MIXED REALITY IN SPORTS TRAINING: A CYBER-PHYSICAL APPROACH TO ENHANCING ROWING TECHNIQUE AND PERFORMANCE

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Rowing is a high-intensity cooperative sport in which consistent training with teammates plays a vital role in learning and improving the inherent techniques and more importantly, coordination among the teammates. However, on-water training is highly dependent on the weather conditions, which drastically affects training schedules and makes individual training difficult, especially in the absence of other teammates and coaches. Current substitutes to on-water training include rowing ergometers which provide preliminary feedback to their users about the forces generated by these users but do not provide any visual feedback, which plays a pivotal role in team coordination and skill adaptation in rowing. This paper presents a novel integration of virtual reality (VR) with ergometer-based training to provide a more "complete" and immersive experience to the user, bridging the gap between on-water and indoor training. Additionally, new feedback cues are designed, leveraging this integration, to help improve the overall technique of the user. The effectiveness of this simulator, to act as an immersive stand-alone VR training module, is demonstrated using human-interaction studies involving trained and novice rowers.

BIOGRAPHICAL SKETCH

Madhav Gupta was born in Kanpur, India in 1997. He earned a Bachelor's degree in Mechanical Engineering from Manipal Institute of Technology in 2019. During his undergrad, Madhav led the creation of a Solar Electric Vehicle, winning the ASME Design Achievement award in 2018. After graduating, Madhav worked at Tata Motors as Project Manager, helping design and prototype the Tata Ace EV which won Indian Electric Commercial Vehicle of the Year in 2022. Seeking to further his education, Madhav joined Cornell University where he worked under Dr. Silvia Ferrari at the Laboratory for Intelligent Systems and Control (LISC), specializing in control and dynamics. At Cornell, Madhav contributed to the Sustainable Design project team, facilitating solar roof installation for carbon-neutral electric bus charging. At LISC, he helped develop the "RealTHASC-A Cyber-Physical XR Testbed" to bridge simulation and reality for human-robot research. Culminating his academic journey, Madhav co-developed an immersive rowing simulator with William Kingston for his thesis. After Cornell, Madhav will join Weber, Inc in Kansas City as a Digital Twin Engineer where he will be spearheading the advancement of Virtual Reality technologies for engineering, marketing, and training.

This document is dedicated to all Cornell graduate students.

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CHAPTER 1

INTRODUCTION

A typical stern-coxed eight-oared rowing boat consists of two stern rowers, four starboard rowers, and two bow rowers, along with one coxswain sitting in front of the last stern rower at the other end of the boat. The coxswain does not row but is responsible for steering the boat and deciding and announcing the stroke rate targets to the rowers amidst the race. The stern pair of rowers implement the decided stroke rate and set the rhythm to be followed by all the other rowers behind them. Thus, with audio feedback from the coxswains and visual feedback from the stern pair, the rowers aim to synchronize their movement. Thus, responding to or interacting with such audio-visual stimulus, experienced during races or on-water training, is a significant part of the rowing technique and hence plays a significant role in determining the on-water performance of the rowers.

Since rowing is a team sport, disambiguating individual performance from team performance is very difficult and subject to a large amount of variance possibly originating from other team members. Thus, professional rowing teams use tools like smart oarlocks [28] and smart padlocks to evaluate the technique of the rowers online, by communicating the displaying the data obtained by these sensors on a screen carried by the coach or for evaluation after training. In an online setting, the coach then observes the information from the sensors and suggests improvements to the rowers. An important thing to note here is that the rower does not observe this information first-hand while rowing due to which some information might get lost during communication with the coach.

Additionally, on-water training is subject to a lot of factors that may prevent consistent training. Strong unfavorable wind and water currents, occasional rainfall, and freezing water in cold-temperate regions are some of the weather conditions which render training infeasible around the year.

These reasons have promoted the use of rowing ergometers to aid indoor training and have been widely adopted by several competitive teams. Significant research has been done to compare on-water training with ergometers and analyze the key differences. Apart from the kino-dynamic and tactile difference due to the design outlined in the literature, this paper aims to focus on the visual information provided to the rower in a session and its significance on the rower's performance. While current ergometers do provide visual feedback about the force curve at each stroke, they do not actively train the user to incorporate the audio-visual stimulus from the coxswain and the stern pair. Additionally, the information displayed to the user is per-stroke information. This underconstrained nature of the visual feedback fails to enforce or imbibe the transition between two strokes or the rhythm required in rowing with teammates.

1.1 Background on a rowing stroke

The rowing stroke is a complex and rhythmic sequence of movements that involves several stages: catch, drive, finish, and recovery. These stages work together to propel the rowing shell through the water efficiently and effectively. Each stage requires coordinated movements from the rowers to generate power and maximize boat speed. In this section, we will provide a brief overview of each stage of the rowing stroke, from catch to release. Exploring specific parameters, technique modifications, and the use of telemetered sensors on rowing skiffs can aid coaches and biomechanists in improving rowing technique and performance [45].

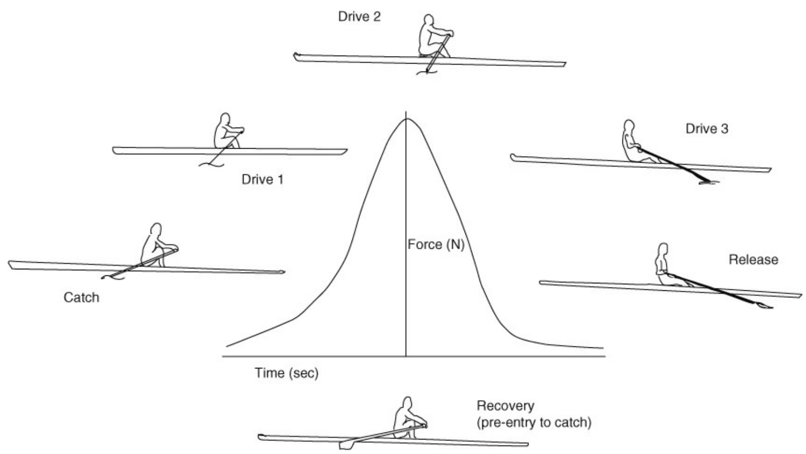

Figure 1.1: Schema of the main phases and force-time characteristics of the propulsive rowing stroke [30]

Catch: The catch is the initial phase of the rowing stroke where the rower prepares to drive the boat forward. It begins with the rower sitting at the front of the sliding seat, knees bent, and arms extended forward. The rower's blade is fully immersed in the water, positioned perpendicularly to the boat's direction. The rower's body is leaning forward, and the core muscles are engaged to maintain stability.

Drive: The drive is the power phase of the rowing stroke where the rower generates force to propel the boat forward. It starts with the rower pushing with the legs while maintaining a firm grip on the handle and initiating the movement with the core and back muscles. As the rower pushes with the legs, the arms start to draw the handle towards the body, and the blade begins to angle towards the stern of the boat, propelling the water aft. The rower's body position shifts from a forward lean to an upright position, while maintaining good posture and engaging the major muscle groups.

Finish: The finish is the final phase of the drive where the rower completes the application of power and prepares for the recovery. The rower continues to push with the legs, while simultaneously pulling the handle towards the body with the arms, keeping the blade angled towards the stern. The rower's body is in an upright position, and the legs are fully extended, with the core and back muscles engaged to maintain stability and transmit power efficiently.

Recovery: The recovery is the phase of the rowing stroke where the rower prepares for the next catch by returning to the starting position. It starts with the rower releasing the handle and allowing the blade to come out of the water smoothly. The rower then begins to slide forward on the seat, allowing the boat to run freely. The rower's arms are extended forward, and the body leans slightly forward. Once the seat reaches the front of the slide, the rower bends the knees and prepares for the next catch.

The rowing stroke is a continuous and coordinated cycle of catch, drive, finish, and recovery that requires precise technique, timing, and strength. Each stage of the stroke is interconnected, and a well-executed stroke can significantly impact boat speed and efficiency. Proper training and technique development are crucial for rowers to master each stage of the rowing stroke and achieve optimal performance on the water.

1.2 Training in Rowing

Three primary training modalities exist for rowers to develop and refine technique: on-water rowing, tank rowing, and ergometer rowing. Each approach confers distinct advantages as well as limitations.

On-water rowing in genuine boats most closely approximates real race conditions. It provides natural hydraulic drag and vessel dynamics. Rowers can practice synchronizing oar strokes with crewmates and adapting to variables like wind velocity. However, outdoor training remains contingent on meteorological suitability and navigable waterways. It necessitates transporting equipment and oversight for safety precautions.

Indoor rowing tanks utilize machines that simulate rowing motions in an enclosed setting unaffected by weather. Tanks proffer stability for focused technique work and analysis. However, the artificial mechanical resistance diverges from authentic aqueous dynamics. Tank facilities require substantial capital to construct and constrain the number of vessels.

Ergometers like the Concept 2 are ubiquitous dryland training implements due to fiscal affordability and compact dimensions. Ergs enable quantitative data capture for comparative metrics. However, they lack the immersive environs of on-water rowing. The seated ergometer posture also differs from the in-boat position.

While valuable, each methodology exhibits deficiencies for comprehensive skill development. Outdoor rowing lacks reliability and geographic scalability. Tanks provide unrealistic sensations. Ergometers isolate rowers from real-time external feedback.

An integrated approach synthesizing indoor control and data with on-water verisimilitude could ameliorate these limitations. A VR simulator endeavors to replicate open water environments while furnishing personalized performance feedback. By synthesizing the advantages of both domains, the objective is translating comprehensive, consistent on-water training indoors.

1.3 Motivation

Virtual Reality (VR) technology has revolutionized the way we train for sports, offering a way to practice in a controlled and safe environment. One sport that has benefitted from VR technology is rowing, which traditionally requires access to natural waterways such as rivers or lakes. In areas where waterways are not always accessible due to weather or other factors, a VR rowing simulator can be an effective solution to maintain training throughout the year. In this essay, we will explore the reasons why a VR rowing simulator can be a valuable training tool, particularly for those living in colder climates where waterways can freeze in the winter.

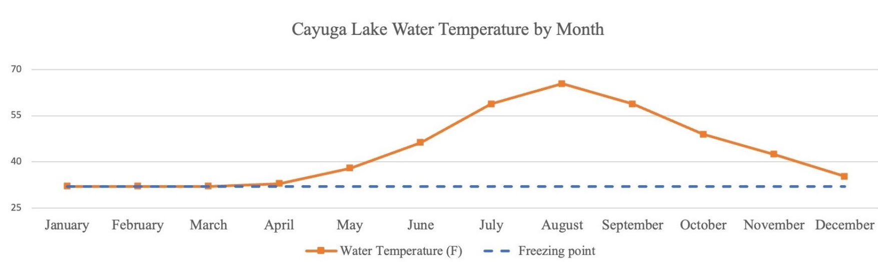

Figure 1.2: Lake Temperatures over the year

Firstly, a VR rowing simulator allows for weather-independent training. Rowing on natural waterways can be affected by the weather, with conditions such as high winds or rough waters making it unsafe or impossible to row. With a VR rowing simulator, weather conditions are irrelevant, and rowers can train regardless of the weather outside. This means that rowers can maintain a consistent training regimen, avoiding interruptions to their progress due to inclement weather. In colder climates such as the Northeast US, where lakes can freeze in the winter, a VR rowing simulator offers a way to maintain training throughout the year, regardless of the season or weather.

Secondly, a VR rowing simulator can be customized to a rower's specific needs. Each rower has different strengths and weaknesses, and a VR rowing simulator can be programmed to focus on specific areas that need improvement. For example, if a rower needs to work on their endurance, the simulator can be programmed to simulate a longer distance or a longer time. If a rower needs to work on their power output, the simulator can be programmed to increase the resistance or the intensity of the workout. This means that each rower can receive personalized training that is tailored to their specific goals and weaknesses.

Thirdly, a well-designed VR rowing simulator can accurately replicate the feel and motion of rowing on water, providing a realistic training experience. This can be particularly useful for beginners or those who are unable to access waterways regularly. In a simulator, rowers can develop their technique and build muscle memory in a controlled and safe environment. This means that when they do eventually get out on the water, they will have already developed the skills and muscle memory needed to row effectively.

Lastly, many VR rowing simulators come equipped with analytics tools that provide real-time feedback on performance metrics such as stroke rate, power output, and distance covered. This can help rowers to monitor their progress and make adjustments to their technique and training plan as needed. Analytics can also be used to compare performance over time, allowing rowers to track their progress and identify areas that need further improvement.

In conclusion, a VR rowing simulator can provide a weather-independent, personalized, realistic, and data-driven training experience for rowers. Investing in a simulator could be a worthwhile investment, particularly if you are committed to improving your performance and unable to access natural waterways regularly. With a VR rowing simulator, you can train year-round, regardless of the weather outside, and receive personalized training that is tailored to your specific needs. Additionally, the ability to practice in a controlled and safe environment can help rowers to develop their technique and build muscle memory, which will ultimately lead to better performance on the water. Overall, a VR rowing simulator is an effective and valuable training tool that can help rowers achieve their goals and reach their full potential.

1.4 Literature Review

Extended reality (XR) is a rapidly evolving technology that has the potential to revolutionize the way humans train. XR encompasses a variety of technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR). These technologies can be used to create immersive and interactive training environments that can help athletes to improve their skills, learn new techniques,

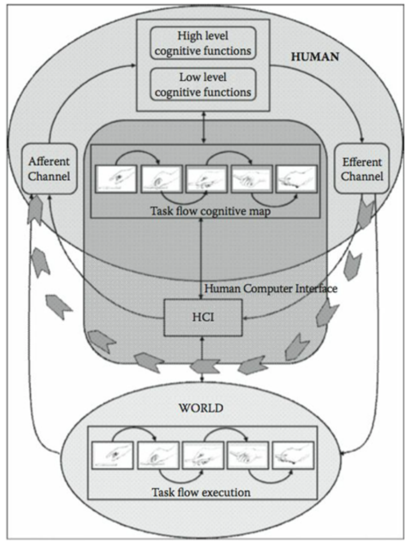

Figure 1.3: The role of human-computer interaction in the performance of a skill [9]

and prepare for competition.

According to the book on skill training in multimodal virtual environments [10], skill acquisition and training is a complex process that involves motor, perceptual and cognitive abilities. As given in 1.3, using environments in extended reality (XR), by concentrating on the thoughtful design of the interaction process between the human operator and the virtual environment, the objective is to enable the human operator to achieve higher performance in the acquisition of the skill.

1.4.1 Virtual Environments for Skill Training

The concept of presence in Virtual Environments (VEs) has been a focal point since the late 1980s. Sheridan (1992) [42] defined three determinants for the sense of presence in teleoperators and VEs: 1) The amount of sensory information conveyed to the human operator affects the sense of being present in the environment. 2) The ability to move sensors enhances the perception of the environment. 3) Control over the environment, including grasping objects, influences the sense of presence. Achieving maximum values for these determinants leads to a true sense of presence, but current VE technologies still fall short due to technological limitations, especially regarding haptics and robotics systems.

Sensorimotor contingencies (SCs) are the relationships between user actions and the corresponding changes in sensory inputs (i.e., actions we perform to perceive). A VE system can support specific SCs that contribute to the perception of the environment. Implementing SCs similar to those in a real environment can create the illusion of presence in the VE, also known as the ”sense of being there” [24]. Involvement of a human operator in a task and their ability to learn and maintain control in the face of perturbations create a perceptual ”flow” in which all components of a multimodal Virtual Environment system exchange information [31].

VE systems usually lack awareness of the task conducted by the human operator, but in Avizzano et al. [5], a digital representation of skill allows the system to understand and model the relationship between constraints and adjust operative conditions for better training performance. This enables functionalities such as benchmarking task performance, generating autonomous characters that learn from human demonstration, and tailoring the training procedure based on individual subject characteristics.

Simulated and virtual environments are increasingly utilized for teaching and training across various domains [15, 19, 22, 27]. Studies have shown that training on simulators improves knowledge acquisition and retention compared to traditional lectures [13]. Multimodal interfaces enhance the sense of presence and experiential fidelity, especially when incorporating haptic sensations [37]. However, one must distinguish between subjective fidelity (presence) and action fidelity (performance transfer) when evaluating training in multimodal environments [46]. Overall, virtual reality proves to be a valuable tool for efficient teaching and learning, providing a more complete and coherent experience of the virtual world [38].

1.4.2 Skill Training and VR in Sports

There is a growing body of research that suggests that XR can be an effective tool for skill training in sports. For example, a study by the University of Southern California found that VR training can help to improve the accuracy of basketball free throws [3]. Another study by the University of Cambridge found that AR training can help to improve the performance of tennis players [12].

According to Dempsey et al. [17], there are a number of benefits to using XR for skill training in sports. First, XR can provide athletes with a safe and controlled environment in which to practice. This is important for sports that involve a high risk of injury, such as football and rugby. Second, XR can be used to simulate real-world conditions and environments. This can help athletes to prepare for competition and to overcome any psychological barriers that they may have. Third, XR can be used to provide athletes with real-time feedback on their performance. This feedback can help athletes to identify and correct any errors in their technique.

The success and validity of virtual worlds are commonly assessed by measures of presence and performer's immersion [40]. However, for skill training platforms, the guiding constructs are relevance, facilitation, and transferability [10]. Relevance involves providing experiences that develop competency and skills for a targeted task. Facilitation includes introducing guidance to accelerate skill acquisition. Transferability emphasizes the transfer of knowledge and competencies from VR training to real-world task performance.

Assistive technologies have seen advancements over the years, contributing to improved physiological, biomechanical, and perception-action skills in sports training. Virtual Reality (VR) has gained attention in highly demanding cognitive tasks and has extended to physical training, including sports training using robotic and haptic systems [32]. Research in sports training focuses on complex skills in goal-oriented and task-oriented situations, as well as specific perceptual and motor patterns [51]. VR has been used to develop immersive scenarios for goalkeepers in football [11] and rowers to evaluate how perception influences decision-making [50]. Rowing, with its periodic and constrained nature, makes it an efficient sport for VR training. While physical competencies are time-consuming to develop, current rowing training systems tend to favor physical capabilities over technique or perceptual-motor variables. Continuous monitoring and systematic training of skills like rowing technique and team coordination are often lacking, making VR training a valuable tool for addressing these limitations [7].

1.4.3 Rowing in VR

Rowing involves intricate technique and synchronization of whole-body movements. While rowing machines like the Concept 2 capture physiological metrics of the rowing action, they lack fidelity in mimicking the on-water experience [44]. Virtual reality has shown potential for enhancing the specificity of indoor rowing training.

In VR environments synchronized with rowing ergometers, rowers can practice rowing technique while receiving real-time biofeedback on parameters like handle force profiles that should match ideal on-water kinematics [29]. Handle force emulate the blade forces of an oar, and its blade force was found to be the only propulsive force to counter the drag forces, consisting of both air drag and hydrodynamic drag, acting on the system, whereas vertical oscillations of the shell are shown to have minimal impact on system dynamics [8]. Moreover, studies show that rowers adjust their form on the machine to more closely reflect proper on-water technique when using VR simulation tools [26][48].

According to Nolte [35], there are three main areas of training: 1) technique optimization, 2) energy management, 3) team coordination. Beyond technique, Ruffaldi et al [39] presents the development of a virtual reality rowing training system called SPRINT that integrates multimodal interfaces, task modeling, performance metrics, and adaptive training protocols to energy management [26], and coordination skills [49].

The research mentioned here uses a variety of technologies for digital representation of feedback. SPRINT integrates instrumented RP3 and Concept 2 ergometers with Vicon motion capture, vibrating bracelets, LCD/VR visuals, and audio to enable multimodal interfaces for performance capture, feedback, and immersive training [39]. Arndt et al [4] used Auglectics Eight2 for force feedback and Unity projects to create visualizations of the virtual environment. The research used ergo handles for a haptic force feedback and Sweetzpot to track breathing. The studies discussed showcase the potential of virtual reality environments to enhance rowing training across key areas like technique, coordination, and energy management. However, rigorously validating these simulated training systems requires carefully designed experimental methodologies.

The SPRINT virtual reality rowing simulator has undergone extensive testing and validation to evaluate its effectiveness for sports training across multiple skill facets. Ruffaldi et al. [39] systematically tested combinations of visual, vibrotactile, and force feedback for improving trajectory accuracy, finding multisensory cues optimal. Studies by Hoffmann et al. [26] and Varlet et al. [49] validated VR protocols for training energy management and team coordination respectively through controlled experiments. Korman et al. [21] quantified improvements in rowing competencies from multimodal feedback. Biomechanical modeling and data fusion enabled personalized feedback on technique. Experiments tracked objective performance metrics like timing errors while also assessing subjective experiences via questionnaires. Both novice and expert rowers were tested. The studies overall validated the benefits of VR training for engagement, motivation, learning outcomes, and real-world transfer. The mixed methods experimentally demonstrated the simulator's capabilities in improving rowing skills.

Beyond training, VR engages other aspects of high-performance rowing.

Rowers report increased motivation and enjoyment of indoor training with VR games and environments compared to ergometer rowing alone [33, 43]. VR facilitates coaching as well - recordings of rowing sessions can be reviewed in slow-motion VR recreations to pinpoint areas for refinement [4].

While VR training aids to optimize technique for movement and coordination, the simulation cannot perfectly replicate the feel of water resistance and boat dynamics [29]. However, studies show that transferring the skills acquired through VR rowing results in performance improvements on actual water [26, 48]. VR is best employed alongside on-water training - not as a complete substitute, but as a supplemental tool for technique instruction, motivation, and previewing the holistic sensations of rowing [1, 4]. Just as with actual rowing, effective VR training requires integrating biomechanical data with subjective feedback from the rower [23]. Further innovations in VR and associated feedback systems can help bring the on-water experience to indoor rowing.

1.5 Objective and Key Contributions

The overarching goal of this research is to transcend the conventional boundaries of sports training by synergizing virtual reality (VR) tools with on-water rowing telemetry and instrumentation. This section elucidates the primary objective of bridging the gap between on-water and indoor training, thereby engendering a cyber-physical paradigm that revolutionizes rowing technique and performance enhancement. Through a meticulous fusion of technology and athletic training, this research endeavors to forge a transformative path towards more realistic and effective indoor training environments.

This research constitutes a pioneering endeavor that yields three significant contributions to the community, ushering in a paradigm shift in sports training methodology:

Realistic Immersion Beyond Simulated Environments: While standard practices frequently rely on simulated environments created using programs like Unity or Netathlon [4, 26]. This research introduces a novel strategy that goes beyond simulated constructs. The simulator developed here distinguishes itself by delivering a truly immersive 360-degree experience. This simulator propels rowers into a training environment that accurately mimics the difficulties and dynamics of actual rowing by fusing VR technology with accurate on-water rowing telemetry. Training effectiveness and realism are elevated to levels that were never before achieved by this authentic and immersive training environment, which represents a major departure from conventional simulated environments.

Data-Driven Feedback Loop for Enhanced Performance: A hallmark contribution of this research lies in its capacity to leverage real training data to establish a dynamic feedback loop for users. Unlike previous state-of-the-art methods that primarily utilized data for retrospective analysis [39, 5], this research pioneers the integration of real performance data into the VR environment. This novel approach empowers rowers with actionable insights derived from their actual on-water training sessions. The assimilation of authentic performance metrics into the VR training domain not only fosters heightened engagement but also fuels a continuous cycle of performance refinement. The integration of data acquisition and live feedback propels rowers towards optimal technique and performance, imbuing training sessions with a heightened sense of purpose and progression.

Real-Time Technique Adjustment: The third pivotal contribution emanates from the research's ability to provide rowers with live feedback on their performance, facilitating real-time adjustments to technique. In contrast to prior approaches such as Arndt's inclusion of text feedback like ″go!″ or ″row″ [4] and Murray's utilization of a box display turning red to indicate when rowing should commence, this research adopts a superior real-time feedback methodology [33]. This approach offers a more nuanced and comprehensive feedback mechanism, enhancing rowers' responsiveness to technique adjustments during their training sessions. This real-time technique adjustment paradigm is a transformative departure from conventional methodologies, bolstering the efficiency and efficacy of training sessions. By integrating immediate feedback with live rowing experiences, this research bridges a chasm that has long hindered the agility of technique refinement in sports training

In essence, this research embodies an avant-garde fusion of cyber-physical realms, rendering the conventional demarcations between on-water and indoor training obsolete. Through its multifaceted contributions, it endeavors to redefine the landscape of rowing training, inspiring a new era of realism, precision, and performance elevation.

1.6 Challenges

The development of the rowing simulator project presented several challenges and required careful implementation considerations to ensure its success. These challenges encompassed various aspects of the project, including video representation, user interface design, minimizing time-lag for real-time feedback, and implementing effective feedback cues.

One of the primary challenges was collecting video footage that accurately represented the rowing technique. It was essential to capture different angles and perspectives that faithfully conveyed the intricacies of proper rowing form. Meticulous planning and coordination were necessary to ensure the availability of high-quality video footage that effectively portrayed the essential elements of the rowing stroke.

Designing an interactive and intuitive user interface posed another significant challenge. The user interface needed to provide a seamless and immersive experience, enabling users to navigate through the training modules and access feedback and performance metrics effortlessly. Extensive user testing and iterative design processes were employed to create a user interface that was intuitive, visually appealing, and facilitated efficient interaction with the simulator.

Minimizing the time-lag between the user's actions and the corresponding feedback from the simulator was a crucial implementation consideration. Real-time feedback was vital to create a seamless and responsive training experience. Advanced programming techniques, data processing optimization, and leveraging high-performance computing resources were employed to minimize time-lag and ensure that the virtual environment and feedback cues were synchronized with the user's movements in real-time.

Providing effective feedback cues for enhanced user experience and evaluation was also a significant consideration. The simulator needed to deliver feedback in a manner that was meaningful, easily interpretable, and facilitated performance evaluation. Algorithms were developed to analyze stroke characteristics, such as timing, stroke length, and maximum force, translating this data into actionable feedback cues. Designing feedback mechanisms that were informative, motivational, and helped users refine their technique and optimize their performance was a primary focus.

By addressing these challenges and implementing thoughtful considerations, the rowing simulator project successfully created an immersive training environment that closely emulated real-life rowing conditions. The project's accomplishments in accurately representing rowing techniques, designing an interactive user interface, minimizing time-lag, and implementing effective feedback cues have significantly enhanced the overall effectiveness, user experience, and evaluation capabilities of the simulator.

The insights gained from overcoming these challenges can serve as a valuable foundation for future research and development in the field of virtual reality-based training systems for rowing and other sports. Further exploration can focus on optimizing video representation, improving user interfaces, reducing latency, and refining feedback mechanisms, ultimately leading to more advanced and immersive training platforms.

Overall, the successful resolution of these challenges and the thoughtful implementation considerations have made substantial contributions to the field of sports training technology. The rowing simulator project provides a valuable tool for rowers and coaches to enhance performance, technique, and overall training outcomes, paving the way for further advancements in the use of virtual reality in sports training.

1.7 Approach

The development of the immersive rowing simulator centered on integrating multiple technologies to enable impactful technique training. The approach focused on three key areas:

Immersive Environment: To maximize training impact, the visualizations are rendered within an engaging, gamified virtual environment. The integration of VR technology with the data analytics pipeline creates a responsive simulation that engages users. The immersive experience also promotes motor learning as users adjust their motions based on real-time visual cues [41]

Real-Time Visual Feedback: The key component of the simulator is the real-time visual feedback delivered to the rower in the virtual reality environment. Visual cues like overlaid force curves, color mappings, and timing markers are generated based on the data analysis, highlighting technique errors. Elite rowing crews keep their force curves similar over multiple strokes and multiple people [25], which leads to the importance of an overlaid force curve. The intuitive visualizations are continuously updated, providing dynamic feedback throughout the rowing motion.

Data Acquisition and Analysis: The rowing ergometer and motion sensors serve as critical sources of biomechanical data during rowing. This real-time data, including handle force profiles, is acquired through custom software scripts. Advanced analysis algorithms then process this data, comparing it against ideal force and timing benchmarks derived from on-water rowing. Any errors or deviations are detected through this comparative analysis.

Through this multi-pronged approach, the simulator provides targeted, customizable, and engaging skill development. The integrated system architecture establishes a closed feedback loop, enabling iterative enhancement of rowing technique through ongoing data analysis, dynamic visual feedback, and immersive practice. This innovative application of emerging technologies is poised to push the boundaries of athletic training.

1.8 Summary and Outline

This thesis presents the development of an innovative mixed reality rowing simulator that merges virtual reality technology with integrated performance data analysis. The motivation behind this project is to transform indoor rowing by closing the gap between ergometer training and on-water technique. The main objectives are to create an immersive VR training environment, enable comparative biomechanical analysis between ergometer and on-water rows, and provide customized performance feedback to rowers and coaches.

The literature review summarizes key research on rowing training methods, the impact of VR in sports, and the potential of pervasive computing for performance analysis. It highlights the need for a solution that combines VR with biomechanical data to enhance technique training. The main challenges encountered in the project encompassed capturing realistic video representation, designing an intuitive interface, minimizing lag, and implementing effective feedback cues.

The core approach focused on acquiring real-time sensor data, analyzing it through comparative algorithms, providing dynamic VR visualizations for feedback, and creating an engaging virtual environment for optimum impact. Overall, this project aims to provide an advanced training simulator that transforms indoor rowing through immersive mixed reality. The insights gained can inform future innovations in VR-based athletic training across various sports.

This thesis is structured into 5 chapters covering the key aspects of developing the mixed reality rowing simulator.

Chapter 1 provides an introduction, outlining the motivation and objectives behind creating an immersive training environment for rowing. It also covers background information on rowing technique, a literature review, the main challenges faced, and the overall approach taken in the project.

Chapter 2 focuses on the video and data collection process. It details the equipment, setup, and sessions conducted to capture 360-degree footage and biomechanical data representing on-water rowing technique. This formed the basis for creating realistic VR environments and performance feedback.

Chapter 3 presents the system architecture and the integration of the various hardware and software components. This includes the ergometer, data analysis, VR environment generation, communication protocols, real-time feedback mechanisms, and testing procedures.

Chapter 4 analyzes the results from user studies evaluating parameters like flow state, presence, and timing error reduction. This provides insights into the simulator's training impact and areas for further refinement.

Finally, Chapter 5 summarizes the key conclusions from the project and discusses potential future work to enhance the capabilities of the mixed reality rowing simulator.

Overall, the thesis provides a comprehensive look at the development, implementation, and evaluation of an innovative sports training platform using virtual reality and integrated performance data. The insights gained can inform future research and innovation in applying immersive technologies for athletic skill development.

CHAPTER 2

VIDEO AND DATA COLLECTION

2.1 Introduction

To achieve an immersive VR implementation, a 360 degree video camera is used. 360-degree videos play a crucial role in the true implementation of virtual reality (VR) experiences. By capturing a full panoramic view of the environment, 360 videos enable users to immerse themselves completely in a simulated world. Unlike traditional videos, which offer a limited field of view, 360 videos allow users to freely explore their surroundings and engage with the content from any angle. This level of interactivity enhances the sense of presence and realism in VR, as users can look in any direction and feel like they are physically present in the virtual environment. Whether it's experiencing a concert, exploring a historical site, or participating in a virtual tour, 360 videos enable a more engaging and immersive VR experience, blurring the boundaries between the real and virtual worlds.

The goal of the video capture is to give the user the best experience with a good surround sound capturing microphone. The Garmin VIRB 360 [47] represents a significant advancement in the field of action cameras, particularly in the domain of immersive content creation. This camera incorporates dual lenses capable of capturing high-resolution 4K 360-degree videos and photos, enabling users to document their experiences with a remarkable level of realism and environmental context. The camera's advanced stabilization technology plays a critical role in ensuring smooth footage, minimizing motion blur and jitters, thus enhancing the overall visual quality. Additionally, the VIRB 360's durable construction and resistance to environmental factors such as water, shock, and dust make it a reliable tool for capturing footage in challenging outdoor conditions like rowing.

Goal of the video capture is to have a video that matches with the forward and backward movement of the rowers. The camera needs to move with the rowers smoothly, safely and without disruptions to the rowers training. This is important to get the best and accurate data of rowing. The videos were captured in two sessions using different apparatus and in different conditions. The 360 camera is placed on a jig in one session and on a helmet in another session.

2.2 Session 1: Jig

The first recording section was held on November 18, 2022 during an afternoon session and was headed by the men's heavyweight head coach, Mr. Todd Kennett. The weather that afternoon was 34 °F and the winds of 12.8 mph. These conditions are supportive of the rowing team's efforts to go out on the water for an on-water training session.

For this session, a jig was fabricated on top of a rowing boat seat. A rowing boat seat is made of carbon fiber and slides on rails fitted for every rower. The sliding motion helps through the phases of rowing cycle. As shown in figure 2.1, the camera is fitted on top of a clampig tripod. The clamping tripod is fixed to the seat using some wooden pieces and clamps. The wooden pieces are to ensure stability of the clamping tripod. The height of the mount is set according to the average eye level of a rower. A connecting rod is used to match the row timing with the rower in front of the rower. It is shown in green in the figure.

Figure 2.1: Camera rig and its placement for the first session

Equipment	Application
Garmin Virb 360	Capture 360 videos of the session
Clamping tripod	Securely mount camera at a height
Vibration Damper	Dampen vibration from movement of the seat
Rower seat	Facilitates clamping of tripod

Table 2.1: Description of components of the first recording session

This setup helps to correctly match with the other rowers, through the connecting road which is a hard constraint. Although, the video output is jerky due to sudden stop of the forward and backward movement. In reality, the rowers bend backward at the end of a stroke and bend forward, and this motion occurs simultaneously with the sliding motion. This cannot be captured by this setup. Moreover, implementing this setup leads to boat imbalance since there is one less rower on a side. Seat of a rower is taken by the setup and hence it is unfair to the rower also.

Due to these limitations, it was decided to not go forward with this setup and use an overhead camera mounting instead.

2.3 Session 2: overhead camera

This video capture session was conducted on March 17th, 2023. At the time of recording, the temperature was recorded as 43 °F, with wind speed of 6 mph in south direction. The camera was placed on rower no.3 on the boat. The day was overcast with slight drizzle. The rowing team typically conducts training in these conditions.

Given the limitations of the jig, and to better accommodate the Men's heavyweight team's training schedule, the 360 video was captured for the whole session. The same camera, a Gramin 360 VIRB has been used and the rower is selected based on height and the rower with the visually shortest torso is chosen to bear the helmet. As shown in figure 2.2, the camera is placed on top of one of the rowers on the starboard side. A bike helmet has been used because it is a lightweight helmet and does not disrupt the rower's attention to training. The weight of the whole setup is 483 grams and is non disruptive. The control of the video capture was conducted using Garmin Virb app [20] using an Apple iPhone 13. The app is connected to the camera using a local network generated through the camera.

Figure 2.2: Rower wearing a 360-camera mounted helmet

In this recording session, a peach powerline system was also used. As shown in figure 3.6, the peach system is a tool for performance data acquisition for each rower. With enough notice, it was possible to set up this system on the boat since each sensor has to be calibrated for accurate measurements before it is deployed.

Equipment	**Application**
Garmin Virb 360	Capture 360 videos of the session
Bike Helmet	Securely mount camera on the rower's head
Vibration Damper	Dampen vibration from movement of the seat
Helmet mount	Mount the camera on the helmet
Peach Powerline system	To acquire performance data of the session

Table 2.2: Description of components for the second recording session

The setup overcomes many challenges which were previously faced in session 1. Using an overhead camera mount helps to visualise the whole movement of the rower. The bending movement of the rower can also be observed in this setup. Moreover, the video is smoother as there is no sudden stop found in the previous session. Since every rower occupies a seat, the boat is balanced and the training session is conducted normally. This helps imitate the real life scenarios of training.

The video footage obtained from the device spans a duration of 48 minutes, which aligns with the maximum recording capacity determined by the limitations of the Garmin Virb's battery life and storage capacity. Within this recording, a diverse range of clips are captured, encompassing varying speeds, headings, and scenarios. The clips are categorized based on their intensity levels, including low intensity (warm-up phase) characterized by approximately 20 strokes per minute, medium intensity (ranging from 23 to 35 strokes per minute), and high intensity (exceeding 36 strokes per minute). Moreover, the recorded footage encompasses a variety of scenarios such as warm-up sequences, race starts, rolling starts, standing starts, and turnings. This comprehensive collection of clips provides users with the flexibility to select specific scenarios, enhancing the simulator experience by incorporating gamification elements.

Observations for future:

When the video is analyzed in a VR Headset there are few things to note to make the immersive experience better. These are given below:

- Special instructions to the rower should be given. The rower should not wobble their head while training.
- Proper fit for the rower is necessary for the rower's comfort.
- The rower should try to look straight as much as possible and refrain from

looking anywhere else. This is to reduce camera sways.

- Each clip should be recorded separately for better analysis and training.

The overhead camera setup is very useful and effective in training the rowers. Moreover, it also helps the coaches analyse shoulder and leg movement of the rowers, to give constructive feedback to improve their rowing technique.

2.4 Video Editing

Editing a 360-degree video using the Garmin VIRB app involves a series of post-production procedures to enhance the visual quality and storytelling of the captured footage. The Garmin VIRB app provides users with a comprehensive set of tools and features for editing 360-degree videos in a streamlined and intuitive manner. This academic discussion will outline two key aspects of editing a 360 video using the Garmin VIRB app: stitching and post-processing.

Stitching, a fundamental step in the editing process, involves combining multiple camera views to create a seamless and immersive 360-degree video. In the Garmin VIRB app, the stitching feature utilizes advanced algorithms to align and merge the individual camera perspectives, minimizing disparities and artifacts. This process requires accurate synchronization and precise alignment of the camera angles, ensuring that the resulting video maintains a coherent and undistorted panoramic view. The app's stitching functionality employs computer vision techniques to analyze and match common features in the camera views, enabling the creation of a continuous and visually cohesive video sphere. By employing this stitching feature, users can seamlessly integrate multiple camera angles into a unified and immersive 360-degree video experience.

Post-processing plays a crucial role in refining the visual quality of the edited 360-degree video. Within the Garmin VIRB app, various post-processing tools and effects are available to enhance the color, contrast, and overall aesthetics of the footage. Color correction allows users to adjust the white balance, saturation, and exposure levels to achieve a desired visual tone and atmosphere. Additionally, the app offers features like sharpening, noise reduction, and image stabilization to improve the clarity and smoothness of the video. These post-processing capabilities enable users to optimize the visual fidelity of the 360-degree video, ensuring that the final output is visually appealing and engaging for viewers. By leveraging the post-processing functionalities of the Garmin VIRB app, content creators can refine and enhance their 360-degree videos to deliver immersive and captivating visual experiences.

2.5 Conclusion

In conclusion, this chapter outlined the video capture and data acquisition processes that were vital to developing an immersive and informative mixed reality rowing simulator. Two video recording sessions were conducted using 360-degree cameras to obtain diverse footage encapsulating different rowing scenarios and intensity levels. The second session involving an overhead camera mount proved most effective in capturing smooth, high-fidelity video showcasing proper rowing technique from multiple angles. Detailed descriptions of the equipment, setups, and shooting conditions provided insights into the considerations for acquiring usable 360 video footage for virtual reality environments.

In tandem with video, the Peach powerline system was utilized during training sessions to gather quantitative performance metrics for each rower. This multidimensional data collection process, encompassing both visual and numerical information, supplied the raw inputs necessary for creating an integrated, interactive training simulator. The methodology and outcomes presented will inform future efforts to develop mixed reality systems reliant on comprehensive capture of real-world data.

CHAPTER 3

SYSTEM ARCHITECTURE

3.1 Introduction

The rowing simulator project encompasses a sophisticated system architecture designed to create an immersive and interactive training environment for rowers. The system architecture comprises several key components that work together seamlessly to deliver a realistic and effective rowing experience. This section provides an overview of the system architecture, highlighting its various elements and their interconnections.

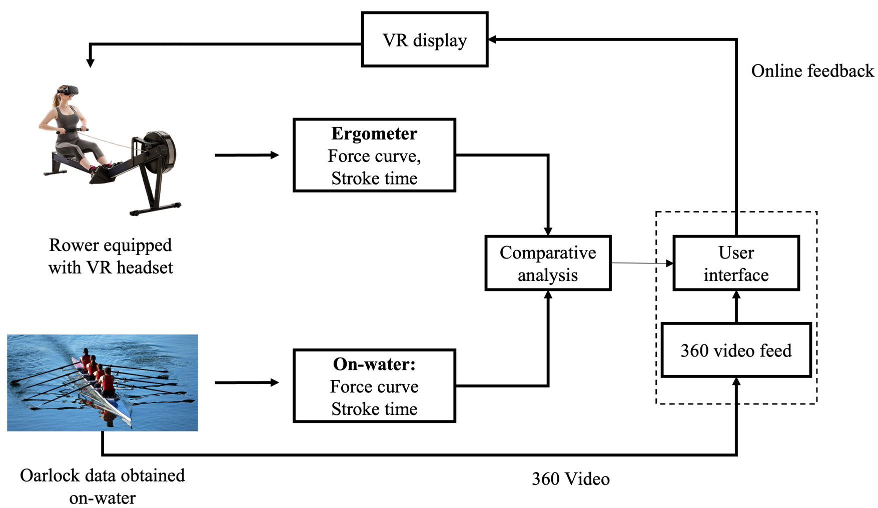

Figure 3.1: System Architecture

Rowing Ergometer: The rowing ergometer, such as the RP3 rowing ergometer, is a critical hardware component of the system architecture. It generates force curves that closely resemble those experienced during on-water rowing, providing a realistic rowing feel for the user. The ergometer's data, including force exertion and stroke characteristics, are captured and used for performance evaluation and comparison with on-water rowing data.

On-water data Acquisition and Processing: The system architecture includes robust data acquisition and processing capabilities. Sensor data from the rowing ergometer, and peach system are collected and processed in real-time. Advanced algorithms analyze the data, extracting key performance metrics such as stroke length, timing, force exertion, and boat velocity. These metrics are used to compare the user's performance with on-water rowing standards and provide insightful feedback.

Visualization and Feedback: The system architecture incorporates visualization tools to present the rowing environment and feedback cues to the user. The VR headset displays the virtual environment, recreating the on-water surroundings with realistic visuals. Feedback cues, such as force curves, stroke analysis, and performance metrics, are presented to the user in real-time, helping them refine their technique and optimize their performance.

User Interaction and Control: The rowing simulator enables user interaction and control through intuitive interfaces. Users can navigate through training modules, select different scenarios, and customize their training experience. User inputs, such as stroke intensity and direction, are captured and processed to update the virtual environment and provide tailored feedback.

As seen in table 3.1, and 3.2, the system architecture of the rowing simulator demonstrates a comprehensive integration of hardware, software, and data processing components. Through the seamless coordination of the VR headset, rowing ergometer, offline peach system, data acquisition and processing, visu-

Hardware	Application
RowPerfect S	Dynamic ergometer used by the rower
Meta Quest 2	Allows the human user to see, hear, and interact with the virtual world
Alienware x17 R1 Gaming Laptop	Laptop that hosts Unreal Engine, runs data processing of Real-Time ergometer data
Samsung Galaxy Tab A7 Lite 8.7″ 32GB	Connects to an ergometer and allows data transfer between ergometer and host
ASUS ROG Rapture Gaming Router (GT-AX11000)	Establishes a connection between ergometer, host laptop and Meta Quest 2

Table 3.1: Description of hardware components of the system

Software	Application
Unreal Engine™ 4.27	Game engine renderer that hosts the virtual environments alongside 360 videos and feedback cues
Python	Realtime data acquisition, cleaning and processing for parameters like force, energy
RP3 Rowing app	Connects to an ergometer and allows data transfer between ergometer and through a public port

Table 3.2: Description of software components of the system

alization, and user interaction, the simulator creates a highly immersive and effective training platform for rowers.

3.2 Ergometer and Data Analysis

Ergometer is the equipment on which the Cornell Rowing Team practices when they are not on the water. Cornell uses RP3 dynamic ergometer. It can be connected to a portable device which gives statistics of force, energy, stroke time and stroke length.

An ergometer, also known as an indoor rowing machine or simply an ”erg,” plays a vital role in the training of rowers. It is a specialized piece of equipment designed to simulate the action and resistance of rowing on water. Rowing on an ergometer allows rowers to train and refine their technique, build strength and endurance, and monitor their performance. The ergometer provides rowers with a consistent and controlled environment, allowing them to focus on specific aspects of their stroke, such as rhythm, power, and efficiency. It serves as an excellent tool for both individual and team training, enabling rowers to track their progress, set goals, and engage in competitive challenges. The ergometer's versatility and accessibility make it an essential component of a rower's training regimen, helping them develop the physical and mental attributes necessary for success on the water.

The RP3 Rowing Ergometer has magnets attached to the flywheel that, when the user rows, pass a sensor. The estimates are based on the time difference between these magnets. It is necessary to make a correction in order to account for mechanical errors before using these pulses for computations. This page explains the process by which this correction occurs, how a drive or recovery is identified, and how different variables, including energy and distance, may be determined.

Figure 3.2: RP3 Ergometer from MoveLabs

Measurements and Pulses: For an accurate calculation of the values to be calculated, it is of decisive importance that p_n is determined as accurately as possible. Due to mechanical inaccuracies, the distance between two magnets is not constant, and a pulse can be missed due to vibrations. Corrections must be made for this.

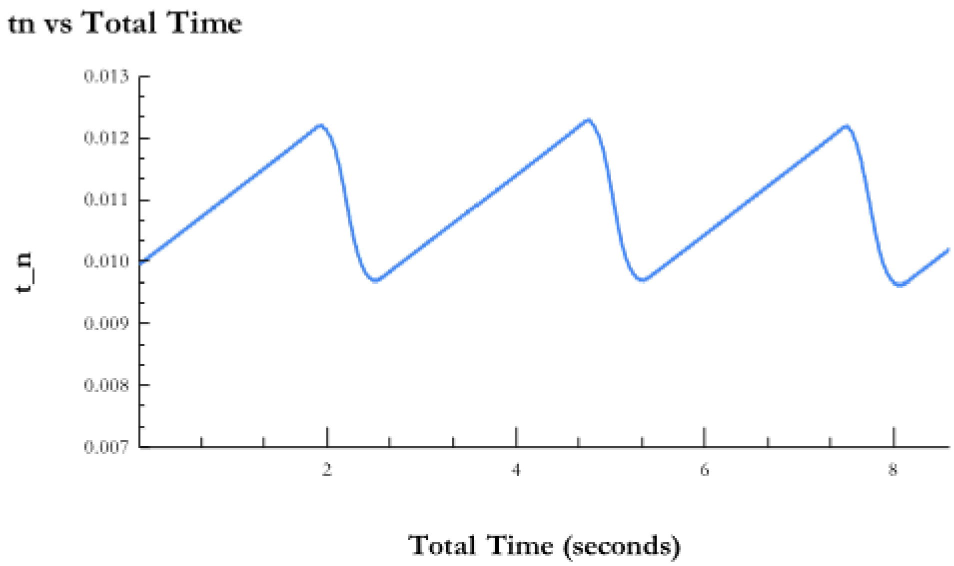

Figure 3.3: t_n vs Total Time

Missed Pulses: When a pulse is missed, the measured value tn in the raw data suddenly becomes a factor of 2 larger than the measured t_{n-1}. When $1.9 < \frac{t_n}{t_{n-1}} < 2.1$, the following correction takes place:

$$t'_n = 2 \cdot t_{n-1} - t_{n-2} \tag{3.1}$$

$$t_{n+1} = t_n + t_{n-2} - 2 \cdot t_{n-1} \tag{3.2}$$

When this is not the case, then $t'_n = t_n$.

Moving Average: To compensate for the mechanical inaccuracies, p_n is calculated as a moving average over a number of pulses. For example, when there are four magnets in the flywheel, then a = 4:

$$
\begin{aligned}
p_0 &= \frac{1}{1} \cdot (t_0) \\
p_1 &= \frac{1}{2} \cdot (t_0 + t_1) \\
p_2 &= \frac{1}{3} \cdot (t_0 + t_1 + t_2) \\
p_3 &= \frac{1}{4} \cdot (t_0 + t_1 + t_2 + t_3) \\
p_4 &= \frac{1}{4} \cdot (t_1 + t_2 + t_3 + t_4) \\
p_5 &= \frac{1}{4} \cdot (t_2 + t_3 + t_4 + t_5) \\
\ldots \\
p_n &= \frac{1}{4} \sum_{i=n-4}^{n} t_i
\end{aligned}
$$

The values of p_n are used for the calculations.

Stroke Detection and Recovery

Flywheel acceleration is used to detect the start of a stroke:

$$\frac{p_{n-1}}{p_n} \tag{3.3}$$

As soon as this value gets greater than 1, we detect the start of a stroke. Figure 1 clearly shows that each peak of the curve represents the start of a stroke. Experiments show that the rower has already delivered power earlier, so the stroke starts earlier. As a guideline, 4cm is used for this, which corresponds to 2 pulses with a magnet number of a = 4. These 2 pulses are included in all calculations.

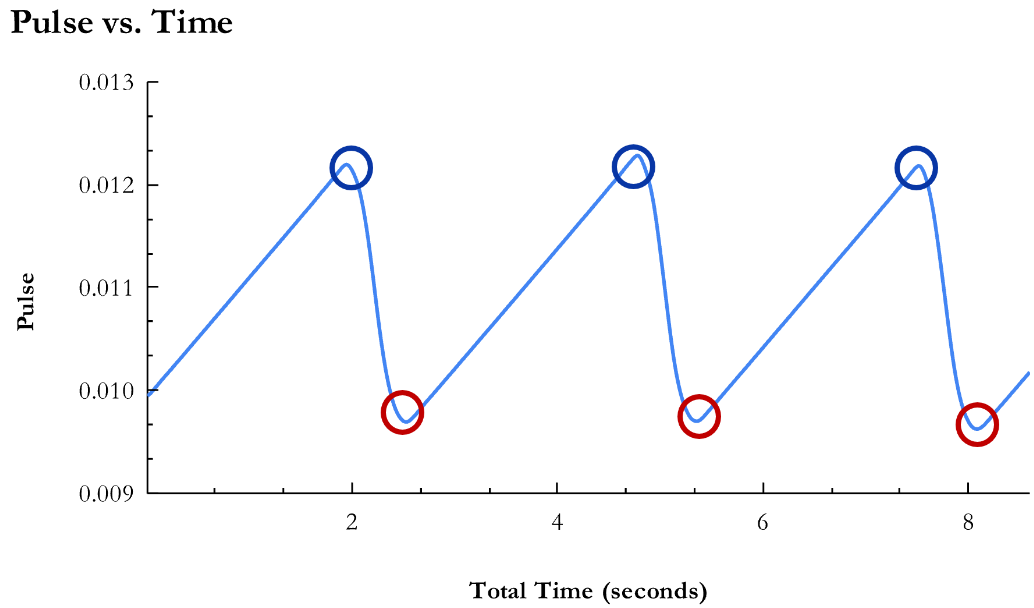

Figure 3.4: p_n vs Total Time

When the acceleration of the flywheel becomes negative, we can conclude that the rower is no longer supplying energy to the flywheel, and the stroke has ended. As shown in Figure 3.4, the crest are the points where stroke has ended. To detect the end of a stroke, the acceleration of the flywheel is also used. When the acceleration of the flywheel becomes negative, we can conclude that the rower is no longer delivering energy to the flywheel, and that the stroke is finished. As shown in Figure 3.4, the troughs are the points where recovery has ended.

Timing: Time is tracked based on the original raw pulses. $T_r(y), T_d(y)$, and $T_c(y)$ respectively represent the recovery time for stroke y, the drive duration of

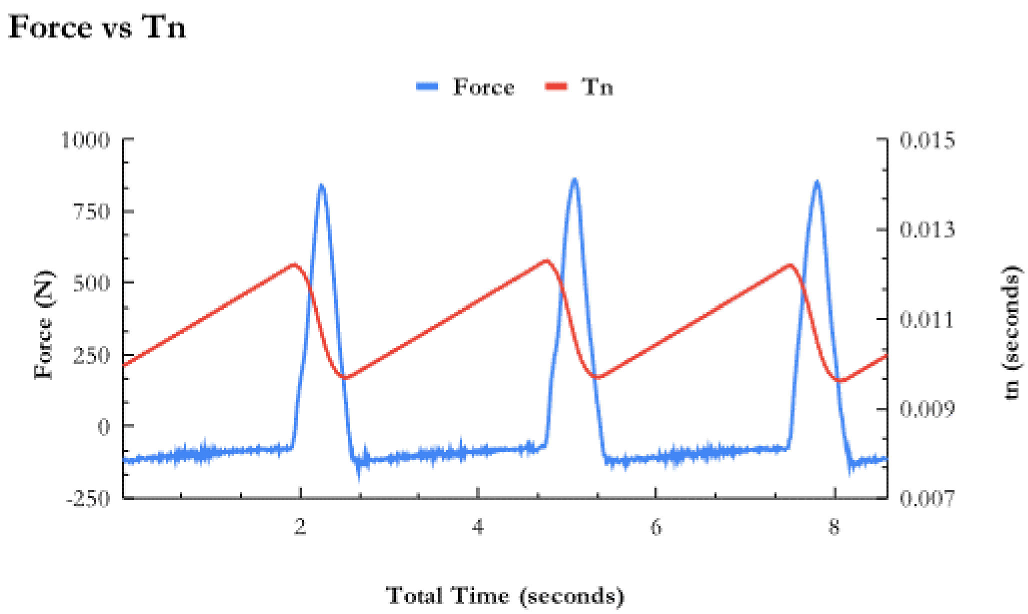

Figure 3.5: Force calculation with t_n from erg

stroke y, and the total recover-stroke cycle for stroke y.

$$T_r(y) = \sum_{n=0}^{N} t_n; \quad t_0 = \text{first pulse of the recovery for stroke } y \tag{3.4}$$

$$T_d(y) = \sum_{n=0}^{N} t_n; \quad t_0 = \text{first pulse of stroke } y \tag{3.5}$$

$$T_c(y) = T_r(y) + T_d(y) \tag{3.6}$$

When the flywheel is not spinning fast enough, a constant pulse is transmitted, which does not correspond to the actual time. Therefore, it is not possible to measure longer periods using pulses.

Force Calculation: The force per pulse in Newton can be used for the force curve and is calculated as follows:

$$F_n = F_{friction} + F_{acceleration} + F_{elastick} \tag{3.7}$$

$$F_{friction} = \frac{K}{4R \cdot A^2} \left(\frac{1}{p_{n-1}} + \frac{1}{p_n} \right) \tag{3.8}$$

$$F_{accel} = \frac{J}{R.A} \left(\frac{\frac{1}{p_n} - \frac{1}{p_{n-1}}}{p_{n-1}} \right) \tag{3.9}$$

$$F_{elastick} = C + f.\frac{n}{a}.b.s \tag{3.10}$$

This equation 3.7 calculates the force per pulse in Newton (N) for the force curve of a rowing stroke. The force is composed of three components: frictional force, acceleration force, and elastic force.

The frictional force is caused by the resistance of the air and is proportional to the power constant K, the square of the blade area A, and the reciprocal of the sum of the previous and current pulse value (p_{n-1} and p_n).

The acceleration force is due to the increase in speed of the flywheel and is proportional to the moment of inertia J, the radius R, and the difference between the current and previous pulse values (p_n and p_{n-1}).

The elastic force is caused by the elastic properties of the rowing machine and is proportional to the elastic constant C, the stroke rate-dependent variable f, the stroke number n, and the amplitude of the stroke acceleration a, multiplied by a function of the stroke length b and the stroke speed s.

By summing up these three forces for each pulse, we can obtain the force curve of a rowing stroke, which is a useful metric for assessing the rower's technique and performance.

Energy per stroke (E_h): The energy delivered by the rower for stroke y in Joules is calculated based on the friction energy of the fan, rotational energy content of the flywheel, and the energy absorbed by the elastic:

$$Eh(y) = \sum_{n=0}^{N} E_{w_n} + E_r + E_e \tag{3.11}$$

where

$$E_{w_n} = \frac{K}{A^3 \cdot p_n^2} \tag{3.12}$$

$$E_e = L \cdot \left(C + f\frac{L}{2}\right) \tag{3.13}$$

For the first stroke (y=1), the following formula applies to Er:

$$E_r = \frac{J}{2 \cdot A^2 p_N^2} \tag{3.14}$$

For all subsequent strokes (y ¿ 1), the following formula applies to Er:

$$Er = \frac{J}{2 \cdot A^2}\left(\frac{1}{p_N^2} - \frac{1}{p_0^2}\right) \tag{3.15}$$

Here, p_0 is the first pulse of the stroke and p_N is the last pulse of the stroke.

Power: The power per stroke in Watts (Ph(y)) is calculated as follows:

$$P_h(y) = \frac{E_h(y)}{T_c(y)} \tag{3.16}$$

Constants:

Symbol	Description	Unit	Value
a	Number of magnets	-	4
A	Magnet factor	-	$\frac{a}{2*\pi}$ = 0.63662
b	Number of teeth on gear	-	11
C	Base tension in elastic	N	21
f	Elastic constant	N/m	10.7
J	Moment of inertia	$\frac{Nms^2}{rad^2}$	0.10880
R	Radius of pitch circle of gear	m	0.014195
s	Chain pitch length	m	0.008

Table 3.3: Constants for RP3 calculations

3.3 On-water performance Analysis

Instrumentation is needed to collect data for on-water performance. Experiments conducted during training sessions are used as reference for on-water performance calculations. The required data should contain parameters similar to that obtained from the RP3 ergometer. This consists of force, duration of stroke, energy, power produced, and timing.

A complete rowing instrumentation system is Peach PowerLine [2]. In order to assess crew technique and performance, it measures the forces, angles, and speeds required. This data is stored and used as an offline reference for evaluation. Figure 3.6, shows how the

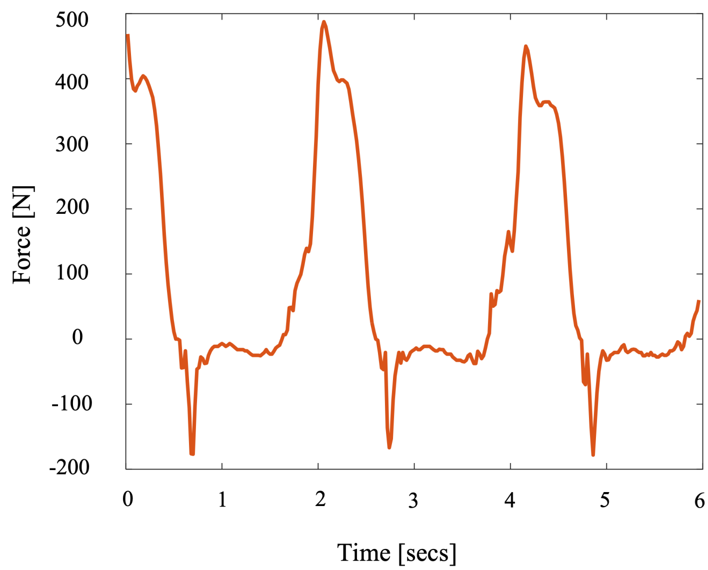

Figure 3.7: Peach Data Visualization

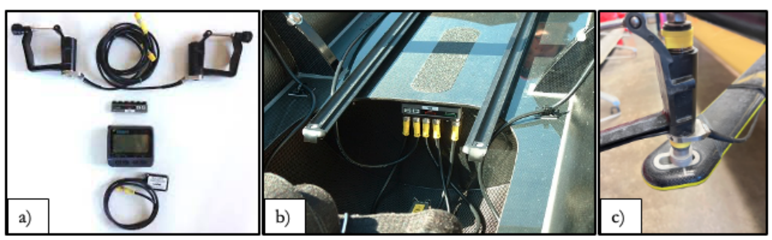

Figure 3.6: Peach PowerLine system: a)Main system components; b)power box installed on the boat; c) Oarlocks fitted with Peach swivels to record data

Each set of data is labelled with a crew list, boat type and venue. The data from the peach systems consists of these parameters: 1. Force (in kg-f) applied by each rower, 2. Angle of the oar of each rower, 3. Speed of the boat, 4. Distance travelled, 5. Acceleration, and normalized time. The data is at a frequency of 50 Hz.

A pipeline has been set up to process each data set. Considering the high density of data points over a given time, pandas is used as a Python package providing fast, flexible, and expressive data structures designed to make working with "relational" or "labeled" data both easy and intuitive [36].

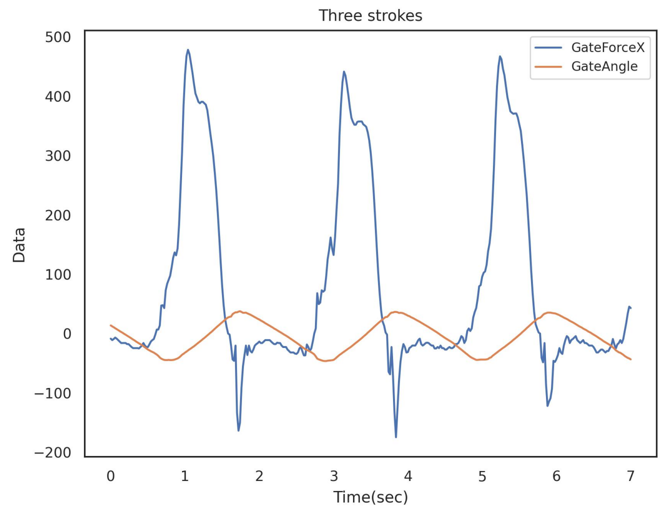

Figure 3.8: Three Strokes of Rowing

Figure 3.8 gives a snapshot of Oar angles and Force curves of rowers over the course of three strokes. The dissertation by Jennifer Coker [14] teaches a comprehensive way to interpret data from the peach system. As seen from the figure, the oar angle data consists of a periodic sinusodial like curve, which consists of crests and troughs. While on the water, when oar angle is at the apex of the crest, the oars have just finished the stroke and the rowers are at the most forward position, with legs fully folded. When oar angle is at the apex of the trough, the rowers have just finished the recovery, starting their stroke and the rowers are at the most backward position, with legs fully extended. This data needs to be segmented to display data for each row cycle systematically.

The first step is to smooth the data by applying a rolling mean with a window size of 5. This means that for every point in the dataset, the algorithm takes the average of that point and the two points before and after it. This helps to reduce noise and make the data more consistent. The next step is to calculate the first derivative of the smoothed data, which represents the rate of change of the data at each point. The code then finds the indices where the derivative changes from positive to negative, which correspond to the crest points in the data. Similarly, it finds the indices where the derivative changes from negative to positive, which correspond to the trough points in the data. Finally, the code creates an empty Pandas DataFrame to store information about the segments between the troughs and strokes, including their start and end times, trough times, and stroke times.

Let OA be Oar Angle of a particular rower, and $n = 5$ is the window size and i represents the index of the data point in the rolling window. Smoothed data point is given by s

$$s = \frac{1}{n} \sum_{i=\frac{-(n-1)}{2}}^{\frac{n-1}{2}} OA[i]$$

The derivative is calculated as:

$$\dot{s} = \frac{d}{dx} s$$

Based on the derivative, the slope is checked for changing orientation. If the slope changes from positive to negative, then it is a crest point, and will be categorized as the start of next cycle, or end of current cycle. Else if the slope changes from negative to positive, then it is a trough point and is categorized as the end of recovery phase and the start of stroke phase.

$$i_{crest} = \{i : \dot{s}[i] > 0 \text{ and } \dot{s}[i+1] \leq 0\}$$

$$i_{trough} = \{i : \dot{s}[i] < 0 \text{ and } \dot{s}[i+1] \geq 0\}$$

where i represents every instance of a data point from the peach PowerLine system. Based on these crest and trough points the data is segmented.

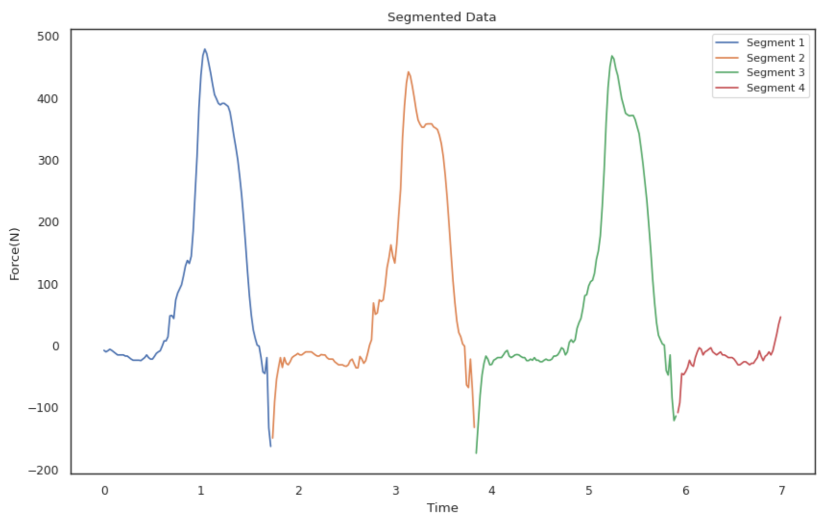

Figure 3.9: Segmented Stroke curves

The results of this segmentation are given in 3.9 where each cycle is shown in a different color. Differentiating the data is important to calculate the real stroke and drive start times of a particular stroke number. This helps to match timing errors with the ergometer data.

3.4 Environment Setup

360 video in Unreal Engine 4 (UE4) is a technique used to create immersive video experiences where viewers can look around in any direction, as if they were present in the scene. The concept revolves around capturing video footage from multiple angles simultaneously and then mapping that footage onto a virtual sphere, creating a 360-degree view. Here's a high-level explanation of how 360 video works in UE4:

1. Capturing the footage: To create a 360 video, a special camera setup is used to capture video footage from multiple angles simultaneously. This can be achieved using a specialized rig with multiple cameras arranged in a spherical configuration or by using a dedicated 360-degree camera. The goal is to capture the entire surrounding environment, ensuring that no part is missed.

2. Stitching the footage: The captured footage from all the cameras is then stitched together to create a seamless spherical video. This stitching process involves aligning the overlapping areas of each camera's view and blending them together to create a continuous, distortion-free 360-degree video. There are various software tools available that can automate this stitching process.

3. Mapping the video onto a virtual sphere: In UE4, the stitched 360-degree video is then mapped onto a virtual sphere. The video frames are essentially wrapped around the inside surface of the sphere, creating a seamless, immersive environment. This virtual sphere serves as the visual representation of the 360-degree video and allows viewers to freely look around in any direction.

4. Playback and interaction: Once the 360-degree video is mapped onto the

virtual sphere, it can be played back within the UE4 environment. Viewers can interact with the video by using a variety of input devices, such as a computer mouse, gamepad, or virtual reality (VR) headset. These input devices enable users to change their viewpoint within the 360-degree video, allowing them to look in different directions or explore the entire environment.

5. Rendering and display: When the 360-degree video is played back, the UE4 engine renders the appropriate portion of the video based on the viewer's current viewpoint. This means that only the video frames that are visible within the viewer's field of view are rendered, optimizing performance and reducing the processing load. The rendered frames are then displayed on the viewer's screen or within their VR headset, providing a real-time immersive experience.

Overall, 360 video in UE4 combines specialized camera capture techniques, video stitching, virtual sphere mapping, and real-time rendering to create an interactive and immersive viewing experience where viewers can explore a 360-degree video environment.

plugin	**Application**
Kantan Charts	The package includes a bar chart, and a time series plot for time-varying data
Blueprint CSV Parsing	Helps to parse the Force data to be interactable
File Helper Plugin	helps to use plain-text files in blueprint through reading, deleting, creating and others.

Table 3.4: Description of widgets used in the UE environment

Adding a line chart in Unreal Engine (UE4) involves utilizing the engine's built-in Blueprint visual scripting system and its robust graphical capabilities.

A line chart is a graphical representation of data points connected by line segments, commonly used to display trends, patterns, or relationships over time or across different variables. UE4 provides a versatile framework for creating and integrating line charts seamlessly into interactive experiences, such as data visualization applications or educational simulations.

To begin, the process typically involves creating a Blueprint actor or widget that will serve as the container for the line chart. This actor or widget acts as a visual representation of the chart and can be placed within the 3D game world or displayed as a UI element on the screen. The Blueprint scripting system in UE4 allows for defining the behavior and functionality of the line chart, including data input, updating, and rendering.

Next, the data points for the line chart need to be prepared. These data points can be obtained from various sources, such as a CSV file, a real-time data stream, or programmatically generated data. Once the data is available, it can be stored in an appropriate data structure, such as an array or a data table, within the Blueprint.

With the data points ready, the Blueprint logic can be implemented to interpret and visualize the data as a line chart. This typically involves iterating through the data points and converting them into screen space coordinates based on the chart's dimensions and scaling. The Blueprint scripting system provides mathematical functions and utilities that facilitate such calculations. These calculated coordinates can then be used to draw lines connecting the data points, effectively creating the line chart visual representation.

To enhance the line chart's visual appearance and usability, additional features can be implemented. This may include adding labels or tooltips to display data values or interactive elements, such as zooming or panning functionality, to allow users to explore the chart in detail. Furthermore, UE4 provides a range of graphical customization options, such as setting line thickness, color, and styling, to tailor the line chart's visual aesthetics according to specific requirements or artistic preferences.

By leveraging the power of the Blueprint system and UE4's graphical capabilities, adding a line chart in Unreal Engine allows developers to create interactive and visually engaging representations of data trends or relationships within their projects. Whether used for educational purposes, data visualization, or gameplay mechanics, line charts in UE4 offer a flexible and intuitive means of presenting information to users in an immersive and interactive environment.

3.5 Communication

Accessing an application with a public port from a laptop using Python's socket connection involves employing the fundamental networking capabilities provided by the Python programming language. Python's socket module facilitates the establishment of a network connection and enables communication between a client, such as a laptop, and a server hosting the application through a designated public port. This approach is based on the underlying principles of the Transmission Control Protocol/Internet Protocol (TCP/IP) networking model, ensuring reliable and efficient data transmission.

To initiate the connection, the client utilizes the socket library to create a socket object. This object represents an endpoint for network communication and allows the client to specify the necessary parameters for establishing the connection, including the server's IP address and the public port associated with the desired application. The socket object is then bound to a specific local port on the client's laptop, facilitating the identification and routing of incoming and outgoing network traffic.

Subsequently, the client employs the socket object's connect() method to establish a connection with the server. This method establishes a TCP connection to the server's IP address and public port, initiating a three-way handshake process to ensure reliable communication. Once the connection is successfully established, the client can transmit and receive data with the server, facilitating interaction with the application hosted on the server.

Python's socket connection provides a versatile means of accessing applications with public ports, offering flexibility and control in network communication. By leveraging the socket module, developers can create robust and efficient client-server interactions, enabling the laptop to seamlessly communicate with the application hosted on the server through the designated public port. This approach empowers developers to build a wide range of networking applications, including remote access, data retrieval, and distributed computing, leveraging the power and simplicity of Python's socket-based communication.

3.6 Integration

The successful integration of various components is crucial to the seamless operation and effectiveness of the rowing simulator. Integration involves harmoniz-

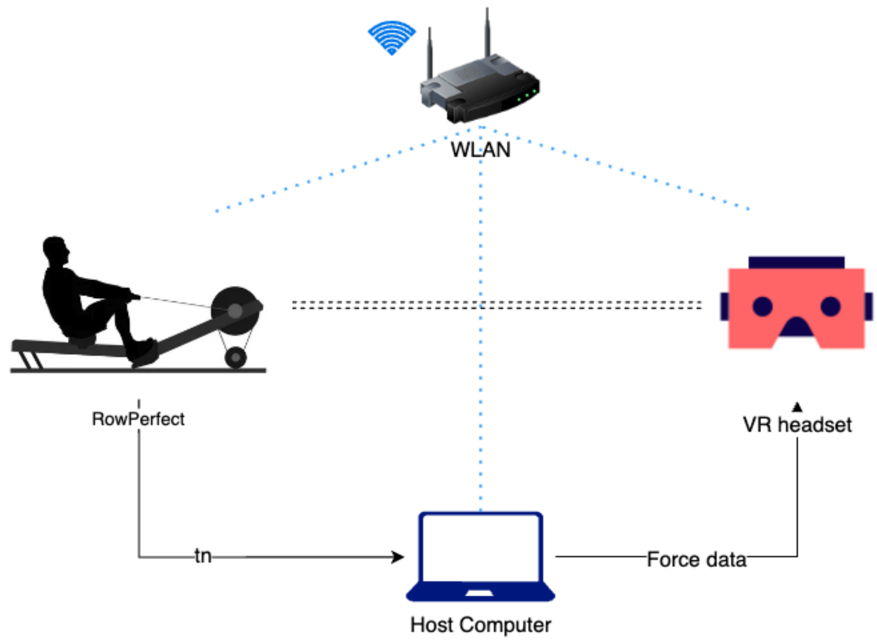

Figure 3.10: Setup Configuration

ing hardware, software, and data processing elements to create a unified system that delivers a realistic and immersive training experience. This section highlights the key aspects of integration within the rowing simulator project.

The rowing simulator incorporates multiple hardware components, including the VR headset, rowing ergometer, and the host laptop. Integrating these hardware components involves ensuring proper connectivity, synchronization, and compatibility. Hardware is used as given by 3.1. The ergometer, the headset and a host laptop is connected to the same Local Wifi Network. The WiFi network created by the AUSU ROG Rapture GT-AX11000 is a 802.11ax WiFi 6 with a data rate of 4x4 (Tx/Rx) 1024 QAM 20/40/80/160MHz, compatible up to 4804Mbps. This ensures that there is no data lost between transmission. This is crucial since the rowperfect sends data to the host computer at a frequency of about 85 Hz. Significant data loss can also lead to the timing errors in the visual feedback, which is undesirable.

Software integration is a critical aspect of the rowing simulator project. It involves developing a cohesive software framework that seamlessly connects the various components and facilitates their interaction. This includes creating communication protocols and interfaces between the VR headset, and rowing ergometer. Data streams from different sources are processed, combined, and analyzed within a unified software environment. The software integration ensures smooth data flow, synchronization, and real-time interaction between the components.

As explained in the previous section, the host computer runs a Python script and acquires ergometer data using a socket connection. The acquired data is used to calculate forces, as explained in section 3.1, and the force data is sent to the VR headset through Unreal Engine. The force data is sent in the form of a list and is sent at the end of every drive phase of the stroke. This is done at the end of the drive, so that the user/rower is not distracted during the drive. As per feedback from the coaches, the user naturally gets more time to focus on the feedback curve during the recovery phase. This helps to assess their mind and adjust to the timing from the next drive phase.

Integration of data acquired from different sources is a fundamental requirement for the rowing simulator's functionality. Calibration techniques are employed to align the different data streams, enabling accurate comparison and analysis. To calibrate the data acquisition from the ergometer, a two check system is integrated. The user first confirms that they are in the right position, the headset is fit properly and the handle is in the hands. With this confirmation the first flag is checked, which makes way to the other gate. As soon as the rower confirms, and then at the reception of the first plausible data point, the second flag is set which starts the comparison script. The plausible data point is determined using various tests, and it is found to be, $t_n > 0.05$. This ensures data calibration and no timing error loss with the video stream.

Advanced data processing algorithms are implemented to extract meaningful insights and performance metrics from the integrated data, facilitating real-time feedback and evaluation.

Integration extends to the user interaction and interface design. The user interface integrates seamlessly with the system components, providing a user-friendly and intuitive platform for navigation, customization, and control. User inputs from the rowing ergometer, VR headset, and other interaction devices are integrated to update the virtual environment and trigger appropriate feedback responses. The integration of user interaction ensures a cohesive and immersive training experience.

There is a base level in the virtual environment which gives the user options of intensity of their choice. Once in the level, the user can select their choice using physical buttons on the host laptop. The three levels are warm-up, medium-intensity, and high intensity. Each option consists of its own prerecorded session and the data is loaded based on the selection. This setup helps the user to train based on their choice.

Integration testing plays a vital role in ensuring the overall functionality and reliability of the rowing simulator. Testing procedures are conducted to verify the seamless integration and interoperability of hardware and software components. Integration tests validate the accuracy of data synchronization, real-time performance, and proper functioning of the entire system. Additionally, user feedback and validation are essential to confirm that the integrated simulator meets the desired training objectives and provides an effective and realistic rowing experience.

The successful integration of hardware, software, data, and user interaction components in the rowing simulator project is a testament to the meticulous planning, coordination, and iterative development processes involved. The integrated system enables rowers to train in a highly realistic and immersive environment, providing valuable insights and feedback for performance enhancement.

In conclusion, the integration of hardware, software, and data processing components within the rowing simulator project is a critical aspect of its success. By seamlessly combining these elements, the simulator achieves a cohesive and interactive system architecture, providing rowers with an immersive and effective training platform.

3.7 Data Synchronization

In the realm of the VR rowing simulator, ensuring precise data synchronization is paramount to fostering a seamless and effective training experience. This section delves into the intricate process of data synchronization, illuminating how the alignment of various datasets enhances real-time feedback and analysis, ultimately contributing to refined rowing technique and performance optimization.

Graphical Representation and Matching: A fundamental step in data synchronization involves the graphical representation of on-water peach data overlaid on the force curve derived from the rowing ergometer. This overlay provides a visual correspondence between real on-water performance and the simulated ergometer-based exercise. The graph is meticulously matched over the total time span covered in the video, establishing a foundational framework for synchronization.

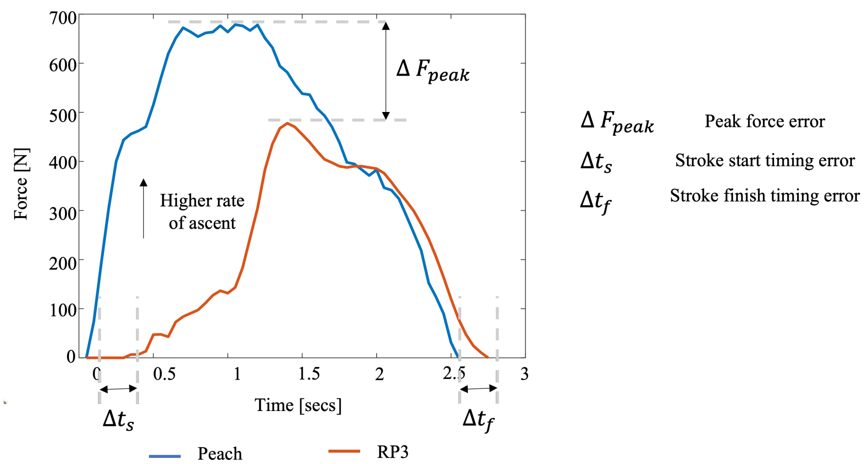

Figure 3.11: online performance comparison

Initiating Synchronization: Data synchronization commences with aligning the start time of the video, which is a pivotal point of reference. The peach data, already synchronized with the video, serves as a reliable baseline. As each stroke concludes in real-time on the rowing ergometer, its start time is juxtaposed against the anticipated stroke number in the video and corresponding dataset. This stroke-number alignment serves as a synchronization anchor, enabling a seamless comparison of metrics.

Utilizing Ideal Stroke Number: With the ideal stroke number established, the simulator extracts the pertinent force and timing data associated with the corresponding stroke from the dataset. This step sets the stage for a comprehensive analysis and feedback loop. As the force and timing errors of the ongoing ergometer stroke are quantified, a precise comparison unfolds, painting a vivid picture of the deviation from the anticipated ideal stroke.

Graphical Comparison for Analysis: Visualizing this comparison through a graph magnifies the dynamic interplay between actual and anticipated performance. By plotting force and timing metrics, the simulator generates a graphical representation that vividly illustrates the variances. This visual feedback serves as a powerful tool for rowers, enabling them to discern their technique's alignment with the optimal stroke and make real-time adjustments.

In tandem with empowering rowers, the data synchronization process extends its reach to benefit coaches. The synchronized data, replete with force and timing insights, is stored and made accessible through the coach's dashboard. This resource equips coaches with a comprehensive overview of individual rowers' performances, enabling targeted guidance and personalized training strategies.

In summary, data synchronization within the VR rowing simulator transcends the realm of technical alignment. It forges a bridge between real and simulated worlds, empowering rowers and coaches alike with a granular understanding of force and timing dynamics. As each stroke merges the tangible and the virtual, data synchronization stands as a testament to the simulator's intricate design, facilitating a transformative training journey that optimizes technique and elevates performance.

3.8 Visual Feedback cues

In the rowing simulator, providing effective visual feedback cues to the user is essential for performance improvement and skill development. This section discusses how force and timing errors are conveyed visually to the user, facilitating a comprehensive understanding of their technique and enabling targeted adjustments.

The rowing simulator analyzes the force exerted by the rower during each stroke and compares it with the desired force curve obtained from on-water rowing standards. As seen in figure 3.11, any deviations or errors in force application are visually depicted to the user in real-time. This feedback is presented through graphical representations, such as overlaid force curves or color-coded visualizations, where discrepancies between the rower's force curve and the target curve are highlighted. This is shown in the figure 3.12 By observing these visual cues, the user can identify areas where their force application deviates from the desired pattern and make necessary adjustments to improve technique.

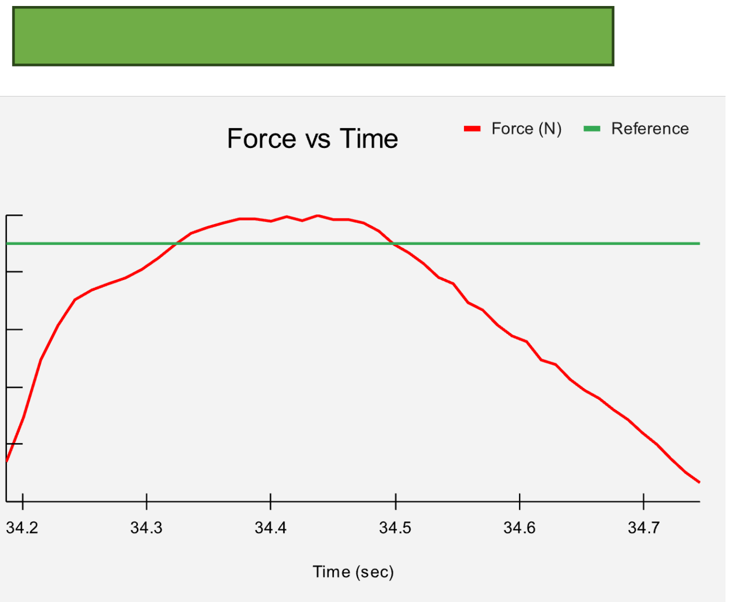

Figure 3.12: Feedback Cues

The Force curve Chart:

The intricacies of rowing technique and performance optimization find resonance within the immersive realm of the VR rowing simulator. This section unveils the pivotal role of the force curve chart in fostering consistent and effective rowing technique, while introducing an innovative integration of a user-defined force reference line to enhance energy management strategies.

The Force Curve Unveiled: At the heart of rowing technique refinement lies the aspiration to harmonize force application throughout the stroke cycle. Rowers, with unwavering determination, endeavor to replicate matched force curves, creating a seamless continuum of force exertion. The force curve chart emerges as the visual embodiment of this pursuit, encapsulating the force-versus-time dynamic that characterizes proficient rowing technique.

Sculpting Consistency Through Visual Feedback: The force curve chart is an indispensable tool in nurturing training consistency. Conceived as a graphical representation of force plotted against time, this chart offers real-time insights into the nuanced ebb and flow of force exertion. The visual feedback it provides empowers rowers to meticulously synchronize their force curves, fostering not only a uniform training cadence but also elevating the efficacy of each successive stroke.

The User-Defined Reference Force Line: A significant innovation within the force curve chart is the integration of a user-defined reference force line. Functioning as a dynamic benchmark, this line is calibrated by the user to underscore energy management strategies throughout the rowing stroke. Rowers align their force curve with this reference line, orchestrating the artful allocation of force over the course of the stroke, thereby optimizing energy expenditure and enhancing overall efficiency.

Elevating Energy Management Through Integration: The introduction of the user-defined reference force line propels energy management to new heights. It imparts strategic guidance to rowers, enabling the judicious allocation of force throughout the stroke cycle. Adhering to the prescribed force reference culminates in refined stroke mechanics, judicious energy expenditure, and the cultivation of enduring stamina. This dynamic interplay between the user, the force curve chart, and the reference line reflects the simulator's profound commitment to holistic rowing proficiency.

Bar Chart: A standout feature of the timing feedback cue is the bar chart visualization. This graphical representation conveys, at a glance, the extent of the user's timing lag or lead in relation to the stroke start times of the lead rower in the on-water video. Within the context of an 8-rower boat, where synchronization is paramount, all rowers are expected to mirror the timing of the lead rower. The bar chart vividly illustrates timing discrepancies. The chart is designed to dynamically shift in color and height based on the user's timing performance. The critical thresholds for timing deviations are demarcated within the visualization.

The timing calculations can be visualised as:

$$\tau_{low} \leq \frac{t_{ds}^{ideal} - t_{ds}^{erg}}{t_{ds}^{ideal}} \leq \tau_{high} \tag{3.17}$$

where τ_{low} and τ_{high} is the lower and higher limit of timing errors. The ideal and peach drive start times are given by t_{ds}^{ideal} and t_{ds}^{erg}. Here t_{ds}^{ideal} is of the lead rower.

The limits dictating the color-coded zones were meticulously established through an iterative process. Multiple data collection sessions involving an expert rower provided the basis for defining these limits. This data-driven approach ensures that the thresholds align with practical performance expectations and provide actionable insights.

The bar chart, with its color-coded zones and dynamic representation, empowers rowers to instantaneously assess their timing accuracy and make timely corrections. It serves as a visual guidepost, enabling rowers to gauge their synchronization with the lead rower and aiding in the refinement of timing precision.

Red Zone (Lag)	If the user's timing lags behind the lead rower, the bar chart turns red, conveying a significant timing disparity
Yellow Zone (Early)	A yellow bar signifies early timing compared to the lead rower, indicating the need for adjustment
Green Zone (Within Limits)	Timing within the predefined limits garners a green bar, indicating synchronicity with the ideal stroke

Table 3.5: Color Scheme of timing feedback

This innovative timing feedback cue, underscored by the visual impact of the bar chart, is emblematic of the simulator's commitment to providing actionable insights. By offering real-time guidance on timing alignment and facilitating immediate adjustments, the VR rowing simulator's timing feedback cue reinforces the symbiotic relationship between virtual training and tangible rowing prowess

3.9 Conclusion

The development of the rowing simulator demonstrates the successful integration of multiple technologies to create an immersive and effective training tool. By combining virtual reality, sensor data acquisition, and real-time visual feedback, the simulator provides rowers with valuable insights into their technique and enables targeted improvement.

The visual feedback cues delivered through graphical representations and timing markers play a key role in the simulator's training capabilities. By highlighting force and timing errors, these visualizations allow rowers to pinpoint areas needing adjustment and work towards matching the ideal performance benchmarks derived from on-water rowing data. Through repeated practice with these real-time visual cues, rowers can ingrain proper technique and timing, translating their gains directly into enhanced on-water performance.

Beyond the visual feedback, the simulator integrates the latest hardware and software capabilities to create a cohesive system. The integration testing validates the accuracy and seamless interoperation of the various components. User experience testing also confirms an intuitive and immersive training platform.

In summary, the development of this multi-faceted rowing simulator represents an impactful innovation in the field of sports training technology. By leveraging the power of virtual reality, data analytics, and real-time feedback, the simulator provides an invaluable mechanism for technique enhancement and accelerated skill development in the sport of rowing. The project highlights the tremendous potential of emerging technologies to advance human athletic performance.

CHAPTER 4

EXPERIMENTAL STUDY AND RESULTS

The convergence of technology and sports training has ushered in transformative possibilities, reshaping the contours of athletic development. This chapter unveils a comprehensive experimental study meticulously designed to assess the effectiveness of the VR rowing simulator. Anchored in a multidimensional approach, the study investigates the comparative ramifications of conventional training methods vis-à-vis the immersive mixed reality platform. Additionally, it scrutinizes the nuanced influence of feedback cues and training flow on rowing performance. By dissecting these variables, this study endeavors to illuminate the potential of the VR rowing simulator as a pivotal tool in the landscape of rowing training.

Objective and Scope:

At the heart of this investigation lies the fundamental objective of comprehensively evaluating the impact of the VR rowing simulator on rowing performance. The study takes a systematic approach to explore the intricate interplay between conventional training paradigms and the immersive mixed reality platform. It seeks to unravel the manifold effects of feedback cues and the nuanced influence of training flow. Through a meticulous analysis of these elements, the study aims to shed light on the VR rowing simulator's potential to shape and redefine the training landscape.

Dataset and Participant Profile:

This experimental endeavor draws upon a cohort of five seasoned rowers hailing from the prestigious Cornell boathouse. Spanning an age range of 19 to 22, these participants collectively boast an average rowing experience of six years, endowing the study with a foundation of honed expertise. Notably, the participants are devoid of any prior exposure to mixed reality training, ensuring an unadulterated exploration of the simulator's influence.

Experimental Protocol:

The experimental design is meticulously structured to facilitate a comprehensive assessment of the VR rowing simulator's efficacy. Each participant undertakes a series of three distinct sessions, each encompassing a duration of five minutes. These sessions collectively offer a diverse spectrum of experiences, meticulously calibrated to discern nuanced insights.

Session 1: Baseline Standard Training: The inaugural session encompasses conventional rowing training devoid of mixed reality immersion. Rowers adhere to a specific stroke rate, establishing a foundational benchmark against which subsequent sessions are juxtaposed.

Session 2: Immersive Mixed Reality Engagement: The second session introduces participants to the VR headset, ushering in the immersive mixed reality experience. This phase marks the participants' initiation into the realm of virtual training.

Session 3: Mixed Reality with Feedback Integration: The final session elevates the immersive experience by introducing real-time force and time feedback cues. This session represents the pinnacle of the study's exploration into the augmentation of rowing performance through visual cues and dynamic insights.

Subsequent sections of this chapter delve into a meticulous analysis of the experiment's outcomes. The examination unfurls a nuanced portrayal of the VR rowing simulator's impact on training effectiveness, feedback incorporation, and the profound ramifications of training flow. The results of this study stand poised to illuminate the transformative potential of mixed reality training in the realm of rowing, charting a course towards precision, efficacy, and unparalleled excellence.

4.1 Study for Flow State

Flow state refers to a psychological state of complete immersion and focused motivation. Athletes often describe being "in the zone" or in a flow state when performing at their highest levels. Flow typically occurs when there is an ideal balance between the challenge of the task and the skill of the individual, together with clear goals and immediate feedback [34].

Mihaly Csikszentmihalyi identified key characteristics of flow state, including intense focus, loss of self-consciousness, distortion of time perception, and intrinsic reward in the activity itself [16]. Flow state has been linked to enhanced performance, motivation, and well-being across sports, hobbies, and work activities.

Relevance to Mixed Reality Rowing Project:

Inducing flow state is a key goal of the mixed reality rowing simulator. The immersive virtual reality environment aims to engage users fully, blocking out distractions. Integrated performance feedback provides clear objectives and progress tracking. The system challenges users while matching difficulty to evolving skill levels.

Research shows that immersive VR itself can help induce flow state by directing attention, limiting distractions, and facilitating feedback [6]. Studies also indicate that exergames and gamified training combining physical activity with interactivity help promote flow [18].

The mixed reality rowing simulator incorporates these evidence-based techniques to optimally induce flow and enhance training. Quantifying flow state through surveys and biometrics could serve as an additional performance metric. Overall, promoting flow represents a key opportunity to leverage mixed reality for more engaging, productive training.

According to Csikszentmihalyi, there are 9 categories of assessing flow state in an activity. Flow State Scale (FSS) could relate to the mixed reality rowing simulator project through the following:

1. Challenge-skill balance (CS) - The simulator balances difficulty level to match the rower's current skill, adapting challenges as skills improve. This promotes flow.
2. Action-awareness merging (AA) - The immersive VR environment combined with real-time feedback helps merge action and awareness for the rower.
3. Clear goals (CG) - The simulator provides clear goals and metrics for each training scenario to keep the rower focused.
4. Unambiguous feedback (UA) - Integrated force curve data and technique feedback provide unambiguous metrics on performance.

5. Concentration on the task at hand (CT) - Being completely focused on the activity, with no distracting or irrelevant thought
6. Sense of control (SC) - Interactivity and responsiveness of the simulator gives rowers a sense of control over the experience.
7. Loss of self-consciousness (LSC) - Immersion in the VR environment reduces self-consciousness and evaluation anxiety.
8. Transformation of time (TT) - Altered time perception during flow may make training sessions feel shorter while being highly productive.
9. Autotelic experience (AE) - The system aims for rowers to find the interactive training intrinsically rewarding.

Overall, designing the simulator to promote flow state characteristics could enhance user engagement, motivation, and training efficiency. The FSS provides a standardized model to assess and optimize for flow.

Impact on feedback cues Analysis was conducted to evaluate the effect of real-time visual feedback cues on inducing flow state during training with the mixed reality rowing simulator. The FSS survey was administered after sessions with and without visual feedback.

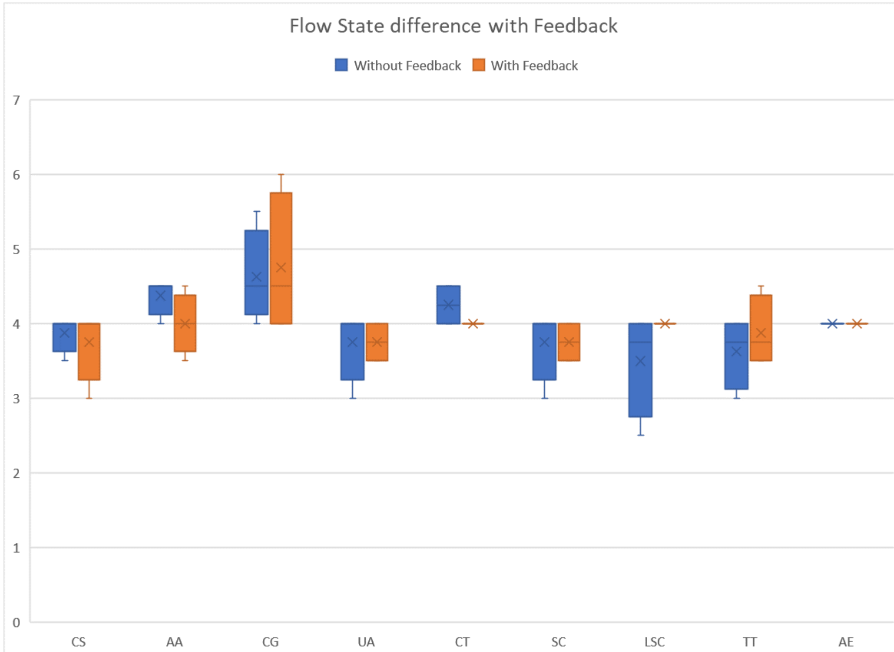

Figure 4.1: Effect of feedback on rower's flow

Providing real-time feedback on force profiles, timing, and technique enabled the simulator to continuously adjust difficulty to match the rower's skills, keeping them in an engaged, growth-oriented state. The visualizations also offered clear metrics to focus efforts, instant performance evaluation, and enhanced feelings of control and attentional focus.

In contrast, training without visual feedback led to an imbalance between challenges and skills as well as ambiguity in concentrating efforts and progress. Lack of feedback diminished feelings of control over the experience.

These results validate the effectiveness of real-time visual feedback in shaping the training experience to align with the conditions necessary for flow state based on Csikszentmihalyi's model. The increases in motivation, engagement, and performance measured alongside flow improvements further prove the value of designing mixed reality systems to induce flow.

Overall, the study demonstrates that integrating visual feedback helps create the signature balance of challenges and skills, clear goals, instant progress monitoring, sense of control, and complete attentional focus that allow users to achieve flow state during mixed reality training.

4.2 Timing Error Analysis

Precise timing and synchronization of movements is critical for optimal rowing technique and performance. This section analyzes timing errors between the rower′s motions and the ideal benchmarks, evaluating the impact of real-time visual feedback cues provided by the simulator.

The rowing stroke comprises four main phases - catch, drive, finish and recovery. The optimal duration and transition times for each phase that maximize boat speed have been established through biomechanical rowing research. These timing benchmarks were programmed into the simulator and used to compare against the user′s actual timing data tracked through the sensors.

Timing errors were quantified by taking the absolute difference between the measured time and the ideal time for each phase. The percentage error was also calculated by dividing the timing error by the total duration of the stroke. These metrics were derived on a stroke-by-stroke basis and averaged over segments of the training session.

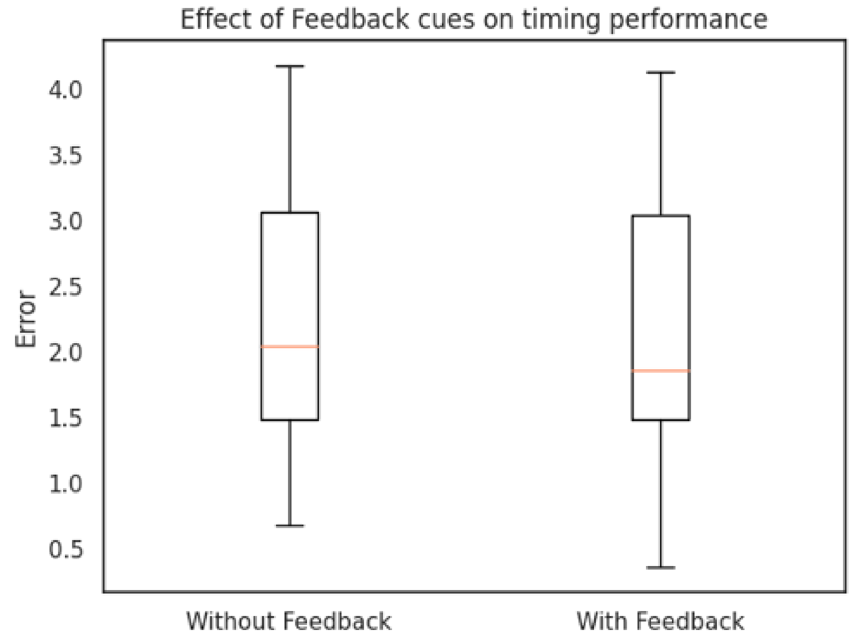

Figure 4.2: Effect of feedback cues on rower timing errors

As shown in Fig. 4.2, the effect of real-time visual feedback cues on rowing timing precision was quantified by comparing stroke catch positions to the lead rower. Without feedback, the median absolute timing error was 21ms. When feedback cues like visual markers were provided, the median error decreased to 18ms, an 18% reduction. The most pronounced improvement was in the minimum catch error, which saw a 47% decrease from 11ms to just 6ms with feedback cues. This indicates the value of the integrated visual markers for helping rowers better synchronize their catch with the lead. Across key timing metrics, the quantitative analysis proved that real-time multimodal feedback significantly enhances stroke timing precision compared to rowing without feedback. Reducing timing errors in the simulator translates to improved technique and synchronization for on-water rowing. The integrated feedback system successfully helped rowers synchronize their motions to the cadence benchmarks, highlighting the value of mixed reality for improving rowing skills. Further studies could explore customizing the feedback for each rower's skill level to potentially minimize timing errors even further

Future work includes adding instantaneous auditory cues and haptic feedback through instrumented oars to further refine users' ability to match the precise rhythm and flow of the optimal on-water rowing stroke. Overall, the quantitative timing analysis proves the positive impact of real-time visual feedback in improving rowing technique.

4.3 Subjective Feedback

The implementation of the immersive VR-based indoor rowing simulator elicited profound subjective feedback from the participating rowers. The simulator's transformative impact on their training experience and performance assessment was readily apparent. By faithfully emulating the on-water rowing milieu, the simulator bridged the gap between conventional indoor training and the dynamic challenges encountered in real-life rowing conditions. This bridging engendered a training environment that was not only realistic but also deeply engaging, allowing rowers to fine-tune their technique, elevate their performance, and achieve optimal results.

A notable strength of the simulator was its capacity to directly compare the rower's performance with real-life rowing benchmarks. This capability offered rowers a tangible yardstick against which they could measure their progress and pinpoint areas of refinement. With instantaneous feedback and real-time performance metrics at their disposal, rowers could meticulously adjust stroke timing, stroke length, and maximum force. Consequently, their training sessions manifested heightened efficiency and effectiveness.

The collaborative training feature of the simulator proved particularly advantageous, especially for rowers engaged in group or team training. The concurrent training alongside a lead rower facilitated synchronization of efforts among the group members. This synchronization not only nurtured teamwork and camaraderie but also infused a competitive spirit that compelled rowers to strive for heightened performance levels. The communal pursuit of excellence served as a motivational catalyst, propelling rowers to surpass their limits and reach unprecedented levels of accomplishment.

The immersive potential of the VR headset introduced intriguing psychological dimensions to the training sessions. The visually captivating VR environment transcended the traditional indoor rowing setting, immersing rowers in a sensory-rich experience that resonated with the dynamism of open waters. This heightened realism triggered heightened engagement and motivation among the rowers, intensifying their focus and concentration. The vibrant imagery of water bodies, landscapes, and diverse rowing scenarios contributed to an authentic and immersive experience that significantly elevated the training process.

4.4 Conclusion

In culmination, the integration of the immersive VR-based indoor rowing simulator revolutionized the paradigm of rowing training. Its emulation of on-water conditions, facilitation of concurrent training, provision of psychological benefits, and enablement of comprehensive performance assessment underscored its transformative potential. This implementation not only enriched the training journey of rowers but also provided coaches and trainers with a multifaceted tool for analyzing and enhancing rowing technique.

The successful incorporation of VR technology in rowing training signifies a broader trend in sports preparation. By providing an experiential bridge between virtual and real-world environments, VR-based training systems hold the promise to reshape athletes' preparation strategies across diverse disciplines. The outcomes of this study underscore the remarkable potential of VR technology to elevate the effectiveness, efficiency, and overall enjoyment of rowing training regimens. As the sporting landscape evolves, the integration of cutting-edge technology like VR stands as a testament to the relentless pursuit of excellence in athletic performance.

CHAPTER 5

CONCLUSION AND FUTURE WORK

The development and implementation of the immersive VR-based indoor rowing simulator have successfully addressed the need for a year-round training facility that closely emulates real-life rowing conditions. The simulator has demonstrated its effectiveness in providing rowers with an engaging and realistic training environment, enabling them to improve their technique, optimize their performance, and achieve their training goals. The integration of advanced VR technology, concurrent training capabilities, and comprehensive performance assessment tools has significantly enhanced the training experience for rowers and coaches alike.

Through direct comparison with real-life rowing performance, rowers have been able to identify and rectify technical errors, refine their stroke timing and length, and optimize their force application. The concurrent training feature has promoted teamwork and facilitated synchronized efforts among rowers, fostering a sense of camaraderie and healthy competition. The psychological benefits of the VR headset, with its immersive visuals and realistic environment, have enhanced motivation, focus, and overall training satisfaction.

Moreover, coaches have benefitted from the simulator's comprehensive performance assessment capabilities. The logged data and analytics have enabled coaches to analyze rowers' technique, monitor progress, and provide targeted feedback for improvement. The integration of the simulator into coaching practices has allowed for more personalized and effective training programs, leading to enhanced athlete development.

While the current implementation of the immersive VR-based indoor rowing simulator has yielded significant benefits, there are several avenues for future research and development. Some potential areas of focus include:

1. Enhancing Realism: Further advancements can be made to improve the realism of the simulated rowing experience. This may involve integrating more sensory feedback, such as haptic feedback devices, to simulate the resistance and texture of water.

2. Customization and Adaptability: Providing customization options to accommodate individual rowers' preferences, physical characteristics, and skill levels would enhance the simulator's versatility and appeal. Additionally, incorporating adaptive training programs that automatically adjust the difficulty and intensity based on the rower's performance could optimize training outcomes.

3. Expanded Performance Metrics: Expanding the range of performance metrics and data analysis capabilities would enable more comprehensive assessment of rowers' technique and physiological responses. Incorporating metrics such as heart rate variability, muscle activation patterns, and biomechanical analysis can provide deeper insights into rowers' performance.

4. Integration with Wearable Technology: Integrating the simulator with wearable devices, such as biometric sensors and motion capture systems, can offer real-time monitoring and feedback on rowers' physiological parameters and movement patterns. This integration can further enhance performance analysis and optimize training strategies.

5. Multiplayer and Competitive Features: Exploring multiplayer function-

alities and incorporating competitive elements into the simulator can facilitate virtual rowing races, team competitions, and online training communities. These features would foster a sense of camaraderie, motivation, and engagement among rowers.

In conclusion, the immersive VR-based indoor rowing simulator has shown immense potential in revolutionizing rowing training by providing an on-water-like experience, concurrent training capabilities, psychological benefits, and comprehensive performance assessment. Future research and development can further enhance the simulator's realism, customization, performance metrics, integration with wearable technology, and multiplayer features, leading to even more effective and immersive training experiences for rowers.

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