VCRS: A Novel Approach to Virtual Reality Cycling for Balance Rehabilitation

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ABSTRACT

This paper presents the hardware and software design of Virtual Cycling Rehab System (VCRS), a novel and affordable system for balance rehabilitation via virtual reality (VR). The system integrates real-time sensor communication with an Oculus Quest-based virtual environment created in Unity. This integration enables precise avatar movement and facilitates the assessment of lateral balance during cycling rehab sessions. The accelerometer data from one side of the pedals is accurately translated into in-game physics to create realistic avatar movement. The system also utilizes gyroscope data to calculate and display a graphic representation of the patient's balancing score to guide the patient's lateral balance. Physicians can monitor the session via live mirroring the VR HMD and graphed balance data on a local device. At the end of each session, the user receives feedback in the form of session time, game score, and a percentage indicating their level of lateral balance.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**.

KEYWORDS

Virtual Reality, Rehabilitation, VR Cycling

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1 INTRODUCTION

In 2021, one in six deaths due to cardiovascular disease is from stroke or complications arising from it, and those that survive can be left with potentially debilitating health complications [7]. Middle cerebral artery (MCA) strokes are the most common type of acute stroke and are associated with unilateral flaccidity, forced gaze deviation, visual field cuts, etc. [10].

Cycling is an established physical therapy found to improve balance, increase mobility, reduce muscle stiffness, increase endurance, improve knee flexibility, and strengthen leg muscles [16]. Cycling allows continuous repetitive motions for an endless span, demanding fewer therapists and involving alternating and coordinated activation of antagonistic muscles. [1].

Virtual reality interventions in rehabilitation can target many consequences of stroke, including reduced motor function, mobility, postural control, and cognitive impairments. A virtual reality environment enables the program designer(s) to have greater control over the patient's sensory experience, to tailor the experience to invoke certain cognitive patterns while eliminating unnecessary stimuli found in organic experience. One issue in physical therapy is loss of motivation or mental fatigue. It is important to keep up patient morale to ensure greater therapy success. Virtual reality has been found to reduce pain perception in rehab patients by 10% [9]. Gamification, adding tasks and goals, encourages a connection between performance and immediate or near-immediate reward [6]. This increases patient motivation and engagement in their recovery process by creating a sense of achievement.

As addressed, post-stroke patients often require rehabilitation to improve muscle strength, balance, and functional abilities in postural control and gait. While traditional physical exercise interventions have shown positive effects, there is a need for more effective and personalized approaches to promote adherence to functional activity programs. Virtual reality (VR) has emerged as a promising technique for encouraging physical activity and creating environments for objective movement assessment.

To this end, we design a virtual cycling rehab system (VCRS) with the goal to enhance the sense of immersion and promote repetitive exercise for post-stroke patients. We design the system with usability and affordability in mind: it should be compatible with affordable generic VR headsets with minimal system complexity by using only essential sensors and reducing external system dependency. Following these requirements, we provide post-stroke patients with a user-friendly and accessible VR cycling platform that can effectively contribute to their rehabilitation process.

Fig. 1 shows an overview of the core components of the virtual cycling rehab system (VCRS). Its design is built upon three pillars: sensor communication, sensor data processing, and data interpretation. The system utilizes a conventional bicycle affixed to a stationary stand that permits both steering and pedaling. The participant's motion will be monitored, particularly with regard to their forward velocity and the pedaling frequency differentials between the left and right sides. Additionally, the participant will receive visual feedback about their balance score, forward trajectory, and obstacles to avoid during the session.

2 RELATED WORK

Virtual reality involves the creation and rendering of virtual world representations on a computer. Users and the virtual world can interact and generate the same feedback information as in the real world so that users feel as if the interaction occurs in the real world. This groundbreaking technology has paved the way for VR fitness solutions for individuals seeking immersive indoor physical training experiences, including cycling. As this entertainment industry embraces the advancements of VR, many studies also evaluated the potential effectiveness of virtual reality rehabilitation systems, particularly for post-stroke patients. In the following, we discuss the current VR cycling systems and products and the outcomes observed in the application of VR rehabilitation.

2.1 VR Fitness Platforms and Body Tracking Systems

The majority of virtual reality cycling programs are targeted at fitness and recreation audiences and are non-medical in nature. For instance, the virtual reality fitness program for cycling, HOLOFIT, uses a cadence sensor to monitor pedal rotation for translation to movement in-game. HOLOFIT currently offers "more than 50 workout tracks in 13 HOLOWORLDS," which are differently themed immersion environments, and five modes to cater to differing workout goals [5]. Another product, CycleVR, is a Kickstarter project still in development that uses a cadence monitor, a GEAR VR virtual reality headset, and an app created for the program. Instead of a created 3D model environment, it uses existing Google Street View information to allow the user to "cycle anywhere in the world" and interact with an online community [8].

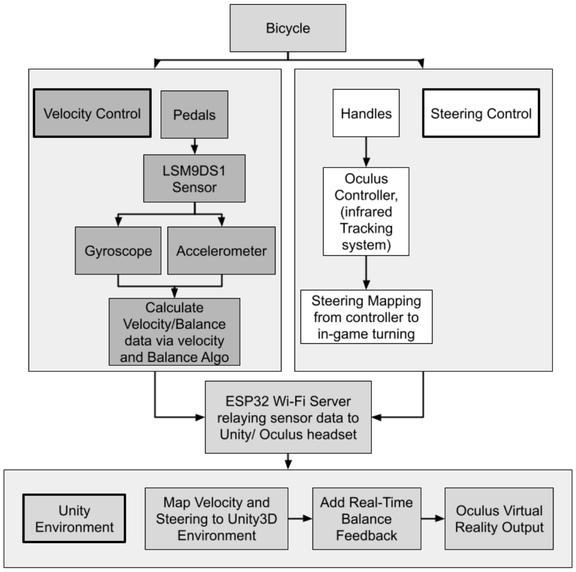


Figure 1: Overview of our Virtual Cycling Rehab System (VCRS). Our hardware setup includes IMU and Oculus controllers that are used for calculating balance, steering, and velocity data for real-time output in Unity/Oculus.

While current VR devices can accurately track head and hand movements, reliable and accurate tracking of other body segments is often limited. For full body tracking, Caserman et al. [3] developed a reliable real-time body tracking VR system using the HTC Vive and the Vive Tracker using efficient inverse kinematic (IK) solver. In addition to full body tracking, VR cycling requires more specific movement information compared to virtual recreation, such as orientation and rotation of the lower limb. Rojo et al. [13] developed a low-cost VR pedaling exercises system that combines an inertial measurement unit (IMU) with the Oculus Quest 2 headset and a stationary pedaling system. This system can accurately track the movement in real-time with a gyroscope and accelerometer attached to the user's thigh, which also has a relatively low cost and simple setup. On the other hand, the solution in [3] cannot track lateral balance and lacks the ability to track turning, which are essential aspects of biking.

2.2 Effectiveness of VR Rehabilitation System for Post-Stroke Patients

Virtual reality rehabilitation includes physiological therapy and psychotherapy based on physiology, which is called physical therapy. It is a treatment for stroke patients using a cycling system combined with game mechanics. Wearing a virtual reality headset puts the patient in a virtual environment, which makes the therapy more engaging and immersive, and also improves the patient's optimism toward their treatment. Demeco et al. [4] systematically reviewed the effectiveness of VR in post-stroke rehabilitation for upper limb function and lower limb function. They concluded that virtual reality rehabilitation is an effective and adaptable method for stroke rehabilitation as a complementary tool to enhance cognitive approaches in neurorehabilitation. A study conducted by Song and Park [2] evaluated both the physical function, such as balance, and psychological characteristics, such as depression, of 40 stroke patients. The result of this study suggested the virtual reality group demonstrated greater physical ability improvements, for instance, weight distribution ratio on the paralyzed side and anterior and posterior limits of stability.

3 SYSTEM DESIGN

VCRS implements a real-time communication system for collecting data from the pedal sensor, which is converted to the velocity of the user's bicycle, and data from the Oculus controller, which is converted to the steering controls for the bicycle. The adoption of steering within the system creates a more immersive cycling experience for the user. The velocity and steering controls of the bicycle are further fed to the virtual environment created in Unity3D to provide appropriate real-time feedback to the user/patient.

3.1 Hardware Communication

The system employs the LSM9DS1, a 9-axis iNEMO inertial module (IMU). The system provides forward velocity information based on pedal movement and sufficient data points over a fixed time period for calculating the balancing score, with a single sensor located on one side. The system also employs an ESP32 module, a low-cost, low-power SOC (system on a chip) with WiFi capabilities. As shown in Fig. 1, after connecting the ESP32 with the sensors, the ESP32 acts as a station and creates a web server to transfer accelerometer and gyroscope data. ESP32 takes data from the accelerometer and gyroscope every 20 ms. The data points are then fetched by the Oculus Quest headset while connecting to the ESP32 WiFi every 200 ms. The system creates a data buffer of an array of length 10 that includes the velocity and tilt corrected z-axis accelerometer data over the last 10 points collected over 200 ms, at 20 ms intervals. The buffer array is then able to be accessible via an API call to a specific route on the ESP32 WiFi server.

3.2 Sensor Data Processing

There are three different sensors at work within this system. The accelerometer, gyroscope, and infrared tracking system of the Oculus controller/headset. These three sensors are used within three parts of our system: velocity measurement, balancing score, and the steering/turning of the bike.

The accelerometer data is used to determine the magnitude of the acceleration of the pedal movement and is translated to forward velocity to move the avatar in the virtual world. The infrared tracking system of the Oculus controller/headset is used to track the bike's steering. Data from both the accelerometer and the gyroscope is used to simulate the balancing score.

The balancing score is generated from data collected at the start of each cycling session. The balancing algorithm calculates the delta between how much time the user spends pedaling down on one side versus pedaling down on the other. The accelerometer and gyroscope work together to calculate the acceleration on the z-axis (up/down direction). Within the current system, to allow for small inaccuracies of the sensor, we add a threshold of $+/-.4m/s^2$ of the z-axis acceleration to register a movement upwards or downwards of the pedal.

The accelerometer registers a non-zero value along the z-axis when in a flat and motionless state due to the earth's gravity, which equates to 9.8 m/s^2. This z-axis reading can be used to detect upward and downward motion on one pedal. However, to obtain the imbalance of the left and right pedal, simply relying solely on accelerometer data along the z-axis is insufficient; this is due to the fact that when the sensor tilts, the z-axis is in relation to the orientation of the sensor, and thus will be inaccurate. For example, if the sensor is flipped sideways, it will report 0 m/s^2 instead of the expected 9.8 m/s^2. Thus we incorporate the use of the gyroscope to enable us to know the orientation of the sensor and cancel out any effect of the sensor's tilt, thus making it as if the sensor was stationary and lying flat on a table. In the current system, the z-axis data fed into the environment when the sensor is stationary in any orientation will be 9.8 m/s^2.

For the system to register an imbalance in either the left or the right foot, the system implements a low pass filter on the latest 10 data points that the system receives (the 10 data points are collected in even time increments over a span of 200 ms). Based on these 10 data points, we calculate the difference in frequency between upward and downward movement and thus create an output of which side was used most during the time interval. When this is calculated many times in a session, we can obtain a more accurate reading of which side is imbalanced in the patient.

Algorithm 1 Update Acceleration History and Compute Average

```
procedure UPDATEACCELHISTORYANDCOMPUTEAVERAGE(accel_history[], accel_x, accel_y, accel_z)
    ACCEL_HISTORY_SIZE ← constant integer
    m ← float
    accel_average ← float
    m ← $\sqrt{accel\_x^2 + accel\_y^2 + accel\_z^2}$
    for i = ACCEL_HISTORY_SIZE − 1 downto 1 do
        accel_history[i] ← accel_history[i - 1]
    accel_history[0] ← $|m - 9.8|$
    accel_average ← 0
    for i = 0 to ACCEL_HISTORY_SIZE − 1 do
        accel_average+ = accel_history[i]
    accel_average/= ACCEL_HISTORY_SIZE
    return accel_average
```

To calculate the velocity, the system implements a buffer array of the previous 10 acceleration data points. The system captures a new data point every 20 milliseconds and removes the oldest data point within the buffer array. The average of the buffer array is taken to obtain the current velocity. This allows for a steady change in velocity in a real-time system. Detail of the algorithm is described in Algorithm 1.

3.3 Virtual Environment Creation

A substantial challenge we encountered during the development was the rendering capability of the Oculus Quest headset. According to Meta Platforms, the Oculus Quest Headset integrates an individual 1440x1600 OLED display with a refresh rate of 72 Hz for each eye. The internally-recommended triangle count ranges are 350k–500k [11].

The terrain system in Unity3D deforms polygon planes with high segment density to create detailed landscapes. While this terrain system offers many benefits, it is not optimized for virtual reality experiences on Oculus headsets, as the created scene can contain a large number of high polygon models. Instead, we used Blender, a 3D modeling software that provides a comprehensive set of tools for creating realistic and detailed terrains and models such as bikes and sprites. We use Blender to create custom terrain assets that are better optimized for performance on Oculus devices. Fig. 2 (a)-(c) show example virtual environments we built via Blender.

Furthermore, to accurately replicate real-life biking dynamics and facilitate turning, we divide the bike model into two distinct components, as shown in Fig. 2(d): the handlebar with the front wheel and the rest of the bike. When the user turns the stationary bike's handlebar, the front section of the bike model rotates and causes the entire bike to pivot and align accordingly, and the center of rotation is set to be near the head tube of the bike.

The primary camera, integrated with the Oculus system, is positioned at the center of the stationary bike, just above the bike seat, and slightly close to the handlebar. This setup aims to replicate the natural body gestures and head position experienced during actual cycling. As the user starts pedaling, the camera will simulate forward motion at the same velocity as the virtual bicycle, accompanied by audible cues simulating the sounds of a bike on the road.

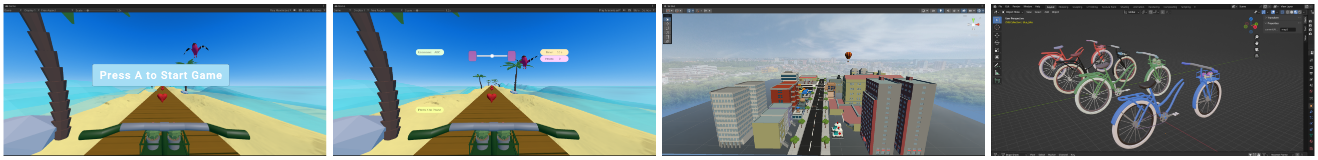
Moreover, the camera will not turn automatically when the user turns the bike's handlebar. Instead, the camera will always respond to the user's head movements, maintaining synchronization between the virtual viewpoint and the user's intended direction to reduce the risk of conflicting visual and physical cues. When the user moves their head, the camera movement is independent of the bike. For example, if the user is pedaling while turning the head, the virtual bike will remain in its orientation while moving forward.

We use a physics engine in Unity3D to simulate real-world forces, such as gravity, collision, and acceleration, making sure objects behave realistically in the virtual world. In particular, we use them for calculating bicycle tilting angles, speeds, and acceleration.

Lastly, the avatar movement is controlled in two ways. The forward velocity is determined by the magnitude of acceleration on one pedal with a multiplier of 6.5 to ensure realistic and reasonable mapping from the physical world to the virtual world to avoid motion sickness. The turning mechanism should be designed with existing materials and tools to attain a cost-effective, straightforward system architecture without additional hardware. The possibility of employing an accelerometer was initially explored, leveraging positive and negative acceleration readings to determine the turning direction. However, accurately translating the magnitude of the turn proved to be a challenging task.

Instead, we drew inspiration from the well-known virtual reality game Beat Saber [15] where the Oculus' handheld controllers were already pre-calibrated for use with the corresponding VR headset and accompanied by an existing code library. Recognizing the potential in this established setup, we decided to use the right-hand Oculus controller. A mounting location was created on the handlebars to facilitate integration with the physical bicycle using industrial-grade Velcro. This approach was chosen due to the requirement of the controller's availability for use in the Home scene in Unity, which requires controller button interaction.

To establish the connection between the in-game bicycle and the physical controller, a game object obtained from the OVR Integration package, accessible through the Unity Asset store, was assigned as a child of the in-game bicycle. By locking the y-axis rotation of the front wheel to match



(a) (b) (c) (d)

Figure 2: (a) Seashore start view (b) Seashore in-game view (c) City full view (d) Bike model in Blender

Table 1: Cost analysis by parts of VCRS

Component	Cost	Purpose
ESP32	\$7.00	Facilitates wireless data transfer through wireless communication.
Acceleration and Gyroscope Module	\$30.00	Provides angular acceleration and orientation data that can be converted into forward velocity in a virtual environment.
Jumper Wires	\$0.20	Connect the sensor, ESP32, and battery to allow electrical current to flow between them.
Rechargeable Battery	\$6.50	Provide stable power for ESP32 and sensor for a portable solution.
3D Printouts	\$3.00	Prevent physical damage and potential interference with the sensor's accuracy and functioning.
Total	\$46.70	

the y-axis rotation of the game object, only this specific rotational value was isolated, enabling a one-to-one mapping for the implementation of turning. For a comprehensive understanding of the orientation constraint and the functionality provided by the handheld controller, further insights can be obtained from the OVRInput library [12].

4 COST ANALYSIS

VCRS is designed to be an affordable solution to virtual reality cycling. Table 1 shows the cost breakdown of our proposed system. (We note that the cost in the table does not include the bike, bike stand, or the Oculus headset.)

First, we found that the cost and size of the ESP32 can be reduced to below \$5.00 by deducting the unused GPIOs while maintaining the regular operation of the device [14]. Furthermore, the cost of the sensor can be lowered to approximately \$30 by using sensors that have only accelerometer and gyroscope capabilities and not including other functions such as temperature detection, which is not necessary for the intended use in the VCRS system.

To ensure the optimal functionality and accuracy of the sensor when affixing it to a bike pedal, a protective 3D-printed case is added to shield it from potential physical damage resulting from contact with external objects. For example, the participant could interrupt or damage the sensor when pedaling by kicking, which occurred in experiments.

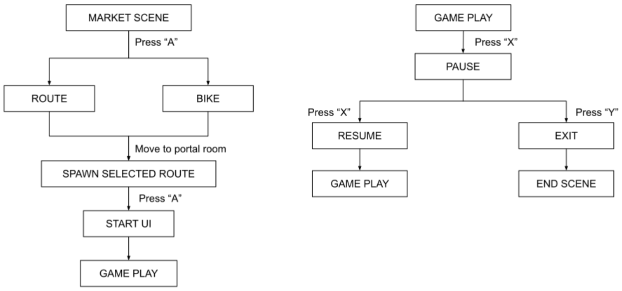


Figure 3: In-session software workflow design

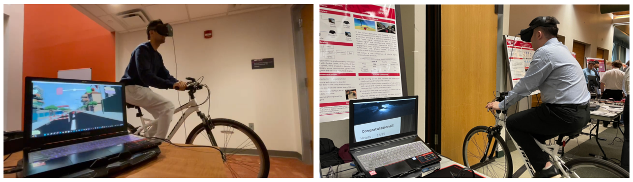


Figure 4: Testing with team members

In addition, a second 3D-printed device will affix the Oculus controller to the handlebars for turning capability. The estimated cost of these two 3D printouts is around \$3 using PLA, under the assumption that a 3D printer is already available. Therefore, the final production cost is \$46.70.

Additionally, regular software updates and maintenance should be carried out to ensure the VR game is running smoothly and to fix any bugs or issues. The cost of these updates and maintenance can be considered low as the team will be responsible for it.

5 INITIAL OBSERVATIONS

VCRS was initially tested by the team members, as shown in Fig. 4. During the Rutgers University ECE Capstone Expo on April 26th, 2023, interested participants in the public were also welcomed to try out our system. In this case, the participants took the role of the patient and the team member took the role of facilitators.

A VCRS session starts with the physical setup that secures a common road bicycle to the bike stand so that the bicycle does not tilt or shake for the safety of the rider. The ESP32, the Oculus headset, and the monitoring computer are powered on and should all be connected to the ESP32's WiFi. After the hardware and physical component setup, the in-game session flow is shown in Fig. 3. The facilitator can instruct the user to hold onto the bicycle handlebars. Then, the session flow shown on the right of Fig. 3 will be followed. Button "A" on the right-hand controller is pressed to activate the scene. At this point, the patient can begin pedaling, and the graphing program will display the balance information on the computer for physician use/analysis.

Almost all participants had no prior experience using a VR headset. This was an unexpected challenge as it required the facilitators to concisely and clearly teach the participants how to utilize the Oculus headset and controllers. Another related issue that unfamiliarity with the controllers contributed to was confusion about the game flow. Where the interaction was thought to have been streamlined and minimized, in practice, participants required multiple reminders of the selection button.

Overall, most participants were enthused and positive about their experience. They reported that the responsiveness of the avatar to pedaling was as expected. However, several participants reported feeling symptoms of VR sickness such as vertigo and dizziness, one even saying, "I was afraid I would fall over." Part of this can be attributed to the large frame of the bicycle used, as it was ill-suited to many participants and restrictive for those under 5'4" who were unable to sit properly and reach the pedals. Otherwise, the sensitivity of the camera to the headset's movement may be too high for people who are unaccustomed to VR, and turning at the same time might increase this effect.

6 LIMITATION AND FUTURE IMPROVEMENT

Sensors. The current system has a very limited monitoring system, where it only can tell the imbalance in the patient. We can enhance it via integration with other technologies, such as sensors that can track a patient's heart rate in real-time, which can provide valuable insights into the effectiveness of the therapy and help tailor the experience to each patient's specific needs. The heart rate sensor can also increase the difficulty of the cycling track and push the patient to try harder depending on the strain on their body.

Wireless communication. Another improvement to the system is to change from an API-based WiFi Server to a WebSocket-based connection between the headset and the WiFi server instead of being an exclusive 1-way connection. In the current system, the WiFi server API has 80 ms of lag, and because of this, the system has to implement buffer arrays so there are no constant requests to the server. Creating a constant via WebSockets would mean a sub-20 ms lag, and each point would be processed without using a buffer array. Having less laggy input creates a more robust and immersive experience for the user and should be implemented.

Software. The software limitations are mostly reflected in the virtual world, including bike physics simulation, 3D scene development, game object modeling, etc. With the integration of more refined steering mechanics, the bike simulation can be enhanced within the virtual environment, which will also create a more realistic and engaging experience for users while decreasing VR sickness. Furthermore, the inclusion of a more diverse array of road types, including off-ramps and viaducts, can provide a broader range of scenarios to navigate and interact with. In addition, this improved immersive experience holds the potential to be extended beyond the general user population and post-stroke patients, such as users who are afflicted with spinal cord injuries or neurological disorders. By affording these individuals an opportunity to enhance their motor skills within a controlled and secure environment, therapeutic benefits can be reaped.

Furthermore, to aid users in better understanding the mechanics of the simulation, additional signage within the virtual environment, a more comprehensive user interface, and a user manual detailing button controls and game progression could be implemented. Additionally, developing a more thorough report at the end of each session would enable the recording of patients' progress and assist physicians in patient improvement analysis. Moreover, implementing a game store system that offers purchasable sprites and bicycle model customization options also can serve as a rewarding incentive for users to further encourage users for physical training and enhance user satisfaction.

Test. Given the system's current state as a proof-of-concept, additional development is necessary before testing with actual stroke patients can take place. All previously mentioned improvements, such as incorporating sensor interaction, like the heart rate sensor, enhancing the user interface for greater user-friendliness, and addressing motion sickness concerns, should be taken into account during the development process. These enhancements will contribute to a more robust and safer system suitable for evaluation with stroke patients.

7 CONCLUSION

In this paper, we present VCRS, an affordable virtual reality cycling system. The implementation of VCRS met the goals defined in its design. The communication between the sensor and headset is easily established and has acceptable latency. The in-game flow is seamless and has a simple learning curve. The sensor data is robustly converted to physics engine-compatible movement that is responsive to the user/patient's inputs.

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