a 5-point scale ranging from *None* to *Severe* [2]. Participants also rated their sense of presence, immersion, control, and emotional engagement using Likert-type scales.

Contrary to our initial expectations, analyses of head motion variability and the frequency of abrupt head movements showed no significant correlations with Simulator Sickness Questionnaire (SSQ) scores ($r = -0.63$, $p = 0.37$). Furthermore, no significant differences were found between participants with low versus high sickness scores in head movement variability ($p = 0.87$) or abrupt movements ($p = 0.34$). While previous research has often linked abrupt movements to simulator discomfort [1], our findings did not show this relationship. For our specific short cycling task, other factors such as individual susceptibility or subtle visual-vestibular mismatches may be more critical determinants of SSQ scores than the gross motion metrics we captured.

Beyond physical discomfort, we explored how emotional experiences differed in both environments. Post-session ratings revealed that participants reported higher feelings of enjoyment and confidence during the real-world cycling sessions. Conversely, frustration levels were significantly higher during VR cycling. We also examined whether torso movement stability during VR cycling was associated with participants' reported feelings of control or enjoyment. However, our correlation analyses found no significant links. The results from this part of the analysis show that the immersive simulation, despite providing a physically similar task, did not fully replicate the positive emotional engagement associated with outdoor cycling.

Visual Attention and Immersion Head movement is a key indicator of visual attention and immersive engagement in first-person locomotion tasks such as cycling. Using head-mounted IMU data, we examined gaze direction patterns and their relationship to self-reported immersion and presence. Analysis of head orientation dynamics, including angular velocity and displacement, showed participants engaged in natural environmental scanning behaviors outdoors. However, our study revealed that the range of yaw angles was significantly higher in the VR condition compared to the real-world setting ($p < 0.05$), indicating that participants engaged in broader lateral head movements while cycling in the simulated environment. Furthermore, the overall frequency of head-turn events per minute was not significantly different ($p = 0.43$). These findings suggest that while the overall frequency of scanning behavior remained similar across contexts. Participants in VR demonstrated a tendency for more exaggerated or exploratory head rotations, possibly reflecting differences in environmental cues or visual search strategies induced by the virtual simulation.Contrary to assumptions about reduced sensory complexity limiting visual exploration in VR, these results indicate that participants actively engaged in exploratory gaze behaviors within the simulated environment. Interestingly, participants who reported higher immersion scores did not show significantly different head movement patterns compared to those reporting lower immersion.

We further investigated whether head motion smoothness, defined as the inverse of high-frequency angular velocity changes, was related to simulator sickness symptoms. Our analysis revealed no significant differences (p: 0.53) in head motion smoothness between the VR and real-world conditions. Additionally, no significant correlation (r: -0.245, p: 0.526) was found between head motion smoothness in the VR condition and participants' simulator sickness scores. The findings indicate that visual behavior in VR cycling differs from real-world cycling, but these observable differences in head movement did not directly link to subjective ratings of immersion or simulator sickness in our study.

4 Discussion and Conclusions

This paper contributed a publicly available dataset, designed to facilitate research on the fidelity of VR cycling simulations. Our analysis highlights the types of insights that can be drawn from this resource, revealing a clear difference: although VR successfully reproduces fundamental locomotor movements, it alters complex motor control strategies and associated user experiences.

The increased torso rotation and broader head movement range observed in VR suggest potential shifts in motor control strategies. Without the rich kinesthetic and vestibular feedback of real-world balancing, participants may adopt a compensatory strategy, relying more heavily on upper-body and head movements to navigate and maintain orientation. The reported decrease in enjoyment and increase in frustration in VR aligns with this physical disconnect, suggesting that a lack of full-body sensory integration impacts emotional engagement. We did not find a direct relationship between our motion metrics and Simulator Sickness Questionnaire (SSQ) scores. Given the limited sample size, this result could reflect a Type II error, or it may indicate that short cycling experiences are more influenced by other factors, such as individual susceptibility or visual realism, rather than gross motion characteristics alone.

These findings must be interpreted within the context of several important limitations. The absence of counterbalancing means we cannot exclude potential order effects influencing subjective responses. Additionally, the differing complexity between environments is a significant factor, restricting the generalizability of the results to more complex traffic situations. Also the sample size also limits the generalizability of the dataset.

In conclusion, this work transparently presents both a novel dataset and its limitations. The clear takeaway is that a significant fidelity gap exists between real and simulated cycling, particularly in the replication of holistic, full-body coordination. We offer this dataset as a robust benchmark for the community to validate simulator designs, explore the nuances of embodied interaction, and develop more ecologically valid virtual environments for research.

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