Extended Reality Waterball for Spinal Rehabilitation

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Figure 1: The incorporation of wearable technology in water-based activities, using a head-up display in a waterball at the formerly accessible Ontario Place West Channel.

Abstract

We propose the use of a waterball (water-walking-ball) for physical exercise (spinal rehabilitation) using an IMU (inertial measurement unit) for realtime tracking of the ball's orientation in a feedback loop with a head-mounted display worn by the occupant of the ball. The display functions like a flight simulator or video game, in which the ball becomes the game-controller (interface) for a simple physical exercise activity of walking while maintaining the polar axis as horizontal (or as vertical) as possible. A score is generated by computing the time-integral of the tilt away from this horizontal line, which becomes an error function to be minimized.

Keywords

IMU, Integral Kinesiology, Rehabilitation, Sensor Fusion

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1 Introduction

The waterball (See Fig 1 and 2) is an inflatable ball a person can enter to walk-on-water. This activity has long been popular at amusement parks, and many other venues as a fun and safe (when used in compliance with ASTM F2374-20) and healthy activity that encourages body movement and development of core strength [18]. We instrument a waterball with an IMU (Inertial Measurement Unit) to "gamify" the unique challenges that the activity presents by way of encouraging the user to engage their core and back muscles [25]. Because this athletic activity demands a great deal of core muscle bandwidth for balancing, it offers a unique opportunity for spinal rehabilitation among those able to stand and walk, but

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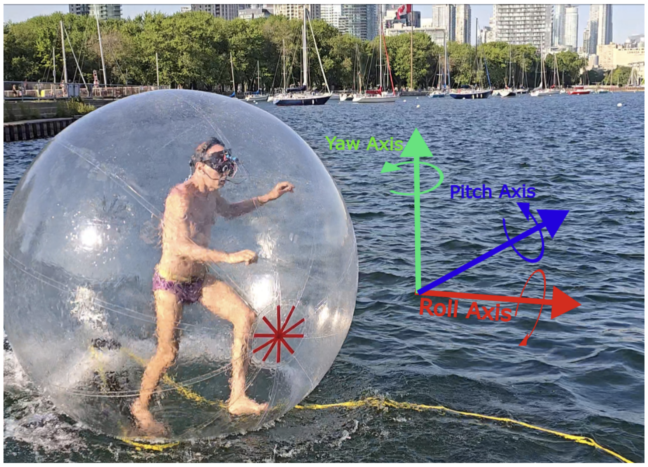

Figure 2: Walking on water inside a waterball while wearing a head-mounted display providing visual feedback similar to a flight simulator or video game. The poles of the ball are marked in a 10-pointed star. The red pole is visible on the lower right side of the ball.

Figure 3: Electromechanical layout of the IMU and M5STAMPS3, made waterproof by insertion in a clear plastic pipe with end-plugs affixed by hose clamps.

unable to tolerate impact (e.g. hard ground)[4],[2]. The soft surface of the water provides a gentle (in terms of impact) yet sufficiently demanding load to stimulate muscle growth.

2 Overview

Maintaining good spinal and back health is essential for overall well-being, and regular exercise plays a pivotal role in achieving this. Balance exercises strengthen the core muscles that support the spine, improving overall health and reducing the risk of spinal injuries [10]. Multiple different techniques of improving spinal health have been researched such as locomoter training, pharmacology techniques, and functional electrical stimulation [15]. Among various forms of exercise, water-walking is particularly beneficial for spine health, and can be combined with XR (eXtended Reality) [3, 4].

3 Methods

3.1 Goal is constant roll

To facilitate the collection of data on pitch and roll angles during exercises, a multi-component setup involving both in-ball and out-of-ball components was developed. To maintain a totally smooth interior surface of the ball, all ball-mounted components must be outside the ball, and therefore must be waterproof. Anything inside the ball must be worn by the occupant (user) of the ball (See Fig 4). The components and their respective configurations are detailed below.

3.2 Ball-Mounted Sensing System

An Inertial Measurement Unit (IMU) was mounted on a perf-board (perforated board) outside the ball [25]. Before being attached to the ball, the assembly was inserted into a clear plastic tube designed to keep water out during use. The tube was subsequently sealed using two stainless steel hose clamps in conjunction with tight-fitting plugs in order to ensure impermeability (see Fig 3) [27]. This setup comprised the following elements:

- Microcontroller: M5STAMPS3
- Battery regulator board ensuring stable power supply
- Power source: A rechargeable battery
- Plastic tube
- 2 stainless steel hose clamps
- 2 plastic plugs

The perf board was designed to securely hold the IMU and the microcontroller, maintaining a compact and efficient layout for accurate data collection while submerged [5, 22]. The current consumption of this set up was approximately 95 mA.

3.3 User-Mounted (Wearable) Hardware

Inside the ball, a 135x240 pixel TFT ST7789 display was connected to another Xiao board, creating an integrated system powered by a VUZIX portable battery. This setup enabled real-time visualization of the pitch and roll angles during exercises [12]. This setup was then mounted to headgear designed for welding helmets that had been modified to integrate with the TFT display and its hardware requirements [6]. This setup allowed the user to observe the collected data in a hands free manner from within the ball [7, 13]. The configuration used the following components:

- Microcontroller: Xiao ESP32C3 (similar to the external setup)
- TFT ST7789 Display: Used for visual feedback
- Power Source: VUZIX portable battery
- Head Mount: welding headgear

The TFT display provides immediate visual feedback to the user, aiding in the correction of posture and movements through a ball simulation as seen in Figure 5. The current consumption of this set up was approximately 120 mA. The weight of this wearable including the welding headgear was around 600 grams.

Figure 4: User inside the ball while wearing the HMD (Head Mounted Display).

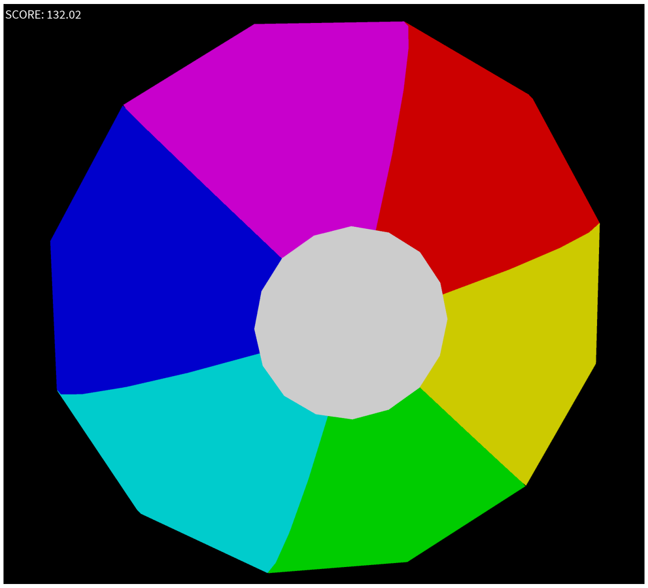

Figure 5: A simulated beach ball, which rotates the same way as the waterball, based on the IMU. Score is presented on the top left corner based on absement (time-integrated roll).

3.4 Additional Ball-Mounted SWIM Display

Under low-light conditions, a fun and exciting kind of display system is possible in addition to, or instead of, the wearable head-mounted display. Clear plastic tubing is used to house a S.W.I.M. (Sequential Wave Imprinting Machine) that is wrapped around the outside of the ball. The clear tubing is sealed in a manner similar to that shown in Fig 3. The SWIM uses wireless communications to receive data from the IMU for game display. Various interactive experiences are designed that display data to the occupant in the ball as well as being visible to others in the surrounding area. This system has the advantage of functioning as a participatory experience that can involve larger groups of people, since the ball by itself has relatively limited reach in terms of large numbers of people. For example, the “SWIMball” of Fig 6 can form part of a performance art event, or other large-scale event visible to thousands of observers as a form of live entertainment.

3.5 Software

Code development was done via Arduino and its native programming language. The Adafruit_GFX, WiFi, and ESP_NOW libraries for the Arduino architecture were also employed for graphics generation [24]. A data processing pipeline was developed in order to translate the acceleration and gyroscopic values captured by the IMU into the relevant pitch and roll values [20].

For sensor fusion, we use the Kalman filter [1], [9] to fuse the 9 degrees of freedom (DoF) data from the accelerometer, gyrometer, and magnetometer.

Kalman Filter Equations and Variables

Prediction Step:

$$\hat{x}_{k|k-1} = F_k \hat{x}_{k-1|k-1} + B_k u_k$$

$$P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k$$

- $\hat{x}_{k|k-1}$: The predicted state estimate at time k based on all information up to time $k-1$.
- F_k: The state transition model applied at step k.
- $\hat{x}_{k-1|k-1}$: The previous state estimate at time $k-1$.
- B_k: The control-input model which is applied to the control vector u_k.
- u_k: The control vector at step k.
- $P_{k|k-1}$: The predicted state covariance matrix
- Q_k: The process noise covariance matrix

Update Step:

$$\begin{aligned} K_k &= P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1} \\ \hat{x}_{k|k} &= \hat{x}_{k|k-1} + K_k (y_k - H_k \hat{x}_{k|k-1}) \\ P_{k|k} &= (I - K_k H_k) P_{k|k-1} \end{aligned}$$

- K_k: The Kalman Gain at step k
- H_k: The observation model that maps the true state space into the observed space.
- R_k: The measurement noise covariance matrix
- y_k: The measurement vector at step k.
- $\hat{x}_{k|k}$: The updated state estimate at time k after incorporating the measurement y_k.
- $P_{k|k}$: The updated state covariance matrix after the measurement at time k.

For magnetic compensation and calibration, we employed the hard and soft iron [23] method as well as [21] to help cancel out the drift in the gyrometer.

3.6 Data Collection

To collect and process the observed data for further analysis, a third ESP32 nodeMCU board was employed. This board facilitated communication between the external and internal setups using the ESP-NOW protocol, a low-power, wireless communication protocol optimized for IoT devices. [19]

Data from both the external IMU and the internal TFT display were transmitted to the third ESP32 board in real time. This board collected all relevant data points, which were then transferred to

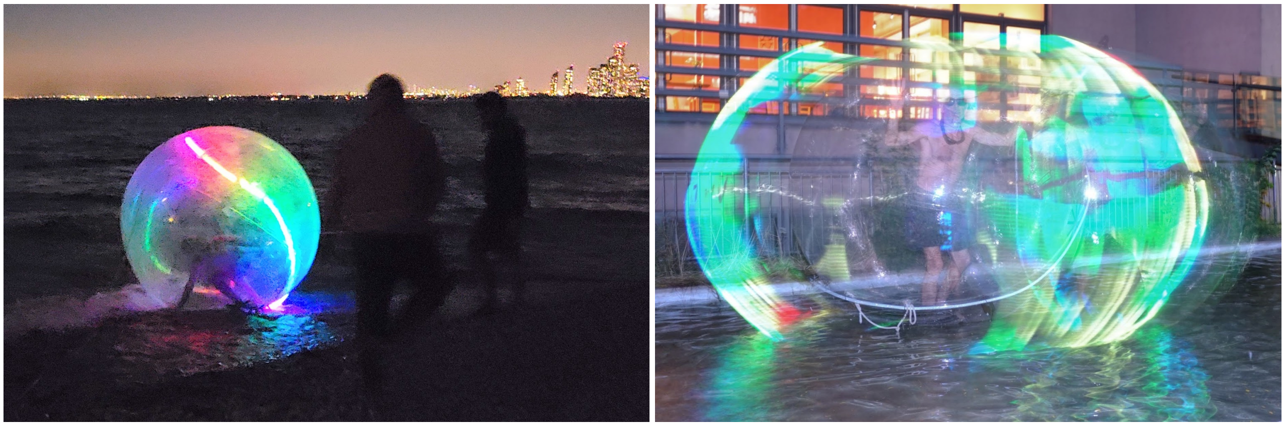

Figure 6: Leftmost: SWIM (Sequential Wave Imprinting Machine) display is mounted in clear tubing attached to the outside of the ball to provide real-time 3-dimensional volumetric game display to the occupant of the ball as well as others observing from outside the ball. Seen at Ontario Place. Rightmost: The same setup seen in action at a fountain within the city.

a computer using the open-source software CoolTerm. CoolTerm enabled efficient serial data collection and logging, ensuring that all exercise data were accurately recorded for subsequent processing and analysis. [28]

The relevant data was then saved as a text file and processed into graphical representations using the Python programming language and its NumPy and Matplotlib libraries.

This comprehensive setup ensured robust data collection and visualization, allowing for precise monitoring and improvement of exercise routines aimed at enhancing spinal and back health.

3.7 Benchmark Comparison

We aim to verify the accuracy of our waterball IMU system with ground truth comparison. Without access to a motion capture system such as VICON, we resort to fiducial marker pose estimation, which is a widely used method for localization and single-camera pose estimation [8]. There are different types of fiducial markers such as ARTag, AprilTag, and ArUco. We select ArUco [17] for its robust and fast detection and easy integration with open-source libraries such as OpenCV. We use an inertial RGB-D sensor (Intel Realsense D455i) to estimate the pose of a 10mm × 10mm ArUco. By fixing the ArUco with the IMU on the ball as shown in Fig 7, we could benchmark the accuracy of our IMU from the single-camera pose estimation of the ArUco given a known frame transform between the marker and the IMU. Fig 7 also shows a simulation of the orientation of the ball which corresponds to the ArUco pose and the IMU orientation.

4 Results

The data collected during the exercises were analyzed and presented in graphical form, in terms of the roll, pitch, and yaw angle measurements over time [16]. Fig 8, Fig 9, Fig 10 illustrate the benchmark comparison between our IMU and the ArUco tag pose estimation. As shown, our wireless IMU tracks the ArUco roll, pitch, yaw angles well with a corresponding RMSE of 5.23, 7.13, and 6.58 degrees. They provide a clear visualization of how the roll, pitch,

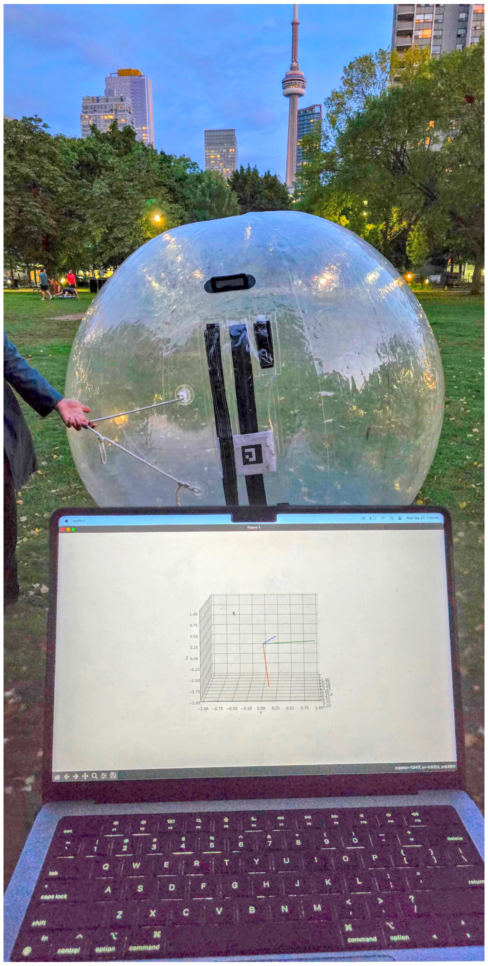

Figure 7: ArUco mount on the waterball for single-camera pose estimation

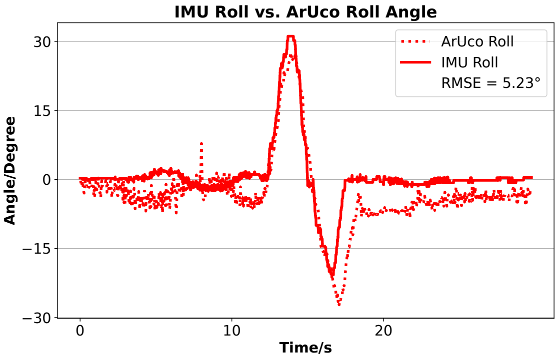

Figure 8: IMU Roll Angle Benchmark Comparison

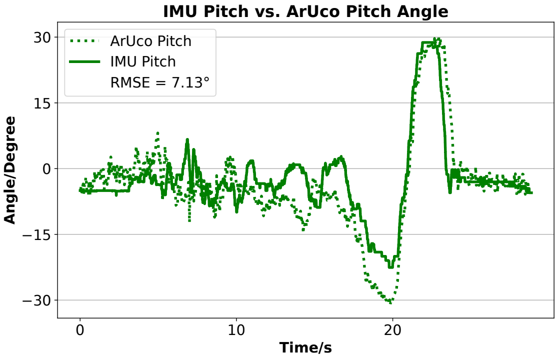

Figure 9: IMU Pitch Angle Benchmark Comparison

and yaw changed during the exercise routines, offering valuable insights into the effectiveness of the movements and the precision of body position measurements. Compared with motion capture systems and visual pose estimation, our wireless IMU system is more robust and flexible for the waterball, regardless of lighting and surrounding conditions. We also show that we do not compromise too much on the accuracy of the motion measurement. More experiments are planned to compare the performance, durability, flexibility, and cost of our system with other commercial solutions.

4.1 Angle Measurements

The angle measurements provided additional detail on the specific positions and movements during the exercises. These measurements were critical in identifying deviations from the optimal posture and enabled a thorough analysis of the exercise techniques employed by the users [14]. The pitch and roll measurements revealed the dynamic changes in body position throughout the exercises. The pitch angle demonstrated how effectively users maintained or adjusted their posture, whereas the roll angle highlighted lateral movements and stability.

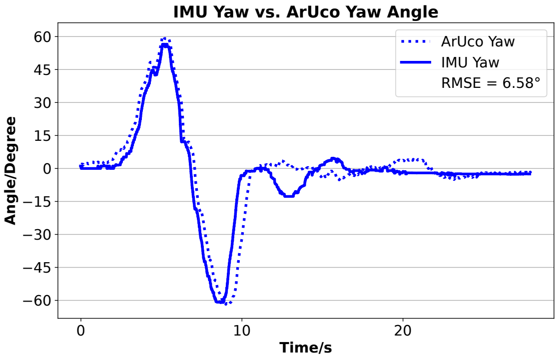

Figure 10: IMU Yaw Angle Benchmark Comparison

Figure 11: Representation of the ball as part of the real-time visualization that would be seen on the head mounted display. For demonstration purposes, it's shown on the laptop to allow both the virtual display and the physical ball to be captured together in a single image.

4.2 Real-Time Visualization

The ball simulator visualization proved to be an effective tool for communicating real-time changes in body position as seen in Figure 11. This immediate feedback was crucial for users, as it allowed them to make on-the-spot adjustments to their posture and movements [11]. The visual representation of pitch and roll angles provided an intuitive and engaging way to monitor and correct body alignment, enhancing the overall exercise experience [26].

Overall, the data presented in the graphs and the real-time visual feedback from the ball simulator visualization underscored the importance of maintaining proper posture and alignment during exercises. This approach not only helped in improving the effectiveness of the exercises but also in preventing common issues such as lower back pain and poor posture.

5 Conclusion

This paper introduces the concept of using an XR waterball for rehabilitation of the spine, where walking in the ball gives real-time feedback through an inertial measurement unit and head-mounted display. The system gamifies the rehabilitation process and encourages users to engage their back muscles to maintain balance. The results are encouraging in the sense that the waterball can provide a unique environment for rehabilitation. This low-impact physical activity and the real-time data allows users to improve their back strength. The head mounted display enhances the user experience allowing for the walk in the waterball to be engaging with real-time feedback. Future work on this project will focus on (1) improving the IMU processing algorithm to add filters which will allow for higher accuracy and reliability to dramatic increase in the pitch and roll measurements; (2) improving the graphics from a ball simulator to more of a game such as Dune allowing for a more immersive experience that connects individuals to their environment; (3) comparing our system with commercially available technologies such as Vicon and other motion capture systems, and further validation of the performance, flexibility, and cost-benefit of our system.

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