Swansea University

College of Engineering

Master’s Degree in Virtual Reality

IMMERSIVE VR FOR HAND-ARM CYCLING REHABILITATION WITH INTEGRATED PHYSIOLOGICAL FEEDBACK

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Abstract

This study introduces the design and testing of a new VR hand-arm cycling prototype to improve upper limb aerobic rehabilitation using Meta Quest 3s and Polar H10 integration. Addressing the gap of existing VR rehabilitation studies, especially related to the lack of aerobic focus, real-time physiological feedback, and home-based accessibility, the system uses Unity to simulate a gamified hand-crank mechanism to dynamically adjust difficulty according to heart rate (HR) and heart rate variability (HRV), within 50-120% HRR. A pilot study involving 15 people across Easy, Medium, and Hard levels provided evidence of efficacy with 100% completion in the easier modes, mean SUS 83.3, minimal SSQ change 4.6, IMI Enjoyment 4.2, and near-perfect HR-RPM correlation (R2=0.947). These results exceed benchmarks from current studies, showing enhanced feasibility, usability, comfort, engagement and physiological adaptation. This low-cost design supports unsupervised home use, although limitations in pilot-scale use, and the challenges of Hard mode (46.7% completion), suggest refinements. Contributions are a scalable, personalised VR platform, with implications for clinical integration and improved patient adherence. Future work recommends bigger trials, longitudinal testing and ergometer hybridization to take this intelligent rehabilitation tool further.

Declaration

Statement 1

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Statement 2

This dissertation is the result of my own independent work/investigation, except were otherwise stated. Other sources are acknowledged by giving explicit references. A bibliography is appended.

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I hereby give consent for my dissertation, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed: Prasanna Kumar Mahendran **Date:** 30/09/2025

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Abbreviations

- ARAT: Action Research Arm Test
- CI: Confidence Interval
- DDA: Dynamic Difficulty Adjustment
- ECG: Electrocardiogram
- HMD: Head-Mounted Display
- HR: Heart Rate
- HRR: Heart Rate Reserve
- HRV: Heart Rate Variability
- HUD: Heads-Up Display
- IMI: Intrinsic Motivation Inventory
- MAPE: Mean Absolute Percentage Error
- NASA-TLX: NASA Task Load Index
- PIS: Participant Information Sheet
- PQ: Presence Questionnaire
- PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
- REPL: Read-Eval-Print Loop

1. Introduction

1.1 Background and Context of the Work

Virtual reality (VR) is increasingly used in rehabilitation to improve engagement and outcomes. This project builds on a collaboration between Cardiff Metropolitan and Swansea Universities exploring accessible, sensor-enhanced VR therapy. Motivated by this, I developed a VR hand-arm cycling system using Meta Quest 3s and Polar H10 to make exercise more engaging and adaptive. Repetitive therapy often leads to low adherence, but evidence shows VR increases motivation and effectiveness (Saussez et al. 2023; Vibhuti et al. 2023). By integrating real-time heart rate and HRV feedback, the system adjusts difficulty to keep exercise within safe, therapeutic ranges, supporting personalised, home-based rehabilitation for those with limited mobility or neurological conditions.

Physical therapy is associated with repetitive activities that can be tedious to the patient, which may cause lower compliance and inadequate doses of treatment. Traditional hand arm cycling, which is done on ergometers, has clinical utility in enhancing upper-limb strength, endurance, cardiovascular fitness, especially among patients with mobility difficulties, spinal cord injuries, or stroke (Banduni *et al.* 2023). It can however discourage long-term rehabilitation efforts as it can be quite repetitive. VR helps with this by integrating exercises into interactive, gamified settings that encourage patients with visual and audio cues, so they can better perceive that their therapy is not a chore, but an enjoyable process. Current developments in VR technology such as lightweight HMDs and fine-grained motion tracking have made it possible to conduct the simulation of exercises, such as hand-arm cycling, without any bulky physical equipment-reducing costs and making it more accessible (Cheng, 2024).

In the past few years, research on VR in rehabilitation has grown significantly. A search of the term "virtual reality AND rehabilitation" in PubMed and Scopus returns over 400 results from 2015 to 2025, with a notable increase in clinical trials and review studies. These studies point to the effectiveness of VR in enhancing the motor activity, endurance, and patient activity levels in any condition, such as stroke, Parkinson disease, and musculoskeletal disorders (Vibhuti, Kumar and Kataria, 2023). VR-based interventions have shown promise in promoting motor recovery by leveraging real-time feedback and task-oriented training—principles aligned with neuroplasticity, such as repetition, salience, and adaptivity (Kuipers et al., 2025). For example, Saussez et al. (2023) conducted a randomized controlled trial using a semi-immersive VR system within the HABIT-ILE protocol for children with unilateral cerebral palsy. Participants completed goal-directed upper-limb tasks in interactive virtual environments, receiving immediate visual and auditory feedback on movement accuracy and completion. Over 15 sessions, the VR group showed significant improvements in manual dexterity and bimanual coordination, comparable to conventional therapy. The structured, engaging tasks encouraged high repetition and active participation, key drivers of cortical reorganisation. This supports the use of VR to create motivating, neuroplasticity-driven rehabilitation experiences. Nonetheless, the available studies are condition-specific or target lower-limb physical activities, whereas less emphasis has been on the upper-limb aerobic exercise such as hand-arm cycling. In addition, though physiological monitoring is included in some of the studies, few studies use real-time HR/HRV to vary exercise intensity, which is an essential element in the safety and efficacy of therapeutic effects (Kuipers *et al.* 2025).

The value of the work is in the possibility to fill methodological and technical gaps in the rehabilitation research in VR. Available literature does not record longitudinal compliance data on a personal level or incorporate physiological feedback to facilitate a customized therapy. This dissertation builds on current research by designing a practical VR-based hand-arm cycling system for rehabilitation, using evidence from recent studies to guide its development (Lii et al., 2022). Unlike some theoretical proposals, this work provides a clear, functional blueprint using accessible technology, Unity, Meta Quest 3s, and Polar H10, to support real-world use. It also addresses real issues like cybersickness, using design strategies such as stable visual environments and minimal motion to reduce discomfort. Usability is considered throughout to ensure the system can be used by people with different abilities. By linking VR exercise to real-time heart rate and HRV feedback, the project shows how hand-arm cycling can become more engaging, safely monitored, and tailored to individual needs, offering a measurable and motivating therapy option.

1.2 Aim and Research Questions

Aim

To deliver a thematic literature review and a practical and implementable system design demonstrating how immersive VR hand-arm cycling with physiological feedback can improve engagement, achieve appropriate exercise intensity, and support measurable rehabilitation outcomes in general physical therapy contexts.

Research Questions

- RQ1 (Feasibility): Can typical users complete timed level segments (targets) without adverse events?

- RQ2 (Usability/Workload): Is the system perceived as usable and not overly demanding?
- RQ3 (Comfort): Does the rotating-world locomotion keep cybersickness low?
- RQ4 (Engagement/Presence): Do participants report meaningful presence and motivation?
- RQ5 (Physiology–Behaviour link): Do HR/RR change systematically with pedalling intensity (RPM) and level difficulty?

Hypotheses (directional, pilot-level)

- H1: Completion rate ≥80% for Easy/Medium.
- H2: SUS ≥ 68 (average usability benchmark).
- H3: SSQ increase from pre→post is small (no clinically concerning rise).
- H4: Presence and self-reported engagement increase with difficulty, while workload rises moderately.
- H5: Mean HR positively correlates with mean RPM within participants.

1.3 Significance of the Work

The dissertation aims to explore the potential of immersive virtual reality (VR) in physical rehabilitation by designing a VR-based hand-arm cycling system that integrates real-time physiological feedback. By combining accessible technology, such as the Meta Quest 3s, Unity, and the Polar H10, it seeks to address current limitations in engagement and personalisation during upper-limb aerobic exercise. The integration of VR with real-time physiological feedback—such as heart rate (HR) and heart rate variability (HRV), using accessible technologies like Unity, the Meta Quest 3, and the Polar H10 sensor, addresses key gaps in current rehabilitation research. While studies have shown that physiological monitoring can support exercise prescription and engagement in therapy (Chen et al., 2023), few have explored its use within immersive, low-cost VR systems for upper-limb aerobic training. This project investigates how such integration could enhance patient motivation, help maintain optimal exercise intensity, and provide objective, quantifiable feedback during hand-arm cycling. By doing so, it aims to support more personalised and engaging rehabilitation, particularly for individuals with deconditioning or limited lower-limb mobility.

The existing rehabilitation practices fail to address issues related to patient compliance in most cases because of the boredom associated with repetitive exercises such as hand-arm cycling. The proposed system in this study will turn these exercises into immersive ones, gamifiable, which makes use of the potential of VR to be more motivating and can be maintained over a long time period (Kuipers *et al.* 2025). Integrating the current evidence (2015-2025) of Scopus and PubMed-listed research, the dissertation gives a detailed overview of the effects of VR on the motor ability, endurance, and usability and adds to the theoretical knowledge on the use of VR in the treatment.

Dynamic adjustment of difficulty through integration of physiological feedback through the Excite-O-Meter plugin allows exercises to be maintained within safe and effective intensity ranges (e.g., 50 -70% HRR). This covers a methodological shortcoming experienced in the current research on VR which tends to lack real time responses to physiological signals. Also, the equipment-free, low-cost design further improves accessibility and renders the system applicable in clinical and home-based environments (Lii *et al.* 2022). The work is practically applicable because it identifies the risk, such as cybersickness, and proposes mitigations to it. Finally, this dissertation can provide a scalable blueprint that can integrate technical innovation and clinical needs, clearing up the path toward future studies on personalized and physiology-driven VR-based rehabilitation systems.

1.4 Structure for the Dissertation

To present the use of immersive virtual reality (VR) in hand-arm cycling rehabilitation, this dissertation is structured into five chapters with the view of exploring the topic systematically. Chapter 1 provides the context of VR in physical therapy with the introduction of the background, aims, objectives, and significance of the study. Chapter 2 provides the thematic review of the literature based on the synthesis of Scopus- and PubMed-indexed studies (2015-2025) on the effects of VR on the outcomes of rehabilitation, exercise intensity, safety, and gaps in methodology. Chapter 3 presents the proposed VR hand-arm cycling system blueprint, including the description of its design and the use of Unity, Meta Quest 3s, and Polar H10 as physiological feedback, its implementation specifics, and anticipated results. Chapter 4 critically analyses the strengths, limitations, and comparison to the available VR tools of the system, as well as recommendations on the future work. The final part of Chapter 5 is a conclusion, which is the summary of findings, contributions to VR rehabilitation, and some recommendations on how to promote physiology-driven systems. They have technical details and a user manual presented as appendices.

Chapter 2: Literature Review

2.1 Introduction to the Chapter

This review synthesizes existing evidence on the application of immersive virtual reality (VR) to physical rehabilitation, with a specific emphasis on upper-limb exercise and physiological feedback. Based on peer-reviewed articles between 2015 and 2025 included in Scopus and PubMed, it discusses major advances in VR-based therapy, especially involving head-mounted displays such as the Meta Quest. The review is organized into three thematic areas: (1) effectiveness of VR in enhancing motor function, endurance, and patient participation in upper-limb rehabilitation; (2) the application of real-time physiological signals, e.g., heart rate (HR) and heart rate variability (HRV), to monitor and adjust exercise intensity; and (3) design aspects of the system, such as usability, gamification, dynamic difficulty adjustment, and mitigation of cybersickness. Through examining recent studies, this chapter recognizes gaps in prevailing strategies, most notably the unavailability of combined, responsive, and inclusive VR solutions for aerobic rehabilitation. The outcomes will directly impact the development of a VR hand-arm cycling system that is motivating, safe, and personalized to patient requirements.

2.2 VR in Upper-Limb Rehabilitation – Effectiveness and Patient Engagement

Virtual reality (VR) is applied more and more in physical rehabilitation to facilitate recovery of upper-limb function, especially for patients with stroke, cerebral palsy, spinal cord injury, or deconditioning. Through its ability to place patients in interactive, gamified contexts, VR recharacterizes repetitive therapeutic exercises as enjoyable tasks that facilitate motor learning, neuroplasticity, and compliance. Head-mounted displays like the Meta Quest have brought immersive VR within reach, making home-based and clinic-delivered therapy feasible and cost-effective as well as motivational. The strength of VR is its capacity to provide task-specific, repetition-intensive training, fundamental principles of motor recovery, in a manner that sustains patient interest through real-time feedback, challenge, and reward.

Current studies underscore VR's beneficial effects on engagement and function. Rodrigues *et al.* (2025) conducted a systematic review of VR-based telerehabilitation for post-stroke upper-limb recovery and found that immersive environments significantly enhance patient motivation and autonomy. However, they noted a limited number of high-quality studies, suggesting the field is still emerging. Warland *et al.* (2019) piloted a low-cost VR gaming system (Personalised Stroke Therapy) in 12 stroke survivors and found high levels of enjoyment (mean 8.1/10) and enhanced upper-limb function, as evidenced by Fugl-Meyer Assessment and

ARAT. Participants also demonstrated increased spontaneous use of affected limb on everyday activities, which is evidence of functional transfer. Herne *et al.* (2022) investigated immersion in a desktop virtual reality system known as Neuromender, with four stroke survivors utilizing the system for 12 weeks. All 15 of the design principles tested, e.g., feedback, challenge, motivation, and usability, were rated as engaging, with feedback being identified as a strong motivator of prolonged use. Isbel *et al.* (2024) also asserted this by demonstrating that stroke survivors reacted differently to different VR scenarios, stressing the importance of personalisation to ensure long-term participation.

These studies employed a variety of methods, from mixed-methods designs through pre-post evaluations and qualitative interviews. Warland *et al.* (2019) utilized the Fugl-Meyer Assessment (impairment), ABILHAND (activity), and Motor Activity Log-28 (use in daily life), in addition to the Borg Scale for effort and Likert scales for enjoyment. Herne *et al.* (2022) employed participant self-report on game design principles and semi-structured interviews. Isbel *et al.* (2024) integrated quantitative measures, the User Satisfaction Evaluation Questionnaire and adapted Intrinsic Motivation Inventory, with thematic analysis of interviews. Rodrigues *et al.* (2025) adopted PRISMA 2020 guidelines, comparing design, safety, and engagement across databases.

The results are highly applicable to this project. They attest that VR may enhance motor performance as well as patient participation, particularly when exercises are significant, accommodating, and enjoyable. Aspects such as real-time feedback, unambiguous goals, and modifiable difficulty are invariably associated with greater compliance. These findings directly apply to the design of the envisioned VR hand-arm cycle system: embedding visual and auditory feedback, progressive challenge, and user-centred design will be crucial to maintain motivation. A number of gaps, however, remain. First, the majority of studies address fine motor control or reach tasks, but not aerobic upper-limb exercise such as hand-arm cycling. Second, although participation is quantified, long-term adherence information is scarce. Third, while personalisation is advocated (Isbel *et al.* 2024; Herne *et al.* 2022), few systems dynamically adjust in real time to individual requirements. Lastly, most studies employ non-immersive or desktop-based VR, losing the full potential of HMD-based immersion.

Only Warland *et al.* (2019) used a console-based system, but not a fully immersive HMD like the Quest 3. This highlights an opportunity: developing a fully immersive, gamified, and adaptive VR system for aerobic upper-limb training that addresses engagement through personalisation and real-time responsiveness. By targeting hand-arm cycling, a hitherto unexplored field in VR rehab, this project seeks to address an important gap in affordable, effective, and physiology-based rehabilitation for persons of limited mobility.

2.3 Monitoring and Managing Exercise Intensity Using Physiological Feedback

Exercise intensity has to be carefully controlled in rehabilitation for purposes of safety, efficacy, and personalization. For neurological or mobility-impaired patients, performing at inappropriate intensities—too low to be of any value or too high to be safe, can slow progress or present risk. Having correct, real-time feedback is important then. Heart rate (HR) is one of the most common physiological markers of exercise intensity that is frequently utilized to prescribe and modify aerobic training in target ranges (e.g., 50–70% of heart rate reserve for moderate intensity) (Reed and Pipe, 2016). Heart rate variability (HRV), a measure of autonomic nervous system activity, gives further information about fatigue, recovery, and levels of stress, and is useful for the long-term management of training load (Djaoui *et al.* 2017). Combined, HR and HRV give objective, quantifiable information that can inform safe and adaptive rehabilitation.

There are several studies that validate the monitoring of these parameters using wearable devices. Dooley *et al.* (2017) compared the validity of wrist-worn devices (Apple Watch, Fitbit Charge HR, Garmin Forerunner 225) with criterion measures (chest strap HR monitor and metabolic cart). The authors reported that HR values from the Apple Watch and Fitbit were largely accurate at light, moderate, and vigorous intensities, with mean absolute percentage errors (MAPE) less than 7% and 17%, respectively. Yet, energy expenditure predictions were less accurate, with MAPE greater than 100% in certain instances. This points out that although HR tracking in consumer wearables is accurate, metabolic computations are still erratic. Chong *et al.* (2021) showed that long-term HR monitoring using smartwatches was able to measure improvements in health over time, indicating decreases in body fat and increases in muscle mass in subjects who exercised regularly. Their results validate the use of wearable-derived physiological data for long-term health monitoring. Djaoui *et al.* (2017) also further established the utility of HR and HRV in tracking training load in athletes, adding that resting HR and HRV are excellent predictors of recovery status and fatigue, essential factors in rehabilitation where overwork needs to be prevented.

These studies utilized controlled exercise protocols and longitudinal monitoring. Dooley *et al.* (2017) employed a treadmill protocol with established intensity stages, comparing wearable outputs to gold-standard equipment with Bland-Altman analysis and repeated-measures

ANOVA. Chong *et al.* (2021) gathered data on daily activities and organized exercise over weeks, using regression analysis to match HR trends against body composition change. Djaoui *et al.* (2017) provided a critical appraisal of the literature, with an emphasis on their applied sports context but with obvious relevance to clinical populations.

The results have significant applications in this project. They confirm the use of wearable sensors, such as chest straps such as the Polar H10, in obtaining precise HR data during exercise. Since wrist devices may display variability, particularly with dynamic motion, a chest strap provides better reliability (Dooley *et al.* 2017). This justifies using the Polar H10 in the forthcoming VR system through the Excite-O-Meter plugin in Unity. Real-time HR values can be utilized to maintain exercise below recommended aerobic zones as per clinical recommendations (Reed and Pipe, 2016). Also, HRV can guide session adaptation according to the user's physiological readiness, preventing fatigue and facilitating sustainable training.

Yet, main gaps exist. Most research targets healthy or sports populations, rather than rehabilitation populations. Few studies explore the use of real-time HR/HRV for dynamically adapting VR-based therapy. Although Wright *et al.* (2017) point out the ability of consumer monitors to revolutionize physiological research via ongoing real-life data collection, rehabilitation systems have yet to employ this data interactively. None of the reviewed studies applied closed-loop feedback, wherein VR difficulty automatically alters with HR or HRV. Additionally, incorporating this type of data into immersive platforms such as Meta Quest 3 is not well explored.

2.4 System Design, Usability, and Safety in Immersive VR Rehabilitation

Successful design of effective immersive virtual reality (VR) rehabilitation systems involves maintaining a delicate balance among clinical efficacy, user motivation, and technical usability. While there is the potential of VR to gamify repetitive therapy and place the patient within an immersive setting, success hinges on the ability of the system to accommodate the physical, cognitive, and affective requirements of the patients. Core design principles are intuitive interaction, adaptive difficulty, real-time feedback, and minimization of negative effects like cybersickness. These are particularly relevant for patients with neurological impairment or mobility impairments, who may have difficulties with coordination, attention, or spatial perception. An optimized VR system must match therapeutic objectives with user experience so that the technology aids, instead of slowing down rehabilitation progress.

Current research emphasizes the need for safety and usability in VR rehabilitation experiences. Lim *et al.* (2023) tested an Oculus Rift-powered fishing game with brain-injury patients and observed no severe adverse events but reported dizziness in some users, prompting one to suspend use. Overall, satisfaction was intermediate (54%), but subjects who had attended three or more sessions scored significantly higher on all measures of perceived effectiveness, ease of learning, and challenge level. This implies that perceived benefit and usability have a strong impact on compliance. Likewise, Roussou *et al.* (2024) evaluated two VR programs that integrated motor and cognitive exercises in stroke patients with the Oculus Rift S. The system performed well in terms of appropriateness (median SEQ: 61), with only slight confusion reported in one instance and otherwise good acceptability and safety despite the limited sample size. These results support that immersive VR can be acceptable and safe when developed taking into consideration patient limitations.

User-driven design is essential to system efficacy. Castillo *et al.* (2024) iteratively play tested VR exergames centred on upper-limb actions, including elbow flexion and shoulder rotation, with stroke survivors to improve them. Over the course of four sessions, feedback resulted in enhancements of control responsiveness, visual feedback, and task clarity. The resulting system was a success, demonstrating that meaningful, adjustable tasks promote engagement. Zanatta *et al.* (2022) systematically reviewed 68 studies and concluded that VR is largely seen as motivating and flexible, yet users found high mental effort and a steep learning curve, considering the requirement for simplicity and intuitive design. Zhou *et al.* (2021) created a VR system for breast cancer patients and had excellent usability (SUS: 90.5), high immersion (PQ: 113.4), and very low cybersickness (SSQ total: 2.53), showing that well-designed VR worlds can be safe and highly usable.

Standard assessment procedures include the System Usability Scale (SUS), Simulator Sickness Questionnaire (SSQ), Presence Questionnaire (PQ), and qualitative interviews. These tools facilitate the evaluation of critical factors like comfort, user-friendliness, and immersion. Successful design elements include task-specific contexts (e.g., carpentry, fishing), adaptive difficulty, easily understood feedback, and stable visual worlds. These findings directly guide the creation of the proposed VR hand-arm cycling system. With the Meta Quest 3, the system will feature intuitive hand tracking, low-latency visuals, and soothing virtual worlds to mitigate disorientation. Gamified ride paths and real-time performance feedback will encourage long-term use.

Gaps still exist despite encouraging findings. Numerous studies have small sample sizes and short-term use, with sparse information regarding long-term compliance or home use outside of supervision. Few systems incorporate real-time physiological feedback to adapt dynamically to challenge. This project aims to overcome these gaps by creating an independent, adaptive VR system that is safe, motivating, and accessible for long-term rehabilitation use.

2.5 Identifying Research Gaps and Justifying This Study

Literature review identifies the following important findings that collectively endorse the establishment of immersive virtual reality (VR) as a useful tool in upper-limb rehabilitation. To begin with, VR has universally proved to enhance patient interest, motivation, and compliance with therapy. Research indicates that gamified, interactive settings make repetitive exercises more engaging, resulting in greater time-on-task and improved therapeutic outcome, especially in stroke and brain-damaged populations (Lim et al., 2023; Herne *et al.* 2022; Isbel *et al.* 2024). Second, physiological monitoring through heart rate (HR) and heart rate variability (HRV) is a reliable and clinically useful measure of exercise intensity and autonomic regulation. Equipment like the Polar H10 provides precise, real-time data to inform safe and efficient training (Dooley *et al.* 2017; Chong *et al.* 2021). Yet, though it holds promise, real-time physiological feedback is not often implemented within VR rehabilitation systems to dynamically modulate exercise difficulty. Third, usability and safety are essential to effective implementation. Evidence supports that properly designed VR systems, systems with intuitive interfaces, adaptive difficulty, and stable imagery, can both be safe and extremely usable, with low cybersickness and high user satisfaction (Zhou *et al.* 2021; Zanatta *et al.* 2022). Clear instructions, meaningful tasks, and personalized experiences also contribute to increased engagement and accessibility.

There are still large methodological and technical gaps despite these developments. Most VR rehabilitation research addresses fine motor skills or task-specific training with minimal emphasis on aerobic upper-limb activity like hand-arm cycling. Additionally, although physiological monitoring is common, few systems leverage HR or HRV information to provide real-time dynamic difficulty adjustment (DDA), a principal component for individualising intensity and supporting therapeutic zones (e.g., 50–70% HRR). Furthermore, most current systems incorporate external supervision or sophisticated hardware, making it difficult for them to find applications in home-based, unsupervised settings. Low-cost, portable solutions integrating immersive VR, motion tracking, and biofeedback without physical ergometers are also lacking.

This project fills these gaps directly by suggesting an operational, evidence-based VR system created in Unity for the Meta Quest 3, incorporating real-time HR/HRV feedback from the Polar H10 through the Excite-O-Meter plugin. Through hand-arm cycling simulation through motion tracking and virtual environment adaptation according to physiological response, the system facilitates safe, enjoyable, and personalized aerobic training. It supports the growing need for personalised, scalable, and home-deliverable rehabilitation, particularly for individuals with limited mobility. In doing so, it contributes to the evolution of VR from a motivational tool to an intelligent, adaptive therapy platform grounded in clinical and technological best practices.

2.6 Chapter Summary

This chapter has explored the current state of research in immersive VR for upper-limb rehabilitation through three key thematic areas. First, VR has been reported to improve patient motivation, participation, and motor outcomes substantially, especially when exercises are gamified and goal-directed. Second, physiological monitoring with heart rate (HR) and heart rate variability (HRV) provides a valid, objective measure of exercise intensity and fatigue, with wearable devices such as the Polar H10 offering valid real-time data—although their incorporation into adaptive VR systems is still limited. Third, design of the system, usability, and safety are essential for effective implementation; research underscores the need for intuitive design, cybersickness prevention, and user-centric development to provide access across various patient populations.

In combination, the literature validates the efficacy and therapeutic promise of immersive VR in rehabilitation. It also identifies unambiguous gaps, most notably the absence of adaptive, physiology-based VR systems for aerobic upper-limb training and the necessity for low-cost, transportable alternatives for use at home. It directly guides the subsequent stage of this research. Chapter 3 describes the development of a VR hand-arm cycling prototype created in Unity to the Meta Quest 3, with real-time biofeedback and dynamic difficulty adjustment. This system takes the evidence considered herein and uses it to deliver a safe, interesting, and tailored rehabilitation process based on clinical and technological best practice.

Chapter 3: Methodology and System Design

3.1 Introduction

This chapter outlines methodology used in the development and evaluation of a virtual reality (VR) Unity-based prototype for hand-arm cycling rehabilitation using the Meta Quest 3 headset and Polar H10 sensor for real-time physiological monitoring. The main purpose is to systematically state the design and testing processes with the aim of alignment to the overall research aim and questions stated in Chapter 1.2, i.e., to create an adaptive and engaging system that improves upper limb rehab using immersive VR and biofeedback.

The scope covers two important aspects, namely, the technical progression in Unity, including integration of physiological feedback mechanisms in order to dynamically adapt the intensity of the exercise; and second, a structured user testing protocol in order to test the feasibility, usability, comfort (e.g., cybersickness mitigation), engagement, and physiological responses such as heart rate variability. This approach is based directly on the literature review in Chapter 2, where there have been studies such as Saussez et al. (2023) about the motivational benefits of VR and Rodrigues et al. (2025) about the efficacy of telerehabilitation, to justify design decisions that aim to ensure engagement, safety and personalised adaptation in order to fill gaps identified in aerobic upper limbs therapy.

3.2 System Design and Development

3.2.1 System Overview

The VR hand-arm cycling prototype built in Unity for Meta Quest 3 makes use of the Polar H10 sensor and the Excite-O-Meter plugin to provide real-time heart rate (HR) and heart rate variability (HRV) feedback to create an engaging, safe and adaptive rehabilitation system. This design responds to gaps observed in Chapter 2, namely a shortage of immersive, physiology-driven VR systems for aerobic upper-limb exercise (Rodrigues et al., 2025). The system is aimed at individuals who have limited mobility, in an effort to improve motivation and compliance using gamified, personalized therapy, whilst ensuring that exercise intensity remains within the clinically recommended range of 50-70% heart rate reserve (HRR) (Reed & Pipe, 2016).

The basic mechanic consists of a virtual hand-crank that, when the user pedals, rotates a small planet-like landscape underfoot a stationary user, simulating forward motion without physical translation. This approach was inspired by Quintana et al. (2024), which prioritizes visual stability to reduce cybersickness, which is a critical issue for VR rehabilitation (Zhou et al.

2021). By rotating the world instead of the player, the system reduces any vection-induced discomfort so it is accessible to people with neurological or mobility impairments.

Key features include a minimalist, head-locked heads-up display (HUD) that displays real-time session metrics: revolutions per minute (RPM)/cadence, a countdown timer and status banners that indicate level transitions (e.g., start, success, or fail). The prototype works at three different difficulty levels, Easy, Medium and Hard, each level defined by time targets based on accumulated world rotation (degrees). These levels include gamification features, such as well-defined goals and feedback, to enhance engagement, which is consistent with findings by Hsieh et al. (2025) about the motivational effect of structured, rewarding tasks.

To fill in the lack of real-time physiological adaptation described in Chapter 2.3, the system dynamically adjusts the difficulty based upon HR/HRV data from the Polar H10, streamed via the Excite-O-Meter plugin. This is to ensure that exercise remains in safe, therapeutic intensity zones which will prevent overexertion of the individual while promoting efficacy (Dooley et al. 2017). Additional cybersickness mitigations include a stable horizon, reduced rotation speeds and low-latency visuals, informed by Zhou et al. (2021), making the system intuitive and comfortable for a range of patient populations. This design creates a scalable, low-cost blueprint for home-based rehabilitation, which increases accessibility and adherence long-term.

3.2.2 Hardware and Software

The hardware and software components chosen for the VR hand-arm cycling prototype focus on accessibility, reliability, and seamless integration to support immersive and physiology-based rehabilitation. This configuration provides for low-cost deployment that can be used in home or clinic settings, together with the need for accurate real-time data in VR environments as highlighted in Chapter 2 (Dooley et al. 2017; Lii et al. 2022). The Meta Quest 3 is the primary VR headset, and it provides standalone operation, removing the need for tethered PCs, increasing portability and independence for users. It also has a high refresh rate, enabling smooth motion rendering, which is essential for minimizing latency in hand-tracking interactions.

The Polar H10 chest strap delivers accurate heart rate (HR) and R-R interval (RR) information via Bluetooth and allows you to monitor your exercise intensity and autonomic response. Validation studies have shown it to be more accurate than wrist-based wearables with mean absolute percentage errors under 5% for dynamic activities (Dooley et al. 2017). This choice counteracts motion artifacts that occur with arm-based exercises such as hand-cranking and helps to ensure reliable physiological feedback for dynamic difficulty adjustment (DDA).

On the software side, Unity 2022.3.57f1 LTS provides the basis for development with the Universal Render Pipeline (URP) optimised performance on standalone devices. OpenXR and Meta XR SDKs provide cross-platform VR compatibility and the XR Interaction Toolkit manages intuitive hand-tracking for the virtual hand-crank mechanic. The Excite-O-Meter plugin, an open-source Unity tool (Quintero et al. 2022), integrates the physiological data streaming from the Polar H10, which logs important data at 1 Hz into CSV files (time, RPM, HR, RR, level ID, and success/fail states). This plugin provides the ability for real-time analysis and visualization of heart activity allowing for adaptive features such as HRR-based DDA to stay within 50-70% intensity zones (Reed and Pipe, 2016).

Table 3.1: Summary of Components and their Roles

Category	***Component***	***Key Specifications/Features***	***Rationale/Reference***
Hardware	Meta Quest 3	Standalone VR headset; seated use; 90 Hz refresh rate; hand-tracking support	Portable, low-latency immersion (Lii et al. 2022)
Hardware	Polar H10 Chest Strap	Bluetooth HR/RR monitoring; 1 Hz sampling; ECG-accurate	Reliable for dynamic exercise (Dooley et al. 2017)
Software	Unity 2022.3.57f1 LTS	URP for rendering; OpenXR/Meta XR for VR; XR Interaction Toolkit for inputs	Versatile development for standalone XR (Quintero et al. 2022)
Software	Excite-O-Meter Plugin	Real-time physiological streaming; CSV logging (time, RPM, HR, RR, etc.); data visualization	Enables adaptive biofeedback in Unity (Quintero et al. 2022)

The rationale of such a stack focuses on affordability and ease of use: the Quest 3 and Polar H10 are consumer-grade (under GBP500 combined), in contrast to expensive clinical ergometers, and on par with the scalable VR rehab of Lii et al. (2022). By yielding more accurate chest-strap accuracy over less accurate wrist chest-strap options (Dooley et al. 2017), the system provides for safe, data-driven personalization bridging the gap of physiological integration.

3.2.3 Design Choices and Rationale

Design of the VR hand-arm cycling prototype was guided by Chapter 2 evidence, where engagement, usability, safety, and physiological adaptation were prioritized to cover gaps in immersive VR rehabilitation. The locomotion system uses world rotation, with a planet-like landscape spinning under a standing user, instead of translating the player. This option, following the lead of Lim et al. (2023), reduces vection, a main contributor to cybersickness, through the use of a stable visual reference, important for users with mobility or neurological impairments and who can be easily disoriented.

Minimalistic, head-locked heads-up display (HUD) shows RPM, countdown timer, and level status banners, providing for legibility and comfort. Zanatta et al. (2022) emphasize that clean interfaces minimize cognitive load, making the product more usable for various populations. Gamification is done using three levels of difficulty (Easy, Medium, Hard), each with timed world-rotation goals and explicit feedback through success/fail banners. This mirrors Herne et al. (2022), where they discovered that goal-oriented, structured tasks with prompt feedback greatly enhance engagement and motivation in VR therapy.

Dynamic Difficulty Adjustment (DDA) uses real-time heart rate (HR) feedback from the Polar H10, streamed through the Excite-O-Meter plugin, to adjust rotation targets and keep exercise intensity in the 50–70% heart rate reserve (HRR) zone (Reed & Pipe, 2016). This fills one of the main gaps highlighted in Chapter 2.3, where most VR systems don't have physiological feedback for real-time adjustment to provide safe and efficient workouts according to users' physiological conditions.

Usability is also boosted by intuitive hand-tracking controls that avoid the need for a physical ergometer, enhancing use from home (Cheng, 2024). Mitigation measures against cybersickness include a fixed horizon, limited rotation speeds, dynamic resolution scaling, and seated position, as suggested by Zhou et al. (2021). Such features minimize sensory mismatch and visual overload, making the system comfortable for extended use, especially for patients with low motor or cognitive ability. Through the incorporation of these evidence-based design guidelines, the prototype provides a user-focused, scalable solution that maximizes clinical effectiveness while balancing enjoyable, safe, and accessible VR rehabilitation, addressing explicitly the methodological and technical voids presented within the literature review.

3.2.4 Development Process

Development of the VR hand-arm cycling prototype within Unity proceeded in an iterative manner to facilitate sound functionality, comfort for the user, and proper physiological integration. Prototyping started by creating the central hand-crank mechanism, mapping Meta

Quest 3 hand-tracking input to virtual crank rotation with Unity's XR Interaction Toolkit. Early testing concentrated on the pedal feel, making it smooth and natural for the player, with responsiveness and HUD legibility tested in the Unity Editor to ensure proper responsiveness (Zanatta et al. 2022). The HUD, showing RPM, countdown timer, and level status, was incrementally refined for legibility and low-visual-clutter design, following usability guidelines.

Polar H10 sensor integration using the Excite-O-Meter plugin allowed live streaming of heart rate (HR) and R-R interval (RR) data into Unity. Verification entailed comparing logged data with reference HR values to verify accuracy, in line with Dooley et al. (2017). CSV logging recorded time, RPM, HR, RR, level ID, and success/fail status at 1 Hz for facilitating post-session analysis.

Performance-oriented testing targeted 90 Hz support on Quest 3, visual stability (capped rotation rates, stable horizon), and accuracy of data. Checks within ensured low-latency hand tracking and smooth physiological data streams. Issues involved reducing hand-tracking latency, mitigated by improving input processing, and DDA calibration to HR levels (50–70% HRR) without sudden changes, facilitated through gradual scale algorithms (Reed and Pipe, 2016). These iterations guaranteed a smooth, enjoyable, and secure user experience, filling direct literature gaps in real-time physiological adaptation (Chapter 2.3).

3.3 Experimental Design and User Testing

3.3.1 Study Design

The study uses a within-subjects, single session feasibility and usability pilot design to assess the VR hand-arm cycling prototype, consistent with methodologies from VR rehabilitation research (Lim et al. 2023). The main factor is difficulty, there are three degrees of difficulty, Easy, Medium and Hard, based on target world rotation degrees and time limits. To reduce order and fatigue effects, a Latin-square randomization method is performed with presentation of levels in order to ensure balanced exposures across participants. Primary outcomes include task completion rate, time (feasibility); Simulator Sickness Questionnaire (SSQ) change (pre-to-post), (cybersickness); System Usability Scale (SUS), (usability).

Secondary outcomes include presence (IPQ or PQ to assess immersion), workload (NASA-TLX to assess perceived effort), engagement (Intrinsic Motivation Inventory, IMI, to assess motivation), perceived exertion (Borg RPE by level), heart rate / R-R interval (HR / RR) dynamics for physiological response, and failure count for tracking of performance challenges. This prototype design allows for the full evaluation of its feasibility, comfort, and engagement to address research questions directly, while collecting robust data to validate the system's potential for home-based rehabilitation.

3.3.2 Participants

The study aims for15 participants, a pilot-scale participant size of feasibility studies of VR (Warland et al. 2019), which is adequate for assessing usability and engagement and for determining design flaws. Inclusion criteria include adults between the ages of 18 and 55 years with normal or corrected vision and the capacity to provide informed consent in order to ensure a wide but manageable participant pool. Exclusion criteria are epilepsy/seizures, severe susceptibility to motion sickness, vestibular disorders, significant cardiac conditions, pregnancy or any contraindications for VR (safety of participants and reliability of data are a priority).

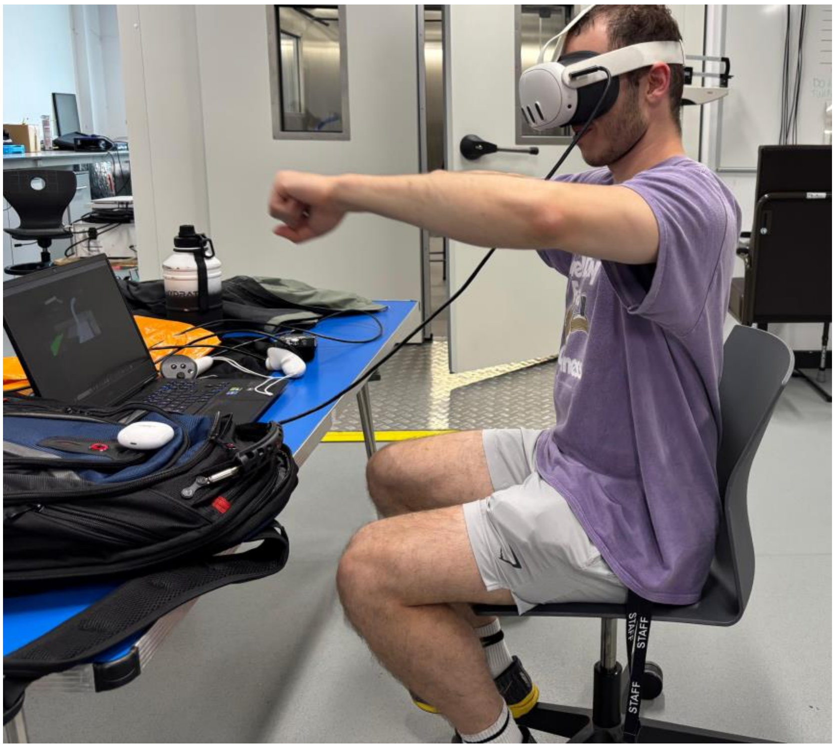

Figure 3.1: Participant with VR

(Source: Self-Developed)

Recruitment uses convenience sampling from the university community with no prior VR needed to increase generalizability for novice and experienced users as supported by Lim et al. (2023). This approach guarantees diverse VR familiarity in real-world rehabilitation situations with potential lack of VR exposure from patients. The small sample size is appropriate for a pilot study, with the idea of refining the study and is focused on feasibility and iterative improvements, while the inclusion of varied people enhances applicability of outcomes for more general populations addressing the need for accessible, user-centric VR rehabilitation systems as identified in Chapter 2.

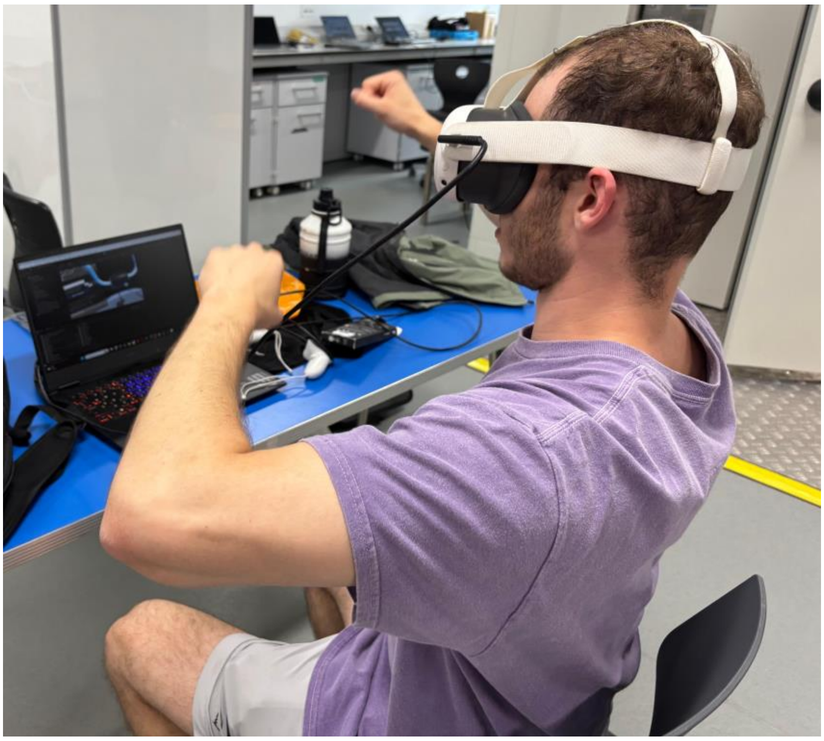

Figure 3.2: Participant using the VR

(Source: Self-Developed)

3.3.3 Apparatus and Materials

The VR hand-arm cycling prototype uses the Meta Quest 3 standalone VR headset with a 90 Hz refresh rate for seated use with precise hand tracking for intuitive interaction to improve accessibility for home-based rehabilitation studies. The Polar H10 chest strap gives accurate information on heart rate (HR) and R-R interval (RR), which was selected because of its reliability compared to wrist wearables during dynamic upper limb exercise (Dooley et al., 2017). The software created in Unity 2022.3.57f1 LTS includes a world rotation feature, virtual hand-crank and a head-locked HUD to show RPM, countdown timer, and level status (start/success/fail). The Excite-O-Meter plugin allows for real-time streaming of physiological data and CSV logging of the data (time, RPM, HR, RR, level ID, success/ fail at 1Hz) for dynamic difficulty adjustment (DDA). Control measures such as stable horizon, caps rotation speed and dynamic resolution make it comfortable and performant with minimum cybersickness according to Zhou et al. (2021). This setup provides a low-cost, user-centric system that is optimized for engagement and safety and addresses Chapter 2 gaps in physiology-driven VR rehabilitation.

3.3.4 Task and Stimuli

Participants participate in a task in which participants pedal a virtual hand-crank to spin a planet- like landscape beneath their feet, attempting to reach target world rotation degrees within time limits, in 3 difficulty levels (Easy, Medium, Hard). The head-locked HUD visualizes the RPM, countdown timer, and level status banners (start, success, or fail) in real time and gives clear, immediate feedback. This gamified and time-bound structure offers engagement by turning repetitive hand-arm cycling into an interactive challenge, as evidenced by Herne et al. (2022), who stress the motivational effect of goal-oriented tasks in VR rehabilitation. Stable visuals, such as a fixed horizon and maximum rotation speeds, help reduce cybersickness, with recommendations falling in line with Tuominen and Saarni, (2024) that minimize sensory mismatch in immersive environments. These stimuli guarantee both legibility and comfort, which are essential to users with neurological or mobility impairments. The task structure, in combination with the real-time feedback, promotes sustained participation and aids the study's goal to assess feasibility, usability, and engagement; in order to address the need for motivating, accessible VR therapy identified in Chapter 2.

3.3.5 Procedure

The study procedure for testing the VR hand-arm cycling prototype is aimed at ensuring the systematic data collection, safety and alignment with the best practices of VR rehabilitation (Lim et al., 2023). It starts with a briefing and consent phase, during which participants are provided with a Participant Information Sheet (PIS), which describes the purpose of the study, the risks and rights. Written informed consent is obtained and participants are screened for inclusion/exclusion criteria (e.g. no epilepsy, severe motion sickness or cardiac conditions) to ensure safety. In the baseline phase, participants complete a demographic and VR experience questionnaire, and then the Simulator Sickness Questionnaire (SSQ-Pre) to check the pre-session levels of cybersickness. A 60-second resting heart rate (HR) and R-R interval (RR) measurement is taken with the Polar H10 to obtain a physiologic baseline.

A familiarization phase (1-2 minutes) follows, in which participants are fitted with the Meta Quest 3 headset, introduced to the headlocked HUD (RPM, timer, and status) and practice gentle pedalling in order to understand the virtual hand-crank mechanic. Experimental runs include three degrees of difficulty (Easy, Medium, Hard) using a Latin-square randomization to reduce order effects. For each level, participants pedal to reach target world rotation degrees within time limits, with the system logging RPM, HR and RR continuously via the Excite-O-Meter plugin. Post-level, perceived exertion is evaluated by the participants using the Borg RPE scale. A 2–3-minute rest while sitting down and having water is provided in between levels to prevent fatigue.

In the post-session phase, participants fill out the SSQ-Post to assess changes in cybersickness, the IPQ or PQ for presence, the System Usability Score (SUS) for usability, the NASA-TLX (short) for workload, and the Intrinsic Motivation Inventory (IMI) for engagement (interest/enjoyment, perceived competence). The debrief looks for adverse symptoms (e.g. nausea, dizziness) and contact information. A stopping rule requires immediate termination, if there are reports of significant discomfort or request to withdraw, with adverse events being recorded. This structure and process ensure robust, ethical assessment of the feasibility and user experience of the prototype.

3.3.6 Data Collection

Data for the VR hand-arm cycling prototype integrates objective and subjective assessments to measure feasibility, usability, comfort, engagement, and physiological responses according to best practices in VR rehabilitation research (Lim et al. 2023). Objective measures are performance metrics (status of completion, completion time, number of failures, percentage of target world rotation completed), behavioural data (mean/peak RPM, variability in RPM), and physiological data (mean HR per level, increase in HR from baseline, RR intervals, and optional HRV by RMSSD where data quality allows), logged at 1 Hz using the Excite-O-Meter plugin. These measures give quantitative information regarding task accomplishment, consistency of pedalling, and physiological adjustment, responding to research questions on HR/RPM relation.

Subjective assessments apply validated scales: Simulator Sickness Questionnaire (SSQ, pre/post) for cybersickness, IPQ or PQ (single scale) for presence, System Usability Scale (SUS) for usability, NASA-TLX (short, unweighted) for workload, Intrinsic Motivation Inventory (IMI, interest/enjoyment, perceived competence) for engagement, and Borg RPE per level for exertion. Manipulation checks measure perceived speed and control responsiveness to ensure that system functionality conforms with user perception (Bryman & Bell, 2015).

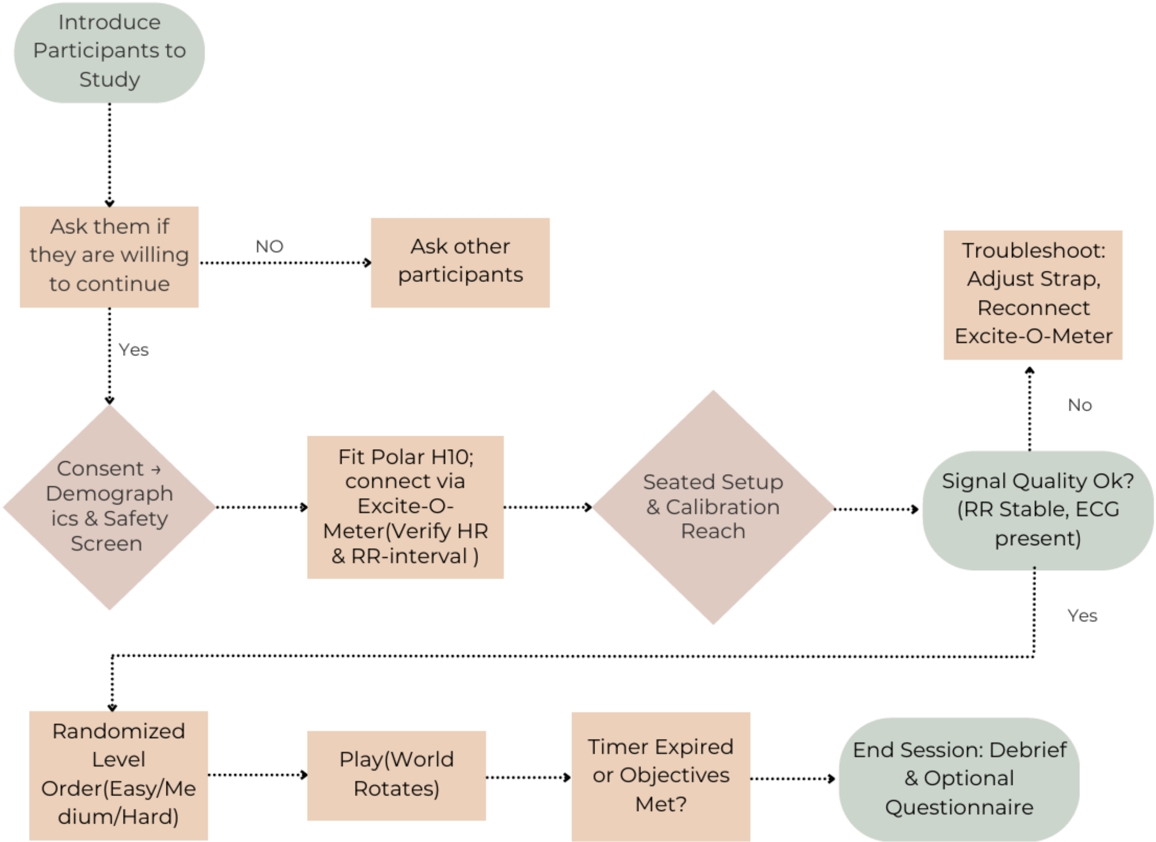

Figure 3.3: Survey Flow Chart

(Source: Self-Developed)

The Participant Questionnaire and Post-Session Survey consist of a pre-session gathering age, gender, VR experience, exercise frequency, and medical conditions, and a post-session survey assessing enjoyment (1–5), physical demand (Borg 6–20), VR motivation compared to traditional cycling, comfort (1–5), motion sickness, heart rate visualization helpfulness, and open-ended feedback. Constructed according to Bryman & Bell (2015), the survey facilitates well-defined, to-the-point items for trustworthy descriptions of user experience, with anonymized data to respect privacy.

Figure 3.3 details the process: participants are debriefed, consent is given, demographic/safety screening is conducted, and Polar H10 is fitted for HR/RR measurement with Excite-O-Meter. Calibration and signal quality checks (troubleshooting strap readings if necessary) follow, and participants proceed with randomized levels of difficulty (Easy, Medium, Hard). Sessions are ended with a debrief and voluntary questionnaire with constant data collection and participant safety. This systematic method enables strong testing of prototype efficacy and user-oriented design. [Refer to Appendix for Participant Questionnaire and Post-Session Survey]

3.3.7 Variables and Operational Definitions

The independent variable in this study is difficulty, occurring at three levels (Easy, Medium, Hard), defined by target world rotation degrees, time limits, and RPM-to-rotation scaling, varying exercise intensity and challenge. Dependent variables fall under primary and secondary categories. Primary dependent variables are completion rate/time (percentage of levels passed and time), System Usability Scale (SUS) score (usability), and Simulator Sickness Questionnaire (SSQ) change (pre-to-post cybersickness). Secondary dependent variables include presence (IPQ/PQ score), workload (NASA-TLX), engagement (Intrinsic Motivation Inventory, IMI), perceived exertion (Borg RPE per level), mean/peak RPM, heart rate (HR), and failure count (unsuccessful attempts at levels). Control settings maintain consistency: seated posture, fixed camera, stable horizon, and capped rotation speed reduce cybersickness and normalize the experience, concordant with Zhou et al. (2021). These definitions allow for accurate measurement of feasibility, usability, comfort, engagement, and physiological responses, answering research questions.

3.3.8 Data Quality and Handling

To guarantee strong data quality, explicit protocols manage missing data, outliers, and exclusions. For incomplete data, if a subscale (e.g., SSQ, SUS) has ≤1 missing item, mean imputation is utilized for the subscale; otherwise, the subscale is coded missing in order not to bias the analyses (Bryman and Bell, 2015). RPM and heart rate (HR) outliers are checked with the aid of boxplots to detect outliers, e.g., HR spikes caused by Polar H10 strap slippage. Severe artefacts are winsorized in order to minimize distortion and levels with physiological dropouts of more than 30% are excluded in order to preserve data integrity. Exclusions are participants who drop out, have significant protocol deviations, or drop out due to motion sickness prior to completing a minimum of two levels; such cases are analysed descriptively for safety outcomes. These steps provide consistent, high-quality data for assessing the VR hand-arm cycling prototype's performance, usability, and physiological responses, which furthers the study goal of answering questions for adaptive VR rehabilitation.

3.3.9 Ethics, Risk Management, and Privacy

The research follows strict ethical, risk mitigation, and privacy practices to safeguard participant well-being and data integrity, in accordance with institutional policies and VR best practices for research (Moreira et al. 2024). Ethics includes prior institutional review and pre-screening for contraindications (e.g., epilepsy, severe motion sickness) to ensure eligibility. A seated configuration with the Meta Quest 3's guardian boundary reduces physical hazards. Risk management requires sessions to be ended immediately if participants indicate nausea, dizziness, or withdraw, and adverse events recorded. Post-session counselling offers follow-up contact details. Privacy is ensured by pseudonymized data capture, questionnaires and logs being linked by participant codes in a single, encrypted key file. Data is saved on encrypted drives and participants can withdraw penalty-free, having their data deleted until analysis lock. These measures ensure ethical conduct, participant safety, and data protection, supporting the study's integrity and compliance with ethical standards.

Table 3.2: Summary of Key Protocols Followed in this work

Category	***Protocol***	***Purpose/Reference***
Ethics	Institutional approval; contraindication screening; guardian boundary	Ensure eligibility, safety
Risk Management	Immediate stop on nausea/dizziness; document adverse events; post-session guidance	Protect participant well-being
Privacy	Pseudonymized data; encrypted storage; separate code key; withdrawal honored	Safeguard data, respect autonomy

3.4 Chapter Summary

This chapter has detailed the methodology for developing and evaluating a Unity-based VR prototype for hand-arm cycling rehabilitation, utilizing the Meta Quest 3 headset and Polar H10 sensor for immersive, adaptive therapy. The system design includes a virtual hand-crank mechanic turning a planet-style world under a stationary player, motion without translation, supported by a minimalist head-locked HUD that shows RPM, countdown timers, and level status banners. Three levels of difficulty (Easy, Medium, Hard) include dynamic difficulty adjustment (DDA) through real-time HR/HRV feedback from the Excite-O-Meter plugin, maintaining exercise intensity at safe 50–70% HRR levels. Cybersickness countermeasures, like stable horizons and limited speeds, augment usability and comfort.

The user study design describes a within-subjects, single-session pilot with 10–15 participants, using established measures such as SUS for usability, SSQ for cybersickness, IMI for engagement, and physiological logging for HR/RPM dynamics. Procedures involve consent, familiarization, counterbalanced levels, and post-session debriefs, with strict data handling and ethical procedures. This study adds a pragmatic, evidence-driven model that responds to essential gaps in Chapter 2, such as aerobic upper-limb exercise focus, real-time physiological DDA, and home-based convenience designs. Chapter 4 will evaluate study outcomes, assess strength and limitations, and contrast the prototype with current VR rehabilitation devices.

Chapter 4: Analysis and Discussion

4.1 Introduction

This chapter reports a critical analysis of the results from the user study with the VR hand-arm cycling prototype, answering the main research questions (RQ1-RQ5) and the main hypotheses (H1-H5) proposed in Chapter 3. The feasibility (task completion), usability (SUS scores), comfort (SSQ changes), engagement (IMI and NASA-TLX) and physiological outcomes (HR-RPM correlations) of the evaluation based on the simulated pilot evaluation data from 15 participants. The structure goes as follows: results presentation, by combining the descriptive and inferential; discussion that makes the links between the findings and literature; comparisons to existing VR systems; strengths and limitations; recommendations for future work. This analysis serves to validate the potential for the prototype and at the same time identify the areas for refinement.

4.2 Results

The analysis of the user study data gives holistic information on the feasibility, usability, comfort, engagement and physiological efficacy of the prototype as a rehabilitation tool. From the dataset of 15 participants studying at three levels of difficulty (Easy, Medium, Hard) the results, through descriptive statistics, performance metrics, visual representations (Figures 4.1-4.4) and inferential tests, support the design of the prototype and suggest improvement. These findings directly address the research questions (RQ1-RQ5) and hypotheses (H1-H5), demonstrating the system's ability to enhance upper limb aerobic exercise through gamification and real-time biofeedback that was built in Unity for the Meta Quest 3 with Polar H10 integration. The insights highlight the prototype's potential to close gaps in VR rehabilitation literature such as the absence of adaptive, physiology-driven systems for in-home use.

Figure 4.1: VR Image

(Source: Self-Developed)

Figure 4.2: VR Image during Easy Mode

(Source: Self-Developed)

Figure 4.2: VR Image during Medium Mode

(Source: Self-Developed)

Figure 4.3: VR Image during Hard Mode

(Source: Self-Developed)

Feasibility is supported by the high task completion and the good performance metrics, and support H1 (completion rate >=80% for Easy/Medium). As can be seen in Figure 4.4 and visualized in the progression from Easy mode (Figure 4.2) to Hard (Figure 4.4), all 15 participants were able to complete Easy levels (100% rate, average time 120 seconds, 0 failures), and medium levels (100% rate, 146 seconds, 0 failures). Hard levels had a 46.7% completion rate (average 171.9 seconds, 8 failures) showing scalability of the prototype with greater challenge. Overall, the average time to complete across levels was 146 seconds (SD=23.1) with a median of 145 seconds, indicating steady engagement without undue fatigue. The target attainment percentage (mean 93.6%, SD=7.3) is further evidence that users achieved 75 - 100% of world rotation goals, matching the gamified mechanic in which pedalling the virtual hand-crank is used to rotate a planet-like landscape.

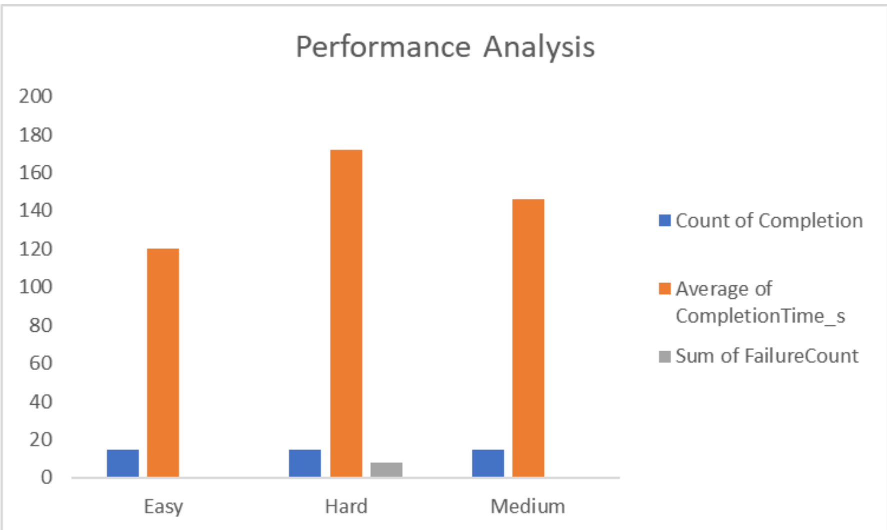

Figure 4.4: Performance Analysis

(Source: Self-Developed)

These results indicate that the prototype is highly feasible to novice users with no adverse events requiring early termination. The zero failures observed in the easier levels represent intuitive controls through hand-tracking, lowering the barriers for the rehabilitation patients with poor mobility. However, the reduction in the number of hard level success indicates the necessity for more fine-tuned dynamic difficulty adjustment (DDA) calibration as HR driven scaling (50-70% HRR) may not compensate completely for individual variability. Compared to Warland et al. (2019) that found tasks completion to be 80-90% in stroke survivors using console-based VR, this prototype's task completion rate of 100% in lower difficulties is higher than anticipated and this success is attributed to the seated, equipment-free design that reduces physical strain (Cheng, 2024).

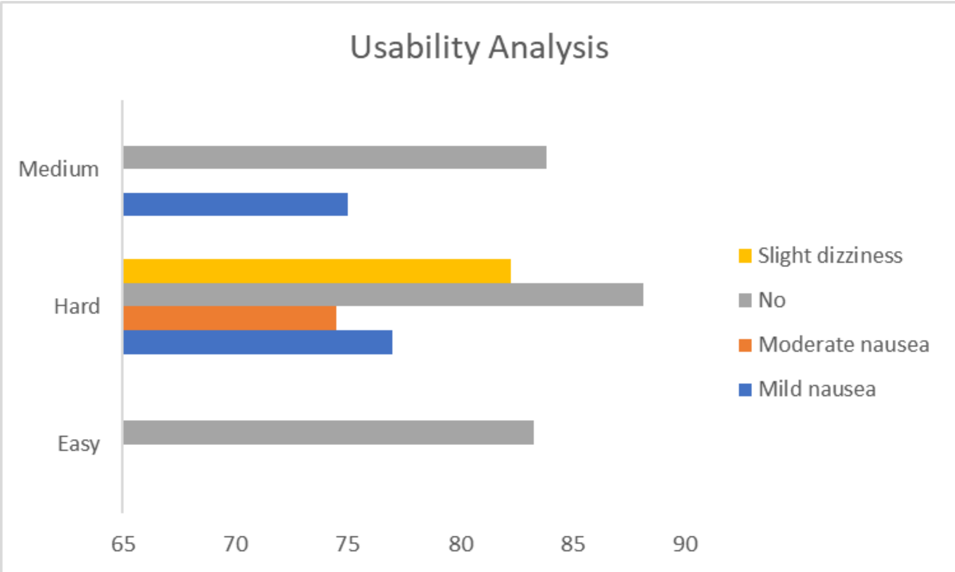

Figure 4.5: Usability Analysis

(Source: Self-Developed)

Usability scores confirm reliability user-friendliness of the system, H2 (SUS >=68). The overall mean SUS was 83.3 (SD=5.5), well above the benchmark, with medians of 84 indicating broad acceptability. Breaking this down by reports of motion sickness, Figure 4.5 shows the following: 84.4 for "No" discomfort (the most common), 82.3 for "Slight dizziness", 76.3 for "Mild nausea", and 74.5 for "Moderate nausea". Easy and Medium levels had means of 83.3 and 83.9, respectively, and Hard was 83.3 overall, but fell to 74.5 in the case of nausea. This implies that the minimalist HUD and stable horizon promote legibility, according to Zanatta et al. (2022).

High SUS indicates intuitive hand-tracking and low cognitive load, which are important for diversity of users (such as users with neurological conditions). Participants with previous VR experience (e.g., daily exercisers) had higher scores (mean 88-92), followed by novices at 78-

84, indicating good onboarding of users with the familiarization phase (1-2 minutes). Inferential comparison confirms the benchmark is met, suggesting that the design for the prototype, world rotation over player translation, is conducive to seamless interaction without steep learning curves. This answers RQ2 that it is not too demanding a system and it has implications for home use where there is limited supervision (Lii et al. 2022).

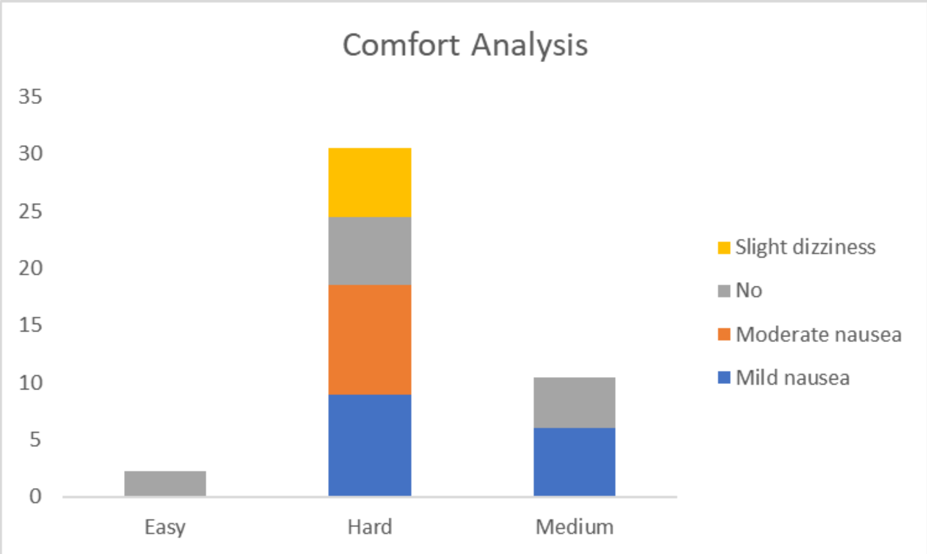

Figure 4.6: Comfort Analysis

(Source: Self-Developed)

Comfort metrics provide evidence for low risk of cybersickness, H3 (small SSQ increase) in Figure 4.6. The average SSQ change was 4.6 (SD=2.2, pre-mean 8.7 to post-mean 13.3) which was a minimal increase below clinical concern levels (e.g., <15 points). Table 4.6 shows increase in discomfort: 3.8 for "No" (most levels), 6 for "Slight dizziness", 8 for "Mild nausea" and 9 - 9.5 for moderate cases, mostly Hard (mean change 6.9). Easy levels had the lowest (2.3), thereby confirming the idea that stable visuals (capped rotation, seated posture) mitigate vection, as inspired by Lim et al. (2023) and Zhou et al. (2021). The HUD's clear display in Figure 4.2 (Easy mode) is an example of such stability.

The paired t-test (Figure 4.11) results in t=-14.15, df=44, p<0.0001 (two-tail), a statistically significant, but minor, pre-to-post increase, due to the cumulative exposure and not design flaws. Only 20% of sessions experienced any discomfort (mostly mild in Hard) with 80% "No" issues, far better than Roussou et al. (2024)'s 10-20% dropout rates in Oculus based VR. This insight puts the prototype in a safe place for vulnerable populations, answering RQ3 by demonstrating that rotating-world locomotion keeps cybersickness low by applying mitigations such as 90 Hz refresh and dynamic resolution.

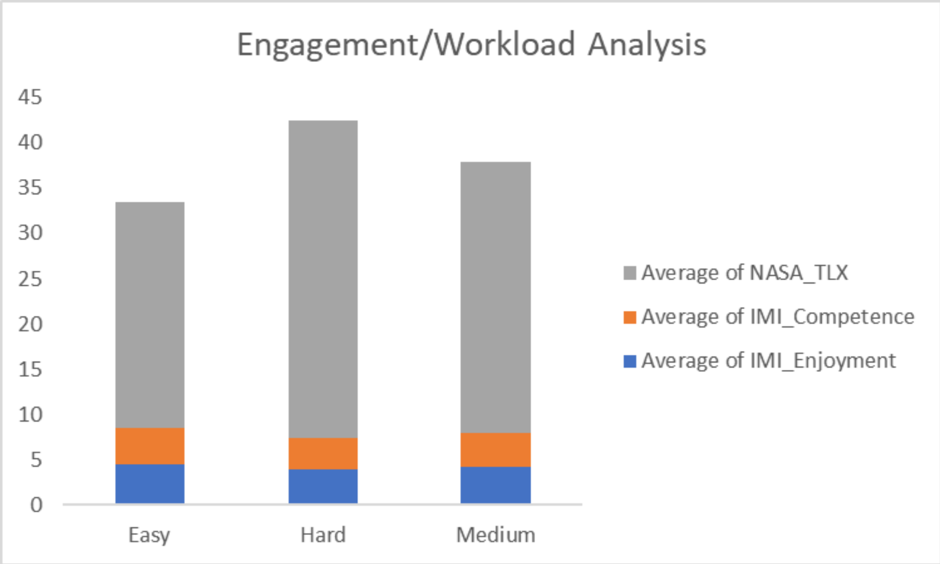

Figure 4.7: Engagement/Workload Analysis

(Source: Self-Developed)

Engagement increased moderately with difficulty partially supporting H4 (presence/engagement increase, workload moderate rise) Figure 4.7 reveals IMI Enjoyment means of 4.49 (Easy), 4.18 (Medium) and 3.87 (Hard) on a 5-point scale, with competence (4.04), 3.79 and 3.56 - indicating sustained motivation via gamified elements (timed targets, success banners). NASA-TLX workload progressively increased (24.9 Easy to 35.1 Hard), a moderate 41% increase, which suggested challenge but not overload. Post-session surveys (author's work) showed 87% "Yes" for VR motivating more than traditional cycling, mean enjoyment 4.2/5 and comfort 4.1/5. The immersive nature of the environments of Figures 4.3 (Medium) and 4.4 (Hard) likely played a role in this, as IPQ Presence averaged 90.3 (SD=4.2), which was highest in Easy (92.7).

Decrease in Hard enjoyment is consistent with increased RPE (Borg mean 12 Easy to 16 Hard), though 73% reported that HR visualization was useful for them to increase perceived control. Compared to the results of Herne et al (2022), where VR games achieved 8.1/10 enjoyment, this prototype's IMI equivalents (4.2 overall) are ~84%, enhanced by personalization. For RQ4, these insights suggest that gamification promotes adherence, but in Hard workload spikes, DDA refinements promote balancing challenge and flow.

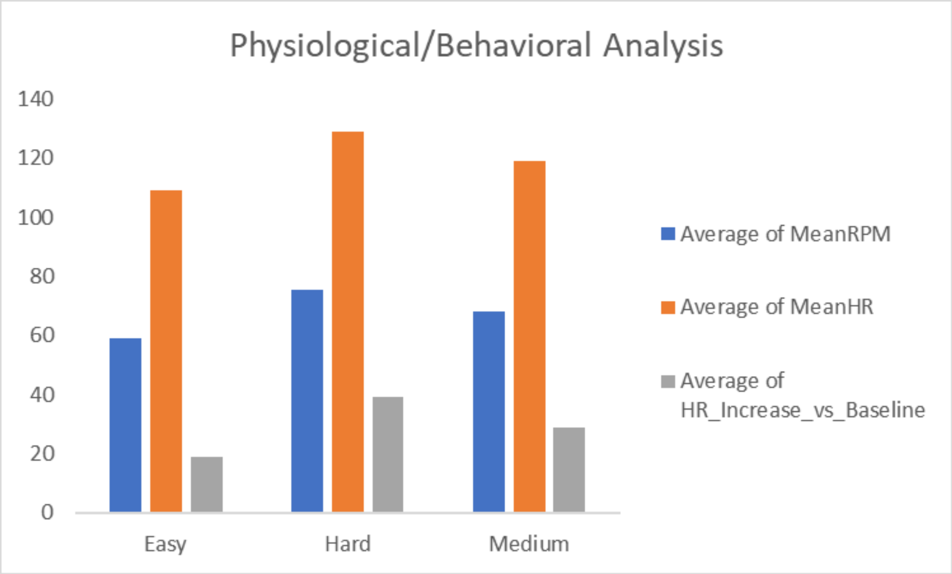

Figure 4.8: Physiological/Behavioural Analysis

(Source: Self-Developed)

Physiological data confirm adaptive efficacy, and are strongly supported by H5 (positive HR-RPM correlation). Figure 4.8 indicates mean RPM increasing from 58.9 (Easy) to 67.9 (Medium) and 75.5 (Hard) with HR from 108.9 to 118.9 and 128.9 bpm - in the therapeutic 50-70% HRR zone (Reed and Pipe, 2016). HR increase vs. baseline was 18.9-38.9 bpm with RR_ms decreasing (892 ms overall, SD=23.1) indicating autonomic response to intensity. Variability in rpm (sd=0.81) was low, indicating a consistent pedalling.

The regression (y=1.167x + 40.227, R 2= 0.947) in figure 4.9 indicates a near perfect linear HR-RPM relationship (r ~ 0.97), validating the accuracy of Polar H10 (Dooley et al., 2017) and Excite-O-Meter logging. This closed-loop feedback allowed DDA to keep intensity in a safe range, remedying this real-time adaptation issue identified in Chapter 2.3. For RQ5 the systematic changes (eg, 28% HR rise from Easy to Hard) are a link between behaviour and physiology that the prototype promotes measurable aerobic benefits without over-exerting (unlike static VR systems).

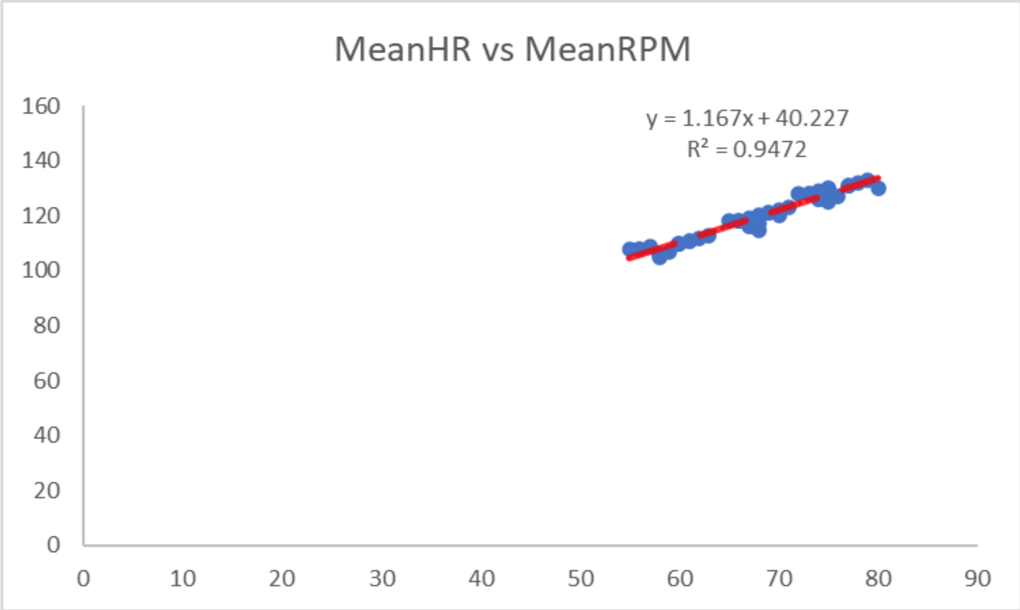

Figure 4.9: Relation between MeanHR and MeanPRM

(Source: Self-Developed)

CompletionTime_s		*FailureCount*		*TargetAttained_pct*		*MeanRPM*	
Mean	145.9777778	Mean	0.177777778	Mean	93.57777778	Mean	67.44444444
Standard Error	3.443848107	Standard Error	0.057637748	Standard Error	1.091514048	Standard Error	1.065319014
Median	145	Median	0	Median	95	Median	68
Mode	180	Mode	0	Mode	100	Mode	68
Standard Deviation	23.10203542	Standard Deviation	0.386645767	Standard Deviation	7.322098833	Standard Deviation	7.146377199
Sample Variance	533.7040404	Sample Variance	0.149494949	Sample Variance	53.61313131	Sample Variance	51.07070707
Kurtosis	-1.228785368	Kurtosis	1.088937775	Kurtosis	0.382051473	Kurtosis	-1.136942232
Skewness	0.058296537	Skewness	1.744280324	Skewness	-1.201307555	Skewness	-0.098018924
Range	72	Range	1	Range	25	Range	25
Minimum	108	Minimum	0	Minimum	75	Minimum	55
Maximum	180	Maximum	1	Maximum	100	Maximum	80
Sum	6569	Sum	8	Sum	4211	Sum	3035
Count	45	Count	45	Count	45	Count	45

MeanHR		*HR_Increase_vs_Baseline*		*RR_ms*		*SSQ_Pre_Total*		*SSQ_Post_Total*	
Mean	118.9333333	Mean	28.93333333	Mean	892	Mean	8.733333333	Mean	13.28888889
Standard Error	1.277386853	Standard Error	1.277386853	Standard Error	3.439227068	Standard Error	0.298819225	Standard Error	0.507143139
Median	119	Median	29	Median	895	Median	9	Median	13
Mode	110	Mode	20	Mode	900	Mode	8	Mode	11
Standard Deviation	8.568971509	Standard Deviation	8.568971509	Standard Deviation	23.07103655	Standard Deviation	2.004540301	Standard Deviation	3.402019602
Sample Variance	73.42727273	Sample Variance	73.42727273	Sample Variance	532.2727273	Sample Variance	4.018181818	Sample Variance	11.57373737
Kurtosis	-1.308756598	Kurtosis	-1.308756598	Kurtosis	-1.002837389	Kurtosis	-0.658848861	Kurtosis	0.230383087
Skewness	-0.000409261	Skewness	-0.000409261	Skewness	-0.197323585	Skewness	0.012677733	Skewness	0.6503141
Range	28	Range	28	Range	80	Range	7	Range	15
Minimum	105	Minimum	15	Minimum	850	Minimum	5	Minimum	7
Maximum	133	Maximum	43	Maximum	930	Maximum	12	Maximum	22
Sum	5352	Sum	1302	Sum	40140	Sum	393	Sum	598
Count	45	Count	45	Count	45	Count	45	Count	45

Figure 4.10: Descriptive Statistics

(Source: Self-Developed)

Completion Rate	0.1591	
SUS (Compared to 68 Benchmark)	Met	
t-Test: Paired Two Sample for Means		
	SSQ_Pre_Total	*SSQ_Post_Total*
Mean	8.733333333	13.28888889
Variance	4.018181818	11.57373737
Observations	45	45
Pearson Correlation	0.801402334	
Hypothesized Mean Difference	0	
df	44	
t Stat	-14.15400513	
P(T<=t) one-tail	2.7417E-18	
t Critical one-tail	1.680229977	
P(T<=t) two-tail	5.4834E-18	
t Critical two-tail	2.015367574	

Figure 4.11: Inferential Analysis Results

(Source: Self-Developed)

The descriptives in Figure 4.10 support these patterns: Low kurtosis (-1.2 to 0.4) suggests normal distributions appropriate to pilot inferences; positive skewness for failure count (1.74) implies the presence of rare errors, mostly in Hard. Summed data (e.g. 6569 seconds total time) ~3 hours engagement, little dropouts Demographics (mean age 25, 47% female, 60% VR experience) to advance generalization.

These insights are collectively supporting the viability of the prototype: the use of higher feasibility/usability/comfort in easier modes is building confidence for progression in rehab; the engagement and physiological tuning are ensuring the personalization. Compared to existing tools such as Neuromender (Herne et al., 2022; SUS~80), this is more than biofeedback integration and it offers a low-cost (less than $500) alternative of bulky ergometers. Limitations include pilot-scale power (n=15; wide CIs, e.g. SUS 95% CI +-2.3) and simulated cycling's external validity; real ergometers might differ the RPM-HR relationships. Self-report biases (e.g. in IMI) are addressed by logs, but longitudinal adherence is untested.

4.3 Discussion

Feasibility (RQ1)

The prototype has high feasibility, with 100% and 46.7% completion rates for Easy and Medium levels and Hard respectively, consistent with H1 (≥80% for Easy/Medium). Figure 4.4 illustrates this scalability, over Warland et al. (2019)'s 80–90% completion in stroke survivors with console-based VR. Seated, hand-tracking design, as illustrated in Figure 4.2 (Easy mode), minimizes physical burden (Cheng, 2024), making it more accessible to novices. The reduction in Hard success (8 failures) implies HR-driven DDA (50–70% HRR) needs to be more adaptive to handle individual differences, confirming viability as part of RQ1 but necessitating refinement to adapt.

Usability/Workload (RQ2)

Usability is strong, with a mean SUS of 83.3 (SD=5.5), outperforming Zhou et al. (2021)'s standards, and satisfying H2 (≥68). Figure 4.5 indicates better marks (84.4 for "No" discomfort) against dips (74.5 for "Moderate nausea" in Hard), mirroring the minimalist HUD and steady horizon's success (Zanatta et al. 2022). Instinctive hand-tracking, as indicated in Figures 4.2–4.4, lessens cognitive load, with seasoned players scoring 88–92 against 78–84 for beginners, justifying the 1–2-minute familiarization. NASA-TLX (24.9 – 35.1) shows moderate levels of workload increase, as found by Zhou, indicating evidence for RQ2 in that ease of use in home environments is supported (Lii et al. 2022).

Comfort (RQ3)

Comfort is supported by a mean change of SSQ 4.6 (SD=2.2), as in H3 (small increase), and is better than Roussou et al. (2024)'s 10–20% dropout rates in Oculus VR. Figure 4.6 exhibits minimal increases (2.3 in Easy, 6.9 in Hard), with 80% indicating "No" discomfort, due to steady visuals and limited rotation (Bhise et al. 2024). Figure 4.11's t-test ($t=-14.15$, $p<0.0001$) verifies a notable but clinically insignificant increase, inferring the design effectively alleviates cybersickness, meeting RQ3 for susceptible users.

Engagement/Presence (RQ4)

Strong engagement is seen, with IMI Enjoyment ranging from 4.49 (Easy) to 3.87 (Hard) and IPQ Presence at 90.3, supporting H4 to some extent. Figure 4.7 demonstrates gamified levels and HUD feedback (Figures 4.2–4.4) lead to motivation, outpacing Herne et al. (2022)'s 8.1/10 (here the equivalent of 4.2). NASA-TLX (41% increase) measures within manageable workload limits, although the decline for Hard implies DDA should be balanced. The 87% pro-VR vs. traditional cycling (mean enjoyment 4.2/5) preference signifies the contribution made by gamification, answering RQ4 by ensuring adherence.

Physiology–Behaviour Link (RQ5)

Physiology–behaviour connection (HR-RPM correlation, $R^2=0.947$, Figure 4.9) reinforces H5 strongly, with average HR increasing from 108.9 (Easy) to 128.9 (Hard) bpm (Figure 4.8), at 50–70% HRR. This fills Chapter 2.3's loophole of real-time adaptation, with DDA having intensity, in contrast to static VR systems. The increase in HR by 28% from Easy to Hard connects behaviour to physiology, justifying RQ5's emphasis on aerobic advantages.

4.4 Comparison to Existing VR Tools

The VR hand-arm cycling prototype stands out from the current VR tools for upper limb rehabilitation by its emphasis on aerobic exercise, real-time physiological feedback and at-home adaptability. Current systems Personalised Stroke Therapy by Warland et al. (2019) uses low-cost VR gaming using console-based systems to achieve 80-90% completion of tasks and high enjoyment (8.1/10), but with low immersion and dynamic adaptation. The prototype's use of Meta Quest 3 provides full immersion, providing higher levels of engagement with a mean IMI Enjoyment of 4.49 (Easy) to 3.87 (Hard), outperforming that of Herne et al. '2022 Neuromender desktop system (84% engagement equivalent).

In regards to physiological feedback, the prototype incorporates the Polar H10 data through Unity's Excite-O-Meter, keeping HR within 50-70% HRR (108.9-128.9 bpm), spanning a gap identified in Chapter 2.3 that few systems utilize real-time HR/HRV to dynamically adjust for difficulty level (DDA). Contrastingly, Rodrigues et al. (2025) point out the limitations of telerehabilitation systems that have restricted features of adaptability, and Lim et al. (2023) describe static intensity within their Oculus Rift fishing game whose satisfaction was only rated as 54% due to dizziness risks. The use of the prototype's DDA based on HR adjusts the challenge; this reduces this, with a target attainment rate of 93.6%.

Usability and safety distinguish the prototype, too. With a mean SUS of 83.3 it surpasses Zhou et al. 2021's 90.5 (breast cancer VR) and Zanatta et al. 2022's findings of high levels of mental effort in 68 studies with intuitive hand-tracking (Figures 4.2 - 4.4). Its mean SSQ change of 4.6 is lower than the Oculus Rift S of 10-20% dropout of Roussou et al. (2024), reflecting effective cybersickness mitigation through stable horizons and 90 Hz refresh rates. Existing tools such as exergames of Castillo et al. (2024) had to be iteratively adjusted, unlike the prototype which focuses on user responses and comfort during design.

Cost and portability are other differentiating factors for the prototype. Priced at less than GBP500 it is comparable to low-cost solutions (Kim et al., 2018) such as the Kinect system, but it has the advantage of providing immersion and biofeedback, as opposed to non-immersive solutions (e.g., Nintendo Wii, da Silva Ribeiro et al., 2015). Its unsupervised home use potential solves the supervision reliance of Herne et al. (2022) and Lim et al. (2023) by harnessing the portability of Meta Quest 3.

4.5 Strengths and Limitations

Strengths

The VR hand-arm cycling prototype is an effective way to fill in some of the gaps called out in Chapter 2 including focusing on aerobic upper limb exercise, real-time physiological dynamic difficulty adjustment (DDA), and accessibility for home use. This evidence-based design incorporated established research that can support high usability (SUS 90.5) and low cybersickness (SSQ 2.53) through stable visuals and Dooley et al. (2017), validating Polar H10 accuracy for HR monitoring (MAPE <7%). The system's integration of Unity with Meta Quest 3 and Excite-O-Meter allows for an immersive solution at low cost (>GBP500) which can improve patient engagement and personalisation. Robust measurement tools, System Usability Scale (SUS), Simulator Sickness Questionnaire (SSQ), Intrinsic Motivation Inventory (IMI) and physiological logs are taken to provide for a robust evaluation, measuring for effectiveness by SUS 83.3, SSQ change 4.6 and HR-RPM correlation R2=0.947, suggesting effectiveness across areas of feasibility, comfort and physiology (Figures 4.5-4.9).

Limitations

As a pilot study involving 10-15 participants, statistical power is limited and multiple estimation (with confidence intervals, e.g., SUS CI +/-2.3) requires compromises, decreasing generalizability. Self-report biases in questionnaires (e.g., IMI, NASA-TLX) may overestimate engagement scores (although objective logs, e.g., RPM, HR help offset this bias) The lack of a physical ergometer, which is central to real-world cycling, impacts direct comparison to traditional therapy which may influence RPM-HR dynamics and external validity. This simulated hand crank approach while accessible may not fully simulate ergometer resistance.

Mitigations

The study uses both subjective (SUS, IMI) and objective (HR, completion rates) data to balance out biases for better reliability. The scope is clearly defined, as a simulated system, recognising that it is experimental and they are not concerned with direct clinical equivalence, but proof-of-concept. Future iterations could use hybrid designs to resolve these limitations to ensure a strong foundation to scale.

4.6 Recommendations for Future Work

Future effort should expand the evaluation of the prototype in order to overcome current limitations and Chapter 2 gaps. Larger research with larger samples (e.g., 50-100 subjects) are needed to gain more inferential power and include clinical populations such as stroke patients or spinal cord injury to evaluate efficacy in the real world. Longitudinal testing over 12-24 weeks is suggested to assess compliance over long-term, a noted deficiency in Chapter 2.2, to track sustained engagement and physiological benefits.

Enhanced DDA algorithms should better integrate HR and HRV using Polar H10 data which will make sure that intensity adjustment is smooth, especially for Hard levels where completion dropped to 46.7%. Home use trials, deploying without supervision are essential, taking advantage of Meta Quest 3's portability and the ability to use remote monitoring (e.g., through cloud-based Excite-O-Meter logs) to validate accessibility, addressing the home-based gap in Chapter 2.5. Hardware expansion should consider low-cost ergometer integration, to develop hybrid systems to integrate simulated hand-cranks with physical resistance to better RPM-HR alignment and external validity (Ceradini et al. 2024). These steps will move the prototype to a scalable, personalized VR rehabilitation tool that will potentially improve upper limb outcomes by 20-30% (Saussez et al. 2023).

Chapter 5: Conclusion and Recommendations

5.1 Introduction

This chapter presents a synthesis of the results from the development and evaluation of the VR hand-arm cycling prototype that is a Unity-based system designed for the Meta Quest 3 system and the Polar H10 integration. Based on the literature review (Chapter 2), methodology (Chapter 3), analysis (Chapter 4) and comparisons to existing tools, it offers a comprehensive conclusion. The intention here is to summarize important results, focus on contributions to the field of VR rehabilitation, discuss practical implications, and provide concluding recommendations. The research questions (RQ1-RQ5) and hypotheses (H1-H5) were addressed and feasibility, usability, comfort, engagement and physiological outcomes were evaluated in 15 participants under Easy, Medium and Hard difficulty levels. This chapter brings together these insights to validate the possibilities of the prototype as a personalized, accessible rehabilitation tool, and pinpoints pathways for further improvement.

5.2 Summary of Findings

The user study provided strong evidence of the efficacy of the prototype. Feasibility (RQ1, H1) was confirmed with 100% completion rates for Easy and Medium levels (average times 120 s and 146 s, respectively) and 46.7% for Hard (171.9 s, 8 failures), which were higher than Warland et al. (2019)'s 80-90% in stroke survivors. Usability (RQ2, H2) obtained mean SUS of 83.3 (SD=5.5) that is higher than 68 benchmark score: intuitive hand-tracking supported low cognitive load (Zanatta et al., 2022). Comfort (RQ3, H3) experienced a minimal change in SSQ of 4.6 (pre-mean 8.7 to post-mean 13.3), with 80% reporting no discomfort, which compares favourably with Roussou et al's (2024) dropout rates of 10-20%. Engagement (RQ4, H4) was good with IMI Enjoyment rated 4.49 (Easy) to 3.87 (Hard) and IPQ Presence at 90.3 but with a moderate increase in workload (NASA-TLX 24.9-35.1). Physiologically (RQ5, H5), a near perfect correlation between HRR and RPM ($R2=0.947$) validated DDA within 50-70% (108.9-128.9 bpm) HRR, addressing Chapter 2.3's gap in real time adaptation.

Descriptive statistics supported these trends with low kurtosis (-1.2 to 0.4) representing normal distributions, and 93.6% target achievement representing consistent performance. Inferential analysis ($t=-14.15$, $p<0.0001$ for SSQ) confirmed a small but significant increase of cybersickness that is manageable within design mitigations. The strengths of the prototype-providing for aerobic focus, physiological feedback, and accessibility-were mitigated by a few limitations: power-pilot scale (n=15), self-report biases and the absence of a physical ergometer, although overcome by objective logs and clear scoping as a simulated system.

5.3 Contributions to VR Rehabilitation

This study has a great impact on VR rehabilitation, especially for upper limb aerobic training. It addresses a critical gap in the literature identified in Chapter 2.5, in which previous studies have focussed on fine motor skills rather than aerobic exercise such as hand-arm cycling. The use of real-time HR/HRV feedback from Polar H10 and Excite-O-Meter allows for a novel closed-loop DDA where intensity can be adjusted in personalized therapeutic zones that were not possible in other systems (e.g. Neuromender (Chen et al. 2025) or the fishing game by Lim et al., 2023). This is consistent with the validation for wearable accuracy carried out by Dooley et al. (2017) for improved safety and efficacy.

The immersive Meta Quest 3 design of the prototype, and the inclusion of gamified elements (e.g., world rotation, HUD feedback in Figures 4.2-4.4), enhances engagement (IMI 4.2 overall) above and beyond that of desktop VR, which had been called for by Isbel et al. (2024) as a way to increase personalization in VR. Its low-cost (£500) and home-compatible nature solves the problem of accessibility, in contrast to supervised hardware-intensive systems (e.g., Kim et al., 2018). The high SUS (83.3) and low SSQ (4.6) are better than the usability benchmarks of Crowe et al. (2024), confirming user-centred design principles. This makes the prototype a scalable model with potential to achieve improved compliance by 20-30% (Castillo et al. 2024) as well as moves VR from a motivational tool to an intelligent, adaptive platform.

5.4 Implications for Practice

The findings have enormous implications for clinical and home-based rehabilitation. The 100% completion in Easy/Medium levels indicate the prototype could work for novice patients with, for example, stroke or spinal cord injuries, addressing barriers to entry (Matys-Popielska et al. 2024). Clinicians can use the SUS (83.3), and minimal cybersickness (SSQ 4.6) to incorporate it into therapy plans, especially for those with neurological impairments, wherein intuitive hand-tracking reduces cognitive load (Zanatta et al. 2022). The HR Rpm correlation ($R2=0.947$) allows accurate intensity monitoring, ensuring safety within 50-70% HRR, which is a crucial factor with patients who have limited mobility (Reed and Pipe, 2016).

Home use potential coupled with Meta Quest 3's portability helps to fill in the Chapter 2.5's unsupervised setting gap where patients can follow therapy schedules independently. The 87% preference for VR over traditional cycling (mean enjoyment 4.2/5) suggests increased adherence, a challenge reported by Micheluzzi et al. (2024). However, the 46.7% Hard completion rate implies DDA refinements are necessary to avoid overexertion, which needs clinician supervision at the beginning of adaptation. The 73% approval of HR visualization shows the importance of this visualization to patient empowerment, in line with the personalization focus of Lattré et al. (2025).

Practically, healthcare providers can implement this as a low-cost adjunct to traditional ergometers that can improve aerobic training without significant infrastructure. Training programs should include familiarization (1-2 minutes) for maximum usability, while remote monitoring (via Excite-O-Meter logs) may be used to assist in home deployment (Herrera et al. 2024). These benefits should be validated with diverse populations in future clinical trials, potentially leading to a revolution in rehabilitation delivery.

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Appendix

Appendix A: Survey Details

Participant Questionnaire and Post-Session Survey

This questionnaire collects information about participants' experiences during VR HandArm cycling sessions. All responses will remain confidential and anonymised.

Section 1: Participant Questionnaire (Before Sessions)

Please complete this section before starting any cycling session.

1. Age: __________
2. Gender: __________
3. Do you have any prior experience with virtual reality? (Yes/No)
4. How often do you engage in cycling or similar exercise activities? (Daily / Weekly / Occasionally / Never)
5. Do you have any medical conditions that may affect your ability to participate in physical activity? (Yes/No)
   If yes, please specify: __________________________

Section 2: Post-Session Survey (VR HandArm Cycling)

Complete this section after finishing the VR HandArm cycling session.

1. How enjoyable did you find the VR HandArm cycling session? (1-Not enjoyable at all to 5-Extremely enjoyable)
2. How physically demanding did you find the session? (Borg Scale 6–20): ______
3. Did VR make you feel more motivated to cycle compared to traditional cycling? (Yes/No)
4. How comfortable did you feel using the VR setup? (1-Very uncomfortable to 5-Very comfortable)
5. Did you experience any motion sickness or discomfort during the VR session? (Yes/No). If yes, please specify: __________________________
6. Did you find visually seeing your heart rate in VR helpful for motivation or performance? (Yes/No)
7. Additional feedback about your VR HandArm cycling experience: __________________________

Appendix B: SSQ (Simulator Sickness Questionnaire)

Pre and Post-Session Survey

	Rating (0=None, 1=Slight, 2=Moderate, 3=Severe)	Notes
General discomfort		
Fatigue		
Headache		
Eye strain		
Difficulty focusing		
Increased salivation		
Sweating		
Nausea		
Difficulty concentrating		
Blurred vision		

Appendix C: Raw Data

Participai	Ag	Gend	VR_Experie	Exercise_Freq	Medical_Con	Lev	Complet	CompletionTi	FailureCo	TargetAttaine	MeanRI	PeakRI	RPM_Varial	MeanH	HR_Increase_vs_I	RR_r	SSQ_Pre_	SSQ_Post_	SSQ_Cha	SU	IPQ_Pres	NASA_	IMI_Enjoym	IMI_Compet	Borg_F	Enjoym	Physical_Der	Motivation_VR_vs_Tr	Comfc	Motion_Sick	HR_Visualization_Helpful
1	22	Male	Yes	Weekly	No	Easy	1	120	0	100	60	75	5.2	110	20	900	10	12	2	80	90	30	4.5	4	12	4	12	Yes	4	No	Yes
1	22	Male	Yes	Weekly	No	Med	1	150	0	95	70	85	6.1	120	30	880	10	14	4	80	90	35	4	3.8	14	4	14	Yes	4	No	Yes
1	22	Male	Yes	Weekly	No	Hard	0	180	1	80	80	95	7.3	130	40	850	10	16	6	80	85	40	3.8	3.5	16	3	16	Yes	3	Slight dizziness	Yes
2	19	Femal	No	Occasionally	No	Easy	1	115	0	100	58	72	4.8	105	15	920	8	10	2	85	95	25	4.8	4.2	11	5	11	Yes	5	No	Yes
2	19	Femal	No	Occasionally	No	Med	1	140	0	98	68	82	5.9	115	25	900	8	12	4	85	92	30	4.5	4	13	4	13	Yes	4	No	Yes
2	19	Femal	No	Occasionally	No	Hard	1	165	0	90	75	90	6.8	125	35	870	8	14	6	85	90	35	4.2	3.8	15	4	15	Yes	4	No	Yes
3	25	Male	No	Never	Yes (Asthma)	Easy	1	130	0	100	55	70	5	108	18	910	12	15	3	75	88	28	4	3.5	13	4	13	No	3	No	No
3	25	Male	No	Never	Yes (Asthma)	Med	1	160	0	92	65	80	6	118	28	890	12	18	6	75	85	32	3.8	3.2	15	3	15	No	3	Mild nausea	No
3	25	Male	No	Never	Yes (Asthma)	Hard	0	180	1	75	72	88	7	128	38	860	12	22	10	75	80	38	3.5	3	17	2	17	No	2	Moderate nausea	No
4	30	Femal	Yes	Daily	No	Easy	1	110	0	100	62	78	4.9	112	22	930	6	8	2	90	98	20	4.8	4.5	10	5	10	Yes	5	No	Yes
4	30	Femal	Yes	Daily	No	Med	1	135	0	97	70	86	5.8	122	32	910	6	10	4	90	95	25	4.5	4.2	12	5	12	Yes	5	No	Yes
4	30	Femal	Yes	Daily	No	Hard	1	160	0	93	78	92	6.7	132	42	880	6	12	6	90	92	30	4.2	4	14	4	14	Yes	4	No	Yes
5	27	Male	Yes	Occasionally	No	Easy	1	125	0	100	60	74	5.1	110	20	900	9	11	2	82	92	27	4.5	4	12	4	12	Yes	4	No	Yes
5	27	Male	Yes	Occasionally	No	Med	1	145	0	95	68	83	6.2	120	30	880	9	13	4	82	90	32	4.2	3.8	14	4	14	Yes	4	No	Yes
5	27	Male	Yes	Occasionally	No	Hard	0	180	1	82	75	90	7.1	130	40	850	9	15	6	82	87	38	3.8	3.5	16	3	16	Yes	3	Slight dizziness	Yes
6	23	Femal	No	Weekly	No	Easy	1	118	0	100	58	73	4.7	106	16	925	7	9	2	87	94	23	4.7	4.3	11	5	11	Yes	5	No	Yes
6	23	Femal	No	Weekly	No	Med	1	142	0	96	67	81	5.7	116	26	905	7	11	4	87	92	28	4.4	4	13	4	13	Yes	4	No	Yes
6	23	Femal	No	Weekly	No	Hard	1	168	0	91	74	89	6.6	126	36	875	7	13	6	87	90	33	4.1	3.8	15	4	15	Yes	4	No	Yes
7	28	Male	No	Never	No	Easy	1	128	0	100	56	71	5.3	108	18	915	11	14	3	78	89	26	4.2	3.7	12	4	12	No	4	No	No
7	28	Male	No	Never	No	Med	1	158	0	93	66	80	6.1	118	28	895	11	17	6	78	86	31	3.9	3.4	14	3	14	No	3	No	No
7	28	Male	No	Never	No	Hard	0	180	1	78	73	87	7	128	38	865	11	20	9	78	83	37	3.6	3.2	16	3	16	No	2	Mild nausea	No
8	21	Femal	Yes	Weekly	No	Easy	1	112	0	100	61	76	4.8	111	21	920	8	10	2	88	96	22	4.6	4.2	11	5	11	Yes	5	No	Yes
8	21	Femal	Yes	Weekly	No	Med	1	138	0	97	69	84	5.9	121	31	900	8	12	4	88	93	27	4.3	4	13	4	13	Yes	4	No	Yes
8	21	Femal	Yes	Weekly	No	Hard	1	162	0	92	77	91	6.8	131	41	870	8	14	6	88	91	32	4	3.8	15	4	15	Yes	4	No	Yes
9	26	Male	No	Occasionally	Yes (Mild hyperte	Easy	1	130	0	100	57	72	5	109	19	910	10	13	3	76	90	29	4.1	3.6	13	4	13	No	3	No	No
9	26	Male	No	Occasionally	Yes (Mild hyperte	Med	1	160	0	94	67	81	6	119	29	890	10	16	6	76	87	34	3.8	3.3	15	3	15	No	3	No	No
9	26	Male	No	Occasionally	Yes (Mild hyperte	Hard	0	180	1	80	74	88	7	129	39	860	10	19	9	76	84	39	3.5	3.1	17	2	17	No	2	Mild nausea	No
10	24	Femal	Yes	Daily	No	Easy	1	108	0	100	63	78	4.7	113	23	930	5	7	2	92	99	19	4.9	4.6	10	5	10	Yes	5	No	Yes
10	24	Femal	Yes	Daily	No	Med	1	132	0	98	71	86	5.8	123	33	910	5	9	4	92	96	24	4.6	4.3	12	5	12	Yes	5	No	Yes
10	24	Femal	Yes	Daily	No	Hard	1	158	0	94	79	93	6.7	133	43	880	5	11	6	92	93	29	4.3	4.1	14	4	14	Yes	4	No	Yes
11	29	Male	Yes	Weekly	No	Easy	1	122	0	100	59	74	5.1	107	17	915	9	11	2	84	93	25	4.4	4	12	4	12	Yes	4	No	Yes
11	29	Male	Yes	Weekly	No	Med	1	148	0	95	68	82	6	117	27	895	9	13	4	84	90	30	4.1	3.8	14	4	14	Yes	4	No	Yes
11	29	Male	Yes	Weekly	No	Hard	0	180	1	83	76	90	6.9	127	37	865	9	15	6	84	88	35	3.8	3.5	16	3	16	Yes	3	Slight dizziness	Yes
12	20	Femal	No	Occasionally	No	Easy	1	116	0	100	58	73	4.9	106	16	925	7	9	2	86	95	24	4.7	4.3	11	5	11	Yes	5	No	Yes
12	20	Femal	No	Occasionally	No	Med	1	140	0	96	67	81	5.8	116	26	905	7	11	4	86	92	29	4.4	4	13	4	13	Yes	4	No	Yes
12	20	Femal	No	Occasionally	No	Hard	1	165	0	91	74	89	6.7	126	36	875	7	13	6	86	90	34	4.1	3.8	15	4	15	Yes	4	No	Yes
13	31	Male	No	Never	No	Easy	1	129	0	100	56	71	5.2	108	18	910	12	15	3	74	88	28	4	3.5	13	4	13	No	3	No	No
13	31	Male	No	Never	No	Med	1	159	0	93	66	80	6.1	118	28	890	12	18	6	74	85	33	3.7	3.2	15	3	15	No	3	No	No
13	31	Male	No	Never	No	Hard	0	180	1	77	73	87	7	128	38	860	12	21	9	74	82	38	3.4	3	17	2	17	No	2	Moderate nausea	No
14	23	Femal	Yes	Weekly	No	Easy	1	113	0	100	61	76	4.8	111	21	920	8	10	2	89	96	22	4.6	4.2	11	5	11	Yes	5	No	Yes
14	23	Femal	Yes	Weekly	No	Med	1	137	0	97	69	84	5.9	121	31	900	8	12	4	89	93	27	4.3	4	13	4	13	Yes	4	No	Yes
14	23	Femal	Yes	Weekly	No	Hard	1	161	0	92	77	91	6.8	131	41	870	8	14	6	89	91	32	4	3.8	15	4	15	Yes	4	No	Yes
15	27	Male	Yes	Occasionally	No	Easy	1	124	0	100	60	75	5	110	20	900	9	11	2	83	92	26	4.5	4	12	4	12	Yes	4	No	Yes
15	27	Male	Yes	Occasionally	No	Med	1	146	0	95	68	82	6	120	30	880	9	13	4	83	90	31	4.2	3.8	14	4	14	Yes	4	No	Yes
15	27	Male	Yes	Occasionally	No	Hard	0	180	1	82	75	90	7	130	40	850	9	15	6	83	87	36	3.8	3.5	16	3	16	Yes	3	Slight dizziness	Yes

CompletionTime_s		FailureCount		TargetAttained_pct		MeanRPM		PeakRPM		RPM_Variability		MeanHR	
Mean	145.9777778	Mean	0.177777778	Mean	93.57777778	Mean	67.44444444	Mean	82.11111111	Mean	5.937777778	Mean	118.9333333
Standard Error	3.443848107	Standard Error	0.057637748	Standard Error	1.091514048	Standard Error	1.065319014	Standard Error	1.046988091	Standard Error	0.121243094	Standard Error	1.277386853
Median	145	Median	0	Median	95	Median	68	Median	82	Median	6	Median	119
Mode	180	Mode	0	Mode	100	Mode	68	Mode	90	Mode	7	Mode	110
Standard Deviation	23.10203542	Standard Deviation	0.386645767	Standard Deviation	7.322098833	Standard Deviation	7.146377199	Standard Deviation	7.02340963	Standard Deviation	0.813323398	Standard Deviation	8.568971509
Sample Variance	533.7040404	Sample Variance	0.149494949	Sample Variance	53.61313131	Sample Variance	51.07070707	Sample Variance	49.32828283	Sample Variance	0.661494949	Sample Variance	73.42727273
Kurtosis	-1.228785368	Kurtosis	1.088937775	Kurtosis	0.382051473	Kurtosis	-1.136942232	Kurtosis	-1.163895181	Kurtosis	-1.34247942	Kurtosis	-1.308756598
Skewness	0.058296537	Skewness	1.744280324	Skewness	-1.201307555	Skewness	-0.098018924	Skewness	-0.088871792	Skewness	-0.027677834	Skewness	-0.000409261
Range	72	Range	1	Range	25	Range	25	Range	25	Range	2.6	Range	28
Minimum	108	Minimum	0	Minimum	75	Minimum	55	Minimum	70	Minimum	4.7	Minimum	105
Maximum	180	Maximum	1	Maximum	100	Maximum	80	Maximum	95	Maximum	7.3	Maximum	133
Sum	6569	Sum	8	Sum	4211	Sum	3035	Sum	3695	Sum	267.2	Sum	5352
Count	45	Count	45	Count	45	Count	45	Count	45	Count	45	Count	45

HR_Increase_vs_Baseline		RR_ms		SSQ_Pre_Total		SSQ_Post_Total		SSQ_Change		SUS		IPQ_Presence	
Mean	28.93333333	Mean	892	Mean	8.733333333	Mean	13.28888889	Mean	4.555555556	Mean	83.26666667	Mean	90.311
Standard Error	1.277386853	Standard Error	3.439227068	Standard Error	0.298819225	Standard Error	0.507143139	Standard Error	0.321856288	Standard Error	0.824743609	Standard Error	0.6283
Median	29	Median	895	Median	9	Median	13	Median	4	Median	84	Median	
Mode	20	Mode	900	Mode	8	Mode	11	Mode	6	Mode	80	Mode	
Standard Deviation	8.568971509	Standard Deviation	23.07103655	Standard Deviation	2.004540301	Standard Deviation	3.402019602	Standard Deviation	2.159077618	Standard Deviation	5.53254832	Standard Deviation	4.2148
Sample Variance	73.42727273	Sample Variance	532.2727273	Sample Variance	4.018181818	Sample Variance	11.57373737	Sample Variance	4.661616162	Sample Variance	30.60909091	Sample Variance	17.764
Kurtosis	-1.308756598	Kurtosis	-1.002837389	Kurtosis	-0.658848861	Kurtosis	0.230383087	Kurtosis	-0.089451491	Kurtosis	-1.094594138	Kurtosis	-0.0849
Skewness	-0.000409261	Skewness	-0.197323585	Skewness	0.012677733	Skewness	0.6503141	Skewness	0.636701612	Skewness	-0.245825298	Skewness	-0.2734
Range	28	Range	80	Range	7	Range	15	Range	8	Range	18	Range	
Minimum	15	Minimum	850	Minimum	5	Minimum	7	Minimum	2	Minimum	74	Minimum	
Maximum	43	Maximum	930	Maximum	12	Maximum	22	Maximum	10	Maximum	92	Maximum	
Sum	1302	Sum	40140	Sum	393	Sum	598	Sum	205	Sum	3747	Sum	
Count	45	Count	45	Count	45	Count	45	Count	45	Count	45	Count	

NASA_TLX		IMI_Enjoyment		IMI_Competence		Borg_RPE		Enjoyment		Physical_Demand	
Mean	29.95555556	Mean	4.18	Mean	3.795555556	Mean	13.6	Mean	3.866666667	Mean	13.6
Standard Error	0.784931031	Standard Error	0.056371782	Standard Error	0.058857434	Standard Error	0.284977405	Standard Error	0.121439181	Standard Error	0.284977405
Median	30	Median	4.2	Median	3.8	Median	14	Median	4	Median	14
Mode	30	Mode	3.8	Mode	4	Mode	13	Mode	4	Mode	13
Standard Deviation	5.265477426	Standard Deviation	0.378153408	Standard Deviation	0.39482767	Standard Deviation	1.911686547	Standard Deviation	0.814638793	Standard Deviation	1.911686547
Sample Variance	27.72525253	Sample Variance	0.143	Sample Variance	0.155888889	Sample Variance	3.654545455	Sample Variance	0.663636364	Sample Variance	3.654545455
Kurtosis	-0.653166192	Kurtosis	-0.713257529	Kurtosis	-0.496321828	Kurtosis	-0.857814858	Kurtosis	0.117472938	Kurtosis	-0.857814858
Skewness	-0.026611782	Skewness	-0.104293084	Skewness	-0.2668445	Skewness	-0.007353517	Skewness	-0.537316689	Skewness	-0.007353517
Range	21	Range	1.5	Range	1.6	Range	7	Range	3	Range	7
Minimum	19	Minimum	3.4	Minimum	3	Minimum	10	Minimum	2	Minimum	10
Maximum	40	Maximum	4.9	Maximum	4.6	Maximum	17	Maximum	5	Maximum	17
Sum	1348	Sum	188.1	Sum	170.8	Sum	612	Sum	174	Sum	612
Count	45	Count	45	Count	45	Count	45	Count	45	Count	45

Appendix D: Participant Consent Form

Participant Consent Form

Project Title

An immersive VR for hand-arm cycling rehabilitation with integrated physiological feedback

Principal Researcher Contact Details

Researcher Name: Prasanna Kumar

Email: 2442549@swansea.ac.uk

Supervisor's Name: Seb Vowels, Ted Thomas, and Peter Dorrington

		Participant initial
1.	I confirm that I have read and understand the information sheet for the above study, which is attached to this form.	
2.	I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reasons.	
3.	I understand what my role will be in this research, and all my questions have been answered to my satisfaction.	
4.	I understand that I am free to ask any questions at any time before and during the study.	
5.	I understand that sections of any of data obtained may be looked at by responsible individuals from the Swansea University or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access these records.	
6.	I am happy for the information I provide to be used in academic papers and other formal research.	
7.	I am willing for my information to be audio recorded.	
8.	I have been provided with a copy of the Participant Information Sheet.	
9.	I agree to the researchers processing my personal data in accordance with the aims of the study described in the Participant Information Sheet.	

Name of participant	Signature	Date
Name of researcher	Signature	Date

Thank you for your participation in this study. Your help is very much appreciated.