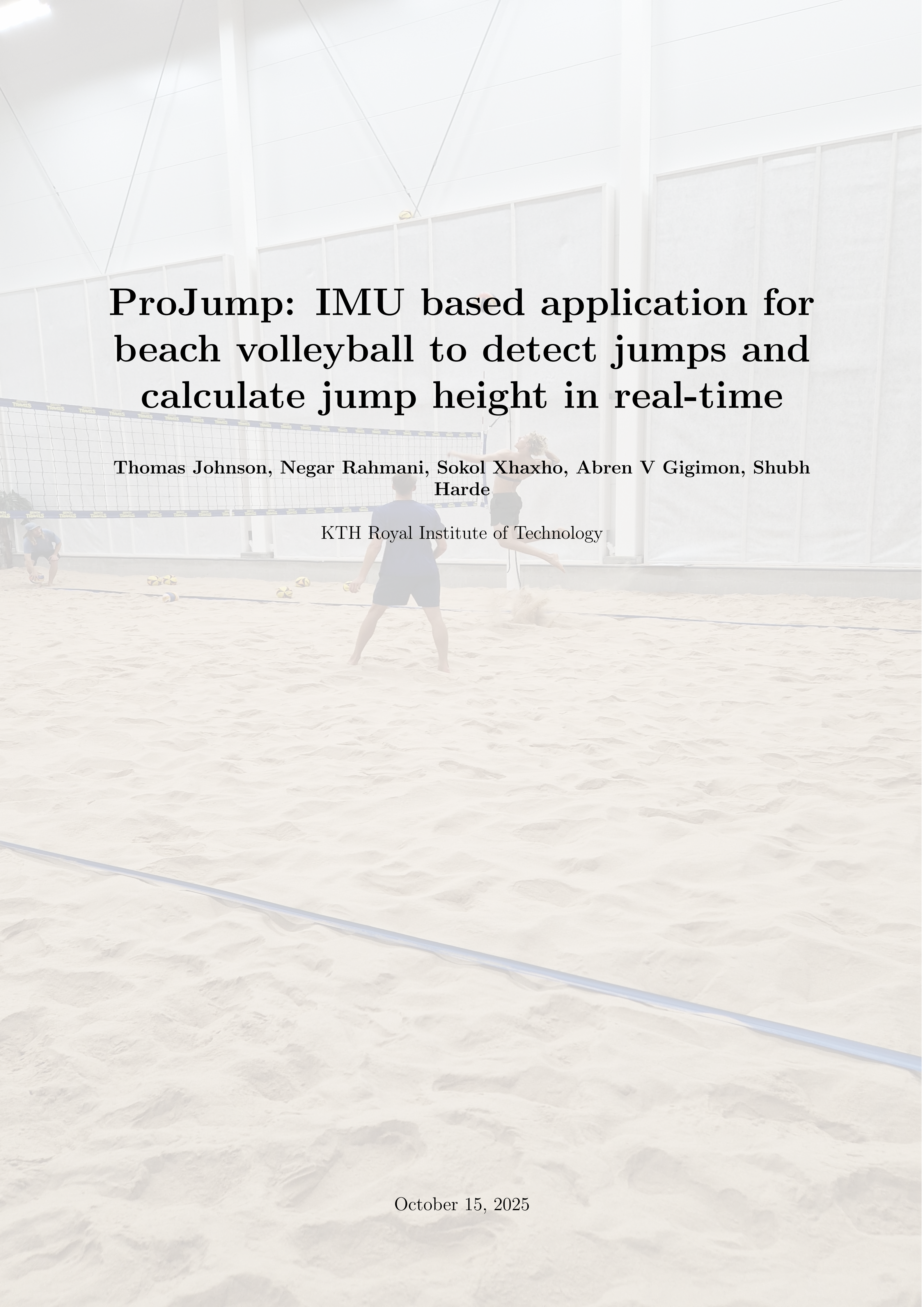

ProJump: IMU based application for beach volleyball to detect jumps and calculate jump height in real-time

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Abstract

Jump height is a key indicator of lower-limb explosive power and is frequently used in volleyball training and performance monitoring. Conventional measurement tools such as force plates or motion capture systems are often expensive, bulky, and not practical in the field. In this work, we develop and evaluate an algorithm that uses data from an inertial measurement unit (IMU), to detect jumps and calculate jump height for beach volleyball players. Our approach is inspired by recent studies showing strong validity and reliability of IMU-based vertical jump height estimation using flight-time methods [1], [2]. We collected data while performing counter movement jumps and detecting in-game using jump features including reduced acceleration during flight time, take-off and landing velocity and acceleration. The core computational approach utilizes the flight time method, supported by a robust signal processing pipeline, including Madgwick filtering to align data to the global vertical axis and a refined detection algorithm based on a 0.5g threshold and velocity peak logic.

The system's performance was validated against video capture methods and a custom force plate (ground truth), where accuracy and reliability were quantified using correlation and ICC. Results showed strong accuracy and reliability: a high Pearson correlation ($r \approx 0.92$) with a low mean error (±4.5cm), and perfect jump detection Recall/Precision (1.000) for chest placement.

The open-source ProJump system successfully addresses the need for a non-laboratory solution, demonstrating that IMU-based estimates can provide real-time, high-fidelity data suitable for practical use in performance monitoring and training analysis.

1. Introduction

1.0.1 Motivation

Vertical jump height is commonly used to assess explosive leg power and neuromuscular performance in athletes. In volleyball, specifically beach volleyball, rapid and repeated jumps are central to both offensive and defensive play, and small improvements or deficits can impact performance. Traditional gold standard methods for measuring jump height (such as force plates or motion capture systems [3]) are accurate but expensive and importantly require controlled laboratory settings. Especially in the case of beach volleyball, it is very difficult to recreate the in-game conditions in the lab, so in-field measurements are much preferred. One way to do so is with the use of inertial measurement units (IMU), which provide linear acceleration and rotation data from an accelerometer and gyroscope respectively. This can be a great way to collect in-game data but IMU are often problematic in that the data is very noisy and require significant post-processing in order counteract common issues such as integration drift.

1.1. Other Solutions and Prior Work

Some authors have attempted to recreate beach volleyball conditions in a laboratory using a force plate [4]. This is limited to stationary jumps and not representative of in-game play. Another potential technology that can be used to estimate jump height is pose estimation, whereby a combination of machine learning models and computer vision can identify joint centres although estimations can be inconsistent [2], depending on the quality of the video capture for example joint occlusions caused by oblique camera angles.

1.2. Gap and Objectives

IMU's offer a low-cost alternative to measure movement dynamics in-field, however, most systems remain non-integrated or lack real-time feedback. Our project aims to address these gaps by collecting IMU data (and optionally force plate data) from beach volleyball players performing multiple jump types, evaluating different computational methods and sensor placements, and developing an algorithm to detect jumps and estimate jump height. Timing is very important when it comes to performance; in volleyball meeting the ball at the top of your jump can help optimise the outcome of the shot [4]. Other future use cases may include injury prevention, as lower-limb injuries in athletes who participate in jump sports, such as volleyball [5], are frequent and associated with poor landing technique, such as asymmetric ground contact or ankle instability.

In this project accuracy will be assessed (bias, mean error) and we will attempt to validate our system with a custom force plates and other comparable methods like video capture in a live game situation. We will make attempts to assess reliability (ICC, test-retest), and trade-offs (cost, ease of deployment) in field settings.

The contributions of this paper are: (1) an algorithm to estimate jump height based on flight time; and (2) initial validation using force plate synchronisation. (3) An application for web and mobile devices. The code and design are open-source via GitHub.

2. System Design

The system consists of an Berg IMU sensor which combines a 9-axis motion sensor (accelerometer + gyrometer + magnetometer) on nRF52832 SoC's Arm® Cortex® M4 processor with a floating point (FP) unit. Additional technical specifications include Bluetooth connectivity, a USB-C charging cable, and a frequency band of 2.400 to 2.4835 GHz, and a maximum output power of 0 dBm. The micro-controller firmware reads the sensor, registers over *I²C/SPI* and converts them to meaningful values (g, °/s) and prints them in readable format via `"Serial.print"`. So, the IMU firmware prepares and sends out these strings ready for logging.

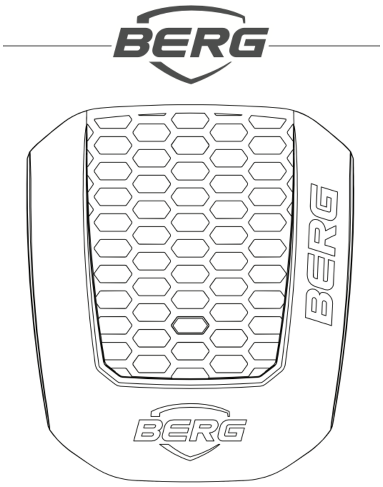

Figure 1: Berg IMU

Figure 2: Example of IMU placement. In this project we have used the chest sensor placement at the base of the sternum

The rough steps taken in this project are chronologically outlined in the figure below. An important first step was performing exploratory data analysis and an accompanying literature review, which continued throughout the project. Signal processing was another area that required a lot of attention for instance logging, filtering, smoothing and plotting. Jump detection and jump height measurement both relied on adequate prior signal processing in order to build a robust algorithm for the application.

Exploratory data analysis was performed on existing in-game volleyball datasets to inform and help build a valid pipeline that detects jumps and measures jump height in real-time. Signal processing and multiple filtering steps enabled us to identify the peaks in acceleration and velocity that corresponded to takeoff and landing. One end goal of the project is to be able to build a machine learning model that is based on our jump detection model which will require more data than we currently have available.

Based on the data analysis, chest placement was deemed the most reliable for predicting jump instances and height measurement. There is also future scope to combine sensors in order to classify different actions in-game, such as serving, blocking, smashing and more whereby the wrist sensor can be synchronised with the chest.

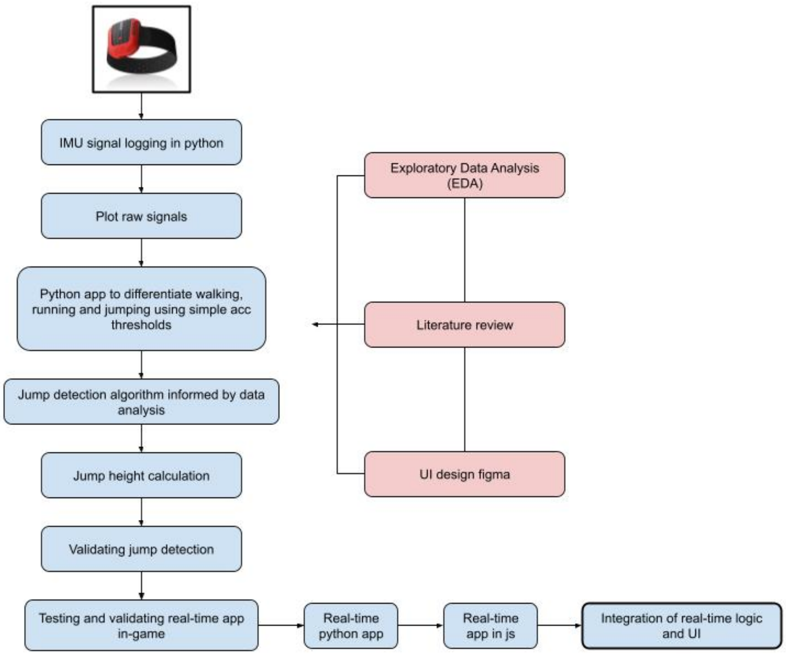

Figure 3: Chronological steps in the project towards the end goal of an application that runs and works in real-time to detect and measure jumps in game situations

A web application and user interface (UI) for mobile applications will be built to incorporate these features and make it easier for players and coaches to visualise, digest and use this information in their training and matches. We see the opportunity for expansion beyond Beach Volleyball into a wide range of sports where an importance is placed upon jumping such as Basketball, Gymnastics and Australian Rules Football and many more. There is also some potential to use the application for injury prevention purposes, classifying specific landing mechanics as "risky" for example, albeit more data is required for this.

3. Evaluation

3.1. Solution

Connecting to the BLE sensor, a signal is received from the IMU to a custom port where arrays of 24-bit timestamps, accelerometer (x, y, z), gyroscope (x, y, z) and magnetic field (x, y, z) data in 16-bit counts which are converted into numbers and sent to a CSV file. The effective accelerometer sampling rate is 202 Hz. A Madgwick filter is then applied to the raw data accelerometer (in g) and gyrometer (deg/s) data to estimate orientation via a quaternion and rotate the data into the global frame followed by further band pass filtering [6].

Each jump produces a recognisable signal whereby at takeoff we see a large acceleration followed by a linear reduction in velocity and acceleration after takeoff as the resultant gravitational acceleration acting on the person "in-flight" causes a linear velocity decrease. The takeoff instance occurs a few milliseconds after the peak velocity because of a slowing down as the toes engage with the surface at the end of this "push-off" phase. The change in direction of velocity and return to 1g of acceleration can be seen to coincide with landing [7].

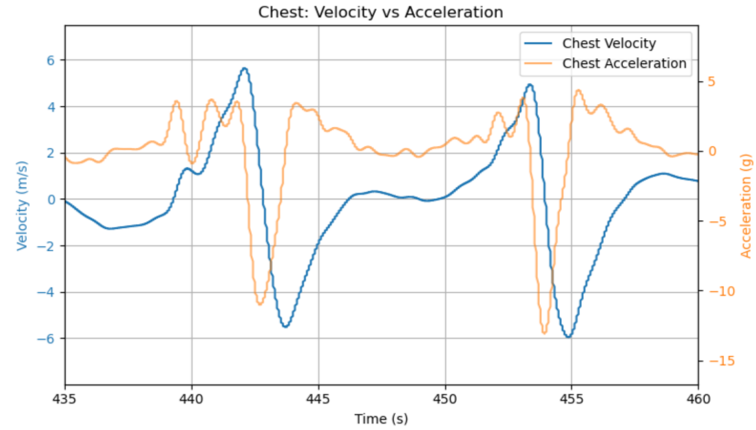

Figure 4: Typical acceleration and velocity plots in a beach volleyball jump

As shown in the figures below, the vertical acceleration (AccZ) - which can now be thought of as truly "up" in the global frame after madgwick filtering - is then integrated, and the velocity is used in (1) A jump detection algorithm which continuously loops during measurement and (2) Measurement of jump height using the flight-time method.

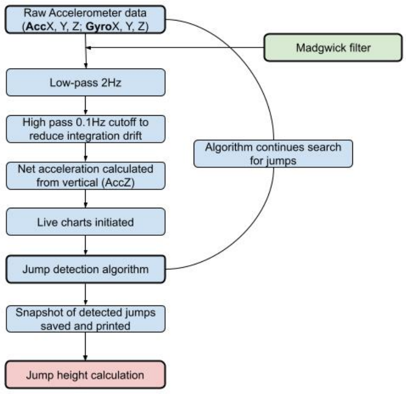

Figure 5: Signal processing steps for jump detection and jump height calculation in real-time

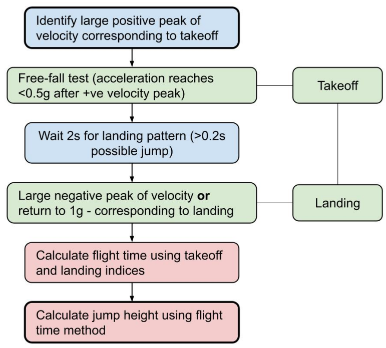

Figure 6: Steps involved in jump height calculation

In the jump detection algorithm specifically, flight time for jumping instances is defined as the time between detected take-off and landing events where vertical acceleration drops below a threshold 0.5g and vertical velocity reduces at a constant rate of gravitational acceleration (-9.81m/s^2). Using flight time jump height is estimated using the following formula:

$$h = \frac{g \cdot t_{\text{flight}}^2}{8}$$

After various iterations, a working prototype of the application was validated against competitor applications that use video and frame rate to calculate flight time and jump height. The next step is to validate the system against force plate measurements and in real-time during beach volleyball training and game situations.

3.2. Results

The system classified activities as still, walking, running using the amplitude threshold, and for jumps it estimated height and keep track of number of jumps and maximum jump height per individual which can be visualized via the app.

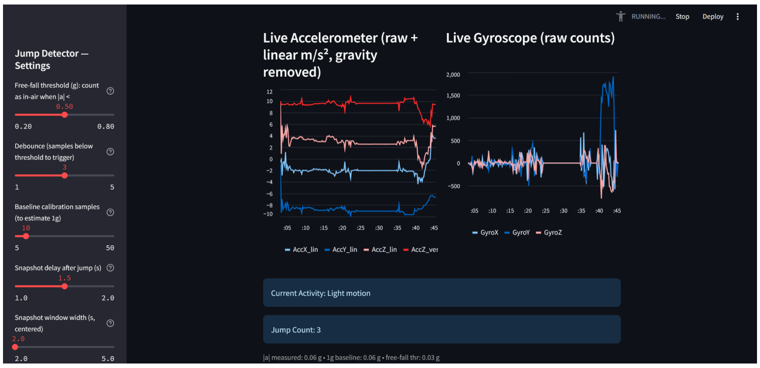

Figure 7: App interface with live acceleration and gyroscope chart

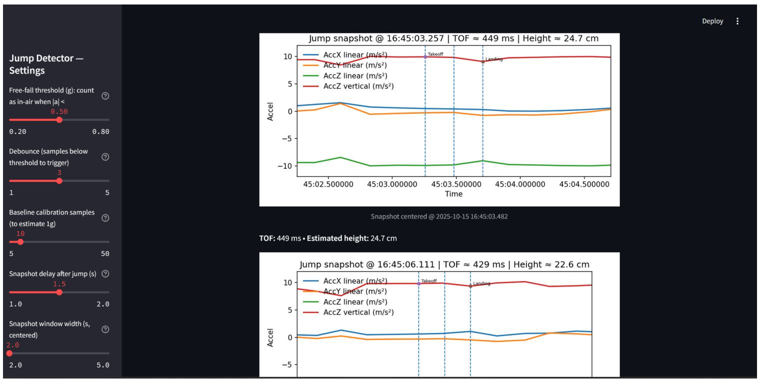

Figure 8: Jump snapshots with take-off and landing markers and jump height

Jump height calculation was also compared with similar applications that use video capture and frame rate to infer flight time and thereby estimate jump height. Jump height estimated using the IMU showed strong correlation with force plate data with Pearson correlation $r \approx 0.92$ and a mean error of ± 4.5 cm.

Table 1: Reliability between measuring systems—force plates (the gold standard), IMU, and video capture

Jumps	IMU	Video capture
1	33.9 ± 3.3cm	30.5 ± 4.3cm
2	38.2 ± 2.5cm	31.6 ± 5.1cm
3	14.9 ± 2.1cm	27.6 ± 5.3cm
4	22.9 ± 2.6cm	28.6 ± 3.6cm
5	23.9 ± 3.1cm	27.6 ± 3.8cm
6	63.9 ± 2.1cm	58.6 ± 2.5cm
7	73.9 ± 4.2cm	77.6 ± 3.7cm
8	64.9 ± 2.2cm	66.8 ± 4.6cm
9	36.9 ± 3.1cm	40.6 ± 3.6cm
10	22.2 ± 2.7cm	18.1 ± 3.8cm
11	56.6 ± 2.8cm	56.2 ± 3.2cm
12	37.9 ± 4.7cm	37.6 ± 5.6cm

4. Conclusions

This work demonstrates that an IMU-based system can accurately and reliably measure jump performance in beach volleyball under real game conditions. By combining orientation estimation through Madgwick filtering, refined signal processing, and a flight-time-based height estimator the ProJump pipeline achieves robust jump detection and precise height estimation (Pearson $r \approx 0.92$) with minimal error. The 0.5 g threshold and velocity-peak logic ensure consistent detection even in noisy, outdoor environments like sand courts. Jump height calculation was also compared with similar applications that use video capture, these methods have been shown to perform well against valid methods like a force-plate measurement [8, 9].

Beyond accuracy, ProJump's is practical and easy-to-use for coaches and players. A single chest-mounted sensor provides reliable data, while the lightweight IMU and instinctive processing pipeline enables real-time visual feedback via mobile or web applications. The system's ability to track jump count, height, and timing offers coaches and athletes immediate insights into optimising performance, training load, and progression over time.

While further data collection is needed to improve personalization and robustness across athletes and environments, the system already establishes a strong foundation for future development. Expanding toward multi-sensor setups could enable detection and classification of different jump types, landing quality, and potential injury-risk indicators. With more data it will be possible to build machine learning models to automatically identify different actions.

In summary, ProJump bridges the gap between complex lab systems and real-world sports technology—delivering accurate, real-time, and accessible jump metrics for athletes and coaches. Its open-source nature promotes further innovation and adaptation across sports where explosive jumping performance is key.

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Appendix

GitHub Repository: `https://github.com/tdjohnson1987/ProJump`

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