The Impact of Bike-Based Controllers and Adaptive Feedback on Immersion and Enjoyment in a Virtual Reality Cycling Exergame

Jonas Keppel
University of Duisburg-Essen
Essen, Germany
jonas.keppel@uni-due.de

Marvin Strauss
University of Duisburg-Essen
Essen, Germany
marvin.strauss@uni-due.de

Shuoheng Zhang
University of Duisburg-Essen
Essen, Germany
shuoheng.zhang@stud.uni-due.de

Markus Stroehnisch
University of Duisburg-Essen
Essen, Germany
markus.stroehnisch@stud.uni-due.de

Stefan Lewin
University of Duisburg-Essen
Essen, Germany
stefan.lewin@stud.uni-due.de

Uwe Gruenefeld
GenerIO
Essen, Germany
uwe@generio.ai

Donald Degraen
HIT Lab NZ, University of Canterbury
Christchurch, New Zealand
donald.degraen@canterbury.ac.nz

David Goedicke
University of Duisburg-Essen
Essen, Germany
david.goedicke@uni-due.de

Andrii Matviienko
KTH Royal Institute of Technology
Stockholm, Sweden
andriim@kth.se

Stefan Schneegass
University of Duisburg-Essen
Essen, Germany
stefan.schneegass@uni-due.de

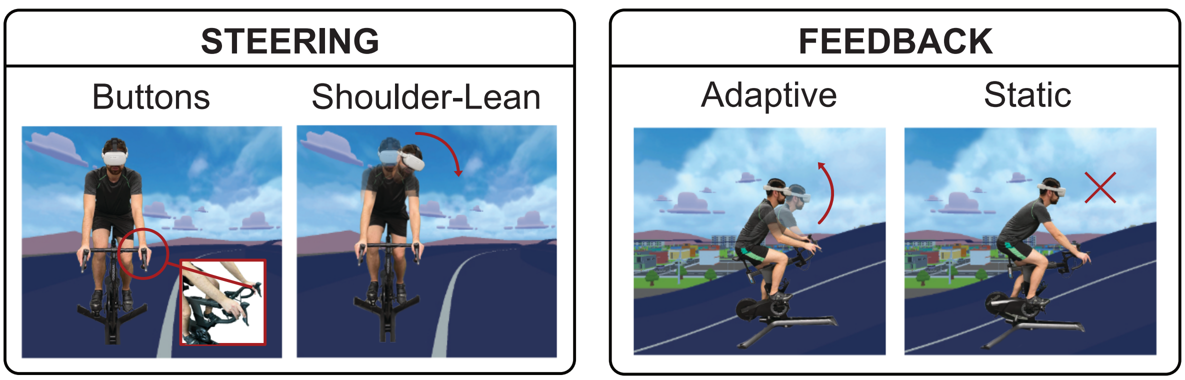

Figure 1: Interaction with a bike-based controller in a VR cycling exergame. The left side illustrates two input techniques for steering through a turn: button steering and shoulder-lean steering. The right side shows two output techniques while riding uphill: adaptive feedback with changes in bike inclination and resistance, and static feedback with a fixed bike angle and no change in resistance.

Abstract

Cycling exergames can increase enjoyment and promote high energy expenditure, making exercise more engaging and, therefore, supporting healthier lifestyles. To improve player experience in a virtual reality cycling exergame using a stationary bike, we investigated how different input and output techniques affect player engagement. We implemented a bike-based controller integrating button and shoulder-lean steering as input, combined with or without adaptive changes in bike inclination and resistance as output. The results of our study with 24 participants indicate that adaptive modes increase effort and perceived exertion. While button steering provides better pragmatic quality, shoulder-lean steering offers a more hedonic experience but requires more skill and effort. Still, this greater enjoyment fosters higher engagement, particularly when players enter a flow state where the increased physical demands become less noticeable. These findings underscore the potential of bike-based adaptive controllers to maximize player engagement and enhance VR cycling exergame experiences.

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CCS Concepts

• **Human-centered computing** → **Virtual reality**; *Interaction techniques*; • **Applied computing** → *Consumer health*; *Computer games*; • **Computing methodologies** → Virtual reality.

Keywords

Exergame, Cycling, Virtual Reality, Sports, Physical Activity, Exertion, Health, Feedback, Controller

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1 Introduction

Regular exercise is crucial for reducing health risks, and indoor cycling has become a popular, effective option. It improves health markers like aerobic capacity, blood pressure, body composition, and lipid profiles, including cholesterol [11, 12, 58]. However, cycling is often seen as monotonous, decreasing motivation for regular activity [57]. Integrating entertainment, such as video games, presents an opportunity to make exercise more engaging [47]. Exergames, which combine gaming with physical exertion, have shown promise in areas like rehabilitation, obesity prevention, and weight loss [27, 44, 55, 56] and offer virtual experiences simulating activities like hiking, swimming, walking, and cycling [1, 4, 13, 22, 61]. Cycling exergames, in particular, enhance motivation to exercise [30, 32, 38, 62] and their popularity has increased due to its convenience, enjoyment, and competitive aspect, especially during the COVID-19 pandemic when platforms like Zwift attracted millions of users [46, 66]. While Zwift primarily relies on a display screen for visual feedback, research suggests that exergames leveraging virtual reality (VR) can provide even higher levels of immersion [17, 53, 63]. This potential for deeper engagement has made VR exergaming a significant area of research [19, 36, 40]. Prior studies have focused on enhancing immersion through various game elements, yet there remains a gap in understanding how bike-based controller interactions influence player engagement, especially for commercial off-the-shelf devices, which facilitate the feasibility of such experiences for home use.

To explore the effects of different input and output techniques of bike-based controllers on player experience, we implemented an Exergame using multiple input methods (buttons, pedals, brake, and shoulder-lean steering) combined with or without adaptive changes as output (bike inclination and resistance). We conducted a study with 24 participants to compare two steering techniques, button versus shoulder-lean steering, and the presence or absence of adaptive bike adjustments. The study focused on evaluating player immersion, VR sickness, enjoyment, effort, perceived exertion, and task performance, such as steering to specific objects on the track. Our results show that adaptive modes lead to higher effort and perceived exertion. While button steering offers higher pragmatic quality, shoulder-lean steering provides a more enjoyable, hedonic experience but demands greater skill and effort.

2 Related Work

Exergames [44] effectively combine video gaming with exertion [2, 16, 29, 54, 55]. They are widely studied across fields such as rehabilitation [27, 45], obesity prevention [16, 62], and weight loss [20, 55, 56, 65]. Thereby, players engage in various sports like hiking [22], swimming [13, 35], walking [61, 62], and cycling [1, 4, 23, 25, 41, 51, 64]. Integrating video games into physical activity routines, such as stationary cycling, can improve health outcomes. Warburton et al. [57] have shown that combining gaming with exercise had a 30% higher attendance rate, a 13% increase in aerobic power, and a significant reduction in blood pressure. These results indicate that pairing interactive video games with cycling can boost engagement and yield greater health benefits than traditional exercise alone. Furthermore, cycling exergames increase the intensity of physical activity and motivate users to exert [6]. Monedero et al. [43] showed that interactive cycling video games are more enjoyable and lead to a decrease in negative feelings about high-intensity exercise. Thus, interactive cycling video games are a motivating alternative to conventional exercise.

Cycling does not often align with traditional video game inputs, such as controllers, buttons, and keyboards, and provides more natural interactions. McGloin and Embacher [38] examined whether controllers' naturalness and the perceived game realism can predict users' sense of immersion in exercise-based virtual environments. Their findings support that greater immersion enhances overall enjoyment during exercising, which was also supported by Shaw et al. [52]. In another study, McGloin et al. [39] explored how video game realism and controller naturalness affect a user's level of aggression. They varied the realism of the game and the naturalness of the controller by using different games and controller types. Their findings showed that greater perceived naturalness enhanced the game's realism, leading to increased immersion. While McGloin et al.'s work primarily examines the psychological aspects of immersion and realism in gaming, Kassim and Said [30] explored practical integration of VR technology in exercise. They introduced an innovative VR cycling game and found that their prototype can make physical activity more engaging and potentially improve fitness levels. But when aiming for off-the-shelf equipment, these usually only support button press steering [31], since manufacturers seldom support rotatable handlebars [37]. This limitation prompts the exploration of body movement-based steering tracked by cameras. Although cycling exergames often operate on predominantly straight tracks [2], where the road is followed automatically and button presses are used to change lanes [46, 64, 66] or avoid (moving) obstacles [1, 23, 41], this design choice constrains the immersive potential of VR cycling. Steering, whether through button inputs [31] or body-based methods such as shoulder leaning [52], enables free navigation and was therefore explored in prior work. Changing resistance and inclination was found to enhance immersion [59] and is now supported by some fitness machines, enabling exploration of this feedback modality in commercial devices. The novelty of our work lies in directly comparing these modalities, focusing on enjoyment of the input and output techniques.

3 Evaluating the Impact of Bike-Based Controllers in VR Cycling Exergames

To explore the potential of VR exergames for immersive workouts with natural controllers for cycling, we investigate how different bike-based controllers affect the user experience in a VR cycling exergame regarding input and output. Therefore, our research question is: *What is the impact of bike-based controllers on players' immersion, perceived exertion, and enjoyment in VR cycling exergames utilizing off-the-shelf devices?*

3.1 Study Design and Apparatus

Our study is a within-subjects design with two independent variables: (1) STEERING (*Button* vs. *Shoulder-Lean*) and (2) FEEDBACK (*Static* vs. *Adaptive*), see Figure 1. By combining all levels of independent variables as 2x2 design, we created four game modes as our experimental conditions incorporating our steering and feedback levels, see Table 1.

To conduct our study, we implemented a VR cycling game to accommodate the four conditions. For this, we used the Wahoo KickR Bike[1] with programmable buttons, variable inclination and pedaling resistance, but immovable handlebar. It supports a two-way communication via the Fitness Machine Service (FTMS) Bluetooth protocol[2] and enables data exchange between the bike and the VR system. For the leaning steering, we tracked the participants' posture, allowing leaning left or right [21]. To achieve this, we positioned an HD webcam facing the bike and utilized the OpenCV[3] and MediaPipe[4] libraries in Python to detect the user and track key body parts, such as the head and shoulders. By analyzing the tracked positions, we determined the extent to which the user leaned their shoulders in either direction. For button-based steering, a longer button press resulted in a stronger steering effect, allowing for gradual or sharp turns based on the duration of the input. For shoulder-lean steering, a greater shoulder angle translated into stronger steering, providing a direct mapping between the user's body posture and the in-game navigation. The resulting steering data is then transmitted via our local network to the exergame.

The VR exergame was developed using the Unity engine and deployed on the Meta Quest 2 headset. It is a racing game that features a track with obstacles, curves, inclines, declines, and extended straight paths leveraging the Unity asset Karting Microgame[5]. We also added collectible pins along the track as an additional gamification element to enhance user engagement during the race (Figure 2). Long straight sections were employed to reduce VR-induced motion sickness, often triggered by sudden turns, and to provide a balanced, intermediate level of difficulty. The game is designed to receive data via Bluetooth on speed of the real-world bike as input to change the players in-game speed and button presses for steering. Further, it adjusts its inclination and resistance according to the track conditions as output.

[1]KickrR Smart Bike: https://www.wahoofitness.com/devices/indoor-cycling/smart-bikes/kickr-bike-buy, last visited on 23/01/2025
[2]FTMS Bluetooth Protocol: https://www.bluetooth.com/specifications/specs/fitness-machine-service-1-0/, last visited on 23/01/2025
[3]OpenCV: https://opencv.org/, last visited on 23/01/2025
[4]MediaPipe: https://developers.google.com/mediapipe/solutions, last visited on 23/01/2025
[5]Karting Microgame: https://assetstore.unity.com/packages/templates/unity-learn-karting-microgame-urp-150956, last visited on 23/01/2025

Table 1: Overview of Conditions Leading to Four Game Modes

Game Mode	STEERING	FEEDBACK
1.	Button	Static
2.	Button	Adaptive
3.	Shoulder-Lean	Static
4.	Shoulder-Lean	Adaptive

Figure 2: In-game view of our exergame for a bike-based controller in first-person perspective, showing the bike, an upcoming left turn, and a target to hit (bowling pin).

3.2 Procedure and Measurements

After collecting participants' demographic data, they self-assess their VR, cycling, and exergaming experience using Likert items with a scale ranging from -3 (never) to 3 (very often). To tailor the bike to each participant's physical specifications, we measured their leg lengths and adjusted the bike accordingly to ensure both safety and the potential for maximum performance. A three-minute warm-up and introduction round was conducted to help participants understand the game goals and to prevent injuries. Participants then played the exergame under each of the four conditions defined by our study's game modes for three minutes each. The order of these modes was determined using a Latin square design to minimize sequence effects. After each run, participants completed questionnaires about their VR experience.

The Igroup Presence Questionnaire (*IPQ*) was used to assess perceived immersion [3, 5, 50], the Virtual Reality Sickness Questionnaire (*VRSQ*) to measure well-being and discomfort during VR interaction [33]. Enjoyment and user experience were evaluated using the short User Experience Questionnaire (*UEQ-S*) [49], effort was assessed using the Intrinsic Motivation Inventory (*IMI-EF*) [18, 34, 48], and Borg's Rating of Perceived Exertion (*Borg-RPE*) to measure perceived exertion [7, 8]. During each study run, we evaluated participants' ability to control the bike within the game environment, where their additional task was to hit pins serving as obstacles, a task requiring precise control and coordination. The number of *Pins Destroyed* was recorded to provide insights into how different control methods and levels of immersive adaptation affected players' in-game behavior.

To obtain qualitative feedback, after the study participants answered the following questions: (1) "Do you think a bike-based controller is suitable for a VR exergame? Why?", (2) "Which control pattern did you find most and least effective in your gaming experience? Why?", (3) "If you could freely choose features, what aspect of the system would you change? Why?".

3.3 Ethics

For conducting this study, we adhered to the ethical guidelines of our institution and obtained approval from our ethics committee. Before participation, we provided each participant with a comprehensive explanation of the study procedure and obtained their written and informed consent. All questions regarding the procedure were thoroughly addressed before its commencement. Participants were required to pedal and exert physical effort; however, the duration of exertion was limited to a few minutes. To mitigate the risk of injury, a brief warm-up was conducted before the main activity. All recorded interviews were manually transcribed, pseudonymized, and subsequently deleted upon the conclusion of the project.

3.4 Participants

We recruited 24 participants[6] through university mailing lists, 12 identifying as women, 11 as men, and 1 preferred not to answer. Ages ranged from 19 to 35 years ($M = 25.7, SD = 3.82$ years). None of the 24 participants had physical restrictions to ride on a stationary indoor bike. Participants rated their experience with VR ($M = -2, SD = 1.96$) and Exergames ($M = -2.00, SD = 1.82$) as low. However, participants rated themselves as having average experience in cycling ($M = 0.50, SD = 1.84$).

3.5 Data Analysis

We used an Aligned Rank Transform (ART) for non-parametric analysis of variance, given the two independent variables with dependent groups (i.e., repeated measures) [15, 60]. We followed with two-way repeated measures ANOVA tests to analyze the effect of *Steering* and *Feedback* on *IPQ Total Score, VRSQ Total Score, UEQ-S Total Score, IMI Effort Total Score*, and *Borg-RPE Score* and their various subscores using Bonferroni correction. These subscores include, for the *IPQ*, *Spatial Presence*, describing the sense of being physically present in the virtual environment, *Involvement*, measuring the attention devoted to the virtual environment and the involvement experienced, and *Experienced Realism*, assessing the subjective experience of realism in the virtual environment. For the *VRSQ*, the subscores comprise *Oculomotor*, evaluating general discomfort, fatigue, eyestrain, and difficulty focusing, and *Disorientation*, capturing symptoms such as headache, fullness of the head, blurred vision, dizziness (with eyes closed), and vertigo. Lastly, the *UEQ-S* subscores measure both the *Pragmatic Quality* and *Hedonic Quality* of the system. We only report the significant results of main and interaction effects, and in this case provide effect sizes for post hoc tests, quantified using Cohen's d.

4 Results

4.1 Presence

The *IPQ Total Score* revealed no significant main or interaction effects. However, analysis of the subscores indicated a significant main effect for *Spatial Presence*, with participants experiencing higher spatial presence when using button steering compared to shoulder-lean steering ($F(1, 69) = 4.78, p = 0.032, d = 0.45$).

[6]We conducted an a priori power analysis using G*Power for a repeated-measures within-factors ANOVA ($f = .25$, $\alpha = .05$, $1 - \beta = .8$) based on the four different game modes (number of measures), yielding $\lambda = 12.0$, $F = 2.74$, numerator df = 3, denominator df = 69.

4.2 VR Sickness

The *VRSQ Total Score* showed no significant main or interaction effects. However, for the *Disorientation* subscore, a significant main effect was found, indicating that disorientation was higher in the adaptive feedback mode compared to the static mode ($F(1, 69) = 4.66, p = 0.034, d = 0.44$).

4.3 Enjoyment

The *UEQ-S Total Score* showed no significant main or interaction effects. However, for the subscores, a significant main effect was observed for *Pragmatic Quality*, which was higher for button press steering ($F(1, 69) = 18.2$, p<0.001, d = 0.87). Additionally, a significant main effect was found for *Hedonic Quality*, which was higher for shoulder-lean steering ($F(1, 69) = 21.5, p < 0.001, d = 0.95$). These findings can be contextualized by comparing them to the UEQ-S benchmark [26], as illustrated in Figure 3.

4.4 Perceived Effort and Exertion

The *IMI-EF Total Score* (see Figure 4a) revealed a significant main effect, indicating that perceived effort was higher in the adaptive feedback condition compared to the static condition ($F(1, 69) = 4.98, p = 0.029, d = 0.456$). The *Borg-RPE Score* (see Figure 4b) revealed a significant main effect, showing that perceived exertion was higher in the adaptive feedback condition compared to the static condition ($F(1, 69) = 14.5, p < 0.001, d = 0.778$).

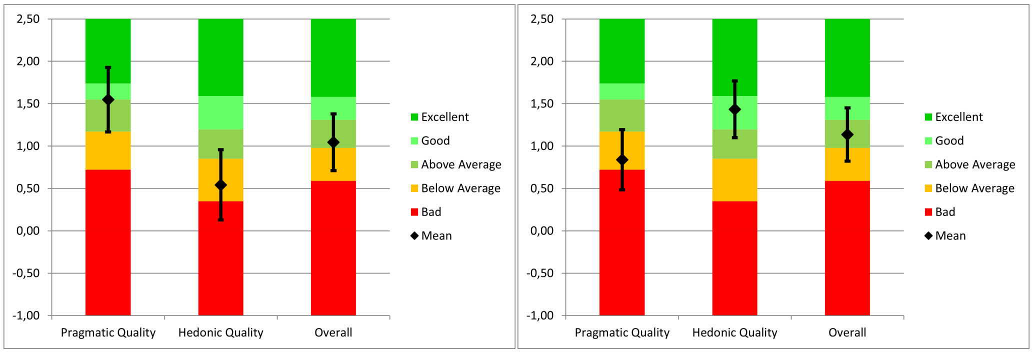
4.5 In-Game Behavior

A significant main effect was found for the number of hits, indicating that participants hit more pins using button steering compared to shoulder-lean steering, suggesting that button steering was preciser ($F(1, 69) = 20.69, p < 0.001, d = 0.93$). Additionally, a second significant main effect was observed here, with more hits recorded in the static condition than in the adaptive condition, indicating that steering was preciser in the static conditions ($F(1, 69) = 5.09, p = 0.027, d = 0.46$).

4.6 Qualitative Results

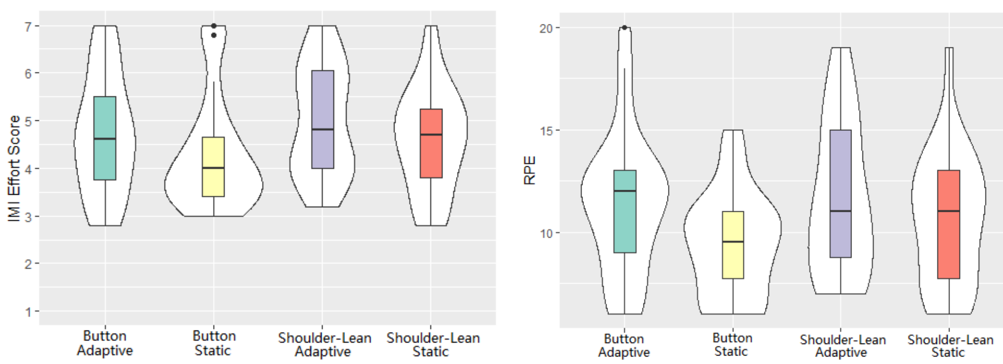
After all four conditions, we asked participants about the overall appropriateness of the bike-based controller, the level of control experienced by users, and potential areas for input system enhancements. The interviews were audio-recorded and transcribed verbatim. Then, we applied Reflexive Thematic Analysis following Braun and Clarke [9, 10], which allows for inductive code and theme generation. The first and third author utilized open coding and afterward discussed the codes to deduct three themes describing key findings of the interviews:

4.6.1 ***Theme 1: Suitability of the Bike-Based Controller***. Participants generally found the bike-based controller suitable for VR exergaming, enhancing immersion and enjoyment. P15 stated: "*The immersion is powerful. The bike tilts up and down, feels like riding a real bike.*" Many noted that the adaptive feedback and shoulder-leaning, while challenging, added a fun element, making the experience engaging despite the increased effort. P6 said, "*it is highly suitable for VR exergames because it is fun and provides a realistic*



(a) ***Button Steering*.** **(b)** ***Shoulder-Lean Steering*.**

Figure 3: Relative Quality Benchmark for the UEQ-S by using *Button Steering* and *Shoulder-Lean Steering*.



(a) IMI-Effort. **(b) Borg-RPE.**

Figure 4: Boxplots illustrating effort and rating of perceived exertion for each game mode.

experience, thus creating immersive scenarios." They preferred a hedonic experience, even if it involved minor disorientation or reduced spatial presence. While some participants favored buttons for their practicality, others appreciated the immersive realism offered by shoulder-leaning and adaptive feedback. The physical challenges, like resistance changes during uphill cycling, were seen as realistic and enjoyable, contributing to a sense of achievement and flow during gameplay. This flow state was mentioned by P3 "*Time flew by as I was cycling, and I definitely got a good workout.*" and similarly by others, e.g. P6 and P4. Overall, the bike-based controller was valued for making exercise more engaging and enjoyable compared to conventional methods.

4.6.2 ***Theme 2: The Sense of Control*.** Participants' perceptions of control significantly influenced their enjoyment of the game. Preferences varied, with some favoring game modes with button steering for its effective control. Limited control, particularly during bike tilting or sensitive shoulder-lean steering, reduced enjoyment for some. Shoulder-lean steering was seen as more natural by some but also more mentally demanding, especially when combined with other game elements like slope changes or obstacles. Button steering, while less physically demanding, could interrupt immersion and focus. The cognitive load was also a key factor, as controlling shoulder movements while navigating complex tasks increased mental exertion for some participants. On the other hand, some found the added physical challenge while tilting or using shoulder-leaning enjoyable despite feeling less secure. P20 stated "*Although I perceive higher insecurity using shoulder-lean, it still provides the most enjoyable game experience in combination with adaption.*" Overall, the sense of control played a critical role in shaping participants' preferences and overall enjoyment in the exergaming experience.

4.6.3 ***Theme 3: Potential Improvements to the Input and Output System*.** Participants suggested enhancements for more intuitive and immersive controls. A commonly recommended improvement was incorporating a rotatable handlebar to better simulate real biking, which participants felt would enhance immersion and encourage longer play sessions. P2 stated: "*A rotatable handlebar would more authentically replicate real biking [...].*" Suggestions for refining *Shoulder-Lean Steering* included increasing sensitivity for better movement detection and adding lateral tilt to mimic real-life biking dynamics. Alternative methods, such as using head movements, body tilt, or a combination of reduced shoulder movement with a rotatable handlebar, were also proposed. Additional features like drifting, attacking, or jumping, controlled via gestures or foot motion, were mentioned to make gameplay more engaging. Overall, participants showed strong interest in refining the steering mechanism and enhancing physical dynamics to create a more realistic and immersive experience.

5 Discussion

5.1 Steering Choices: Balancing Ease of Use with Engagement

The choice of steering mechanism in VR exergames significantly affects user experience and engagement. While button steering was perceived as easier to use, many participants agreed that shoulder-lean steering contributed to a higher fun factor and increased engagement. Given that the core objective of exergames is to motivate users to engage in physical activity, we suggest incorporating body-based approaches similar to shoulder-lean steering despite its challenges. This method not only promotes physical activity by engaging more muscle groups but also leads to greater enjoyment and, consequently, higher engagement. However, this recommendation must be considered carefully, as implementations like shoulder-lean steering may enhance VR sickness. Although the duration of our conditions might have been too short to reveal statistical differences in VR sickness, qualitative feedback from interviews suggests that this steering method feels less secure, thereby reducing the sense of control. Research by Mittelstaedt et al. [42] highlighted that VR, especially with head-mounted displays (HMDs), is associated with higher sickness scores compared to other display methods, such as large screens. Additionally, Matviienko et al. [37] found that steering methods like handlebar turning resulted in less VR sickness without compromising cycling performance [59], but manufacturers did not adopt this innovation yet. The main drawbacks of rotatable handlebars in consumer devices include increased cost and mechanical complexity, and reduced stability, which may not suit athletes focused on high-performance sport rather than immersive experiences. Nonetheless, our findings combined with previous research suggest that while shoulder-lean steering can increase engagement and enjoyment, its potential to induce VR sickness must be carefully managed. Strategies like gradual adaptation to shoulder-lean movements or using a combination of steering methods could mitigate these effects, ensuring that the advantages outweigh the potential drawbacks.

5.2 Adaptive Feedback: Enhancing Challenge and Realism in VR Exergames

Adaptive feedback, such as dynamic changes in bike resistance and inclination, significantly impacts perceived effort and exertion. Our findings show that both effort and perceived exertion were higher in adaptive feedback modes. Despite this, we still recommend using adaptive feedback for VR cycling exergames, given the primary goal of these games is to promote physical activity and healthy lifestyles. While these adaptive elements are challenging, they were seen by participants as adding a fun element, making the experience more engaging despite the increased effort. Participants perceived physical challenges, like resistance changes during uphill cycling, as realistic and enjoyable, which aligns with the aim of promoting fitness through exergames. Moreover, according to our qualitative results, as mentioned by multiple participants, the experience of adaptive feedback appears to support players in entering a state of "Flow," a concept described by Csíkszentmihályi as a state of deep absorption where self-awareness diminishes, and time perception becomes distorted [14]. This state is often associated with high levels of immersion and increased enjoyment and engagement. When participants reach a flow state during gameplay, they might perceive the increased effort less intensely, enhancing their overall experience while training more. However, while adaptive feedback may contribute to disorientation, research suggests that reducing tilt intensity below real-world levels could mitigate these effects [59].

6 Limitations

We acknowledge several limitations in our study. Although we ensured a gender-balanced participant group, our selection process at the university introduced a bias, predominantly involving younger individuals. For the more natural steering condition, we utilized shoulder-leaning, which has been explored in related work [59]. However, other natural steering methods, such as using a dynamic handlebar, might have yielded different results. While shoulder-leaning was sufficient for our racing game, it may not be suitable for other games or interactions that require additional body or limb movements. Additionally, our feedback mechanism only included a forward and backward tilt, without considering lateral tilting [59]. We also did not incorporate airflow to simulate headwind, as it has been done in similar studies [37]. Furthermore, we assessed the concept of flow through hedonic enjoyment measures and qualitative interview feedback. To gain a deeper understanding, future work should build on this by incorporating more specific measurement tools, such as established flow state questionnaires [24, 28], and physiological measurements such as heart rate or power output to validate the impact of adaptive feedback on workout intensity. Lastly, future research could explore strategies to balance realism with comfort, such as identifying thresholds for subtle micro-adjustments or integrating haptic cues that remain below conscious awareness.

7 Conclusion

This study explored the effects of different input and output techniques on engagement, immersion, and enjoyment in a VR exergame using a stationary bike. Our results show that both steering methods and adaptive feedback shape the user experience. Button steering offers ease of use, while shoulder-lean steering provides higher engagement and enjoyment, although with greater physical demands and a risk of VR sickness. To maximize engagement and physical activity, body-based controls like shoulder-lean steering should be implemented carefully to mitigate these risks. Adaptive feedback, through dynamic changes in bike resistance and inclination, increases perceived effort, aligning with the exergame goal of promoting physical activity. While it introduces more physical challenges, it also enhances realism and can help players reach flow states, where effort feels less intense. Thus, adaptive feedback can boost engagement if balanced with player comfort. Overall, our findings highlight the potential of bike-based adaptive controllers to enhance engagement and enjoyment in VR exergames.

Acknowledgments

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