Vault One Mark I: Internal Validation Study of Uncalibrated Force-Sensing Mat for Vertical Jump Assessment

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Abstract

Vault One Mark I is a portable, high-resolution mat designed to capture pressure-based ground reaction force data during athletic movements. Unlike traditional force plates, Vault One reports uncalibrated, relative force signals from an array of 40 discrete capacitive sensors. This study evaluates whether Vault One can deliver force plate-comparable insights, particularly for estimating vertical jump height.

We validate Vault One against a laboratory-grade force plate, deriving vertical jump height from impulse-momentum-based calculations. Our results show that despite lacking absolute force calibration, Vault One achieves a strong linear correlation with force plate measurements ($R^2 = 0.9899$), with minimal trial-to-trial variability. A linear correction factor can further align Vault One outputs with force plate results, enabling accurate, relative tracking of athletic performance.

Additionally, we highlight Vault One's unique capability to generate high-dimensional spatiotemporal force maps, enabling richer biomechanical insights than traditional force plates. These results suggest that Vault One offers a scalable, field-deployable alternative to force plates for jump assessment—and forms the foundation for future AI-driven applications in injury prediction, training optimization, and rehabilitation.

1 Introduction

Vault One Mark I is the first generation of an intelligent force measurement mat designed to capture high-resolution pressure data during athletic movements. Unlike commercial force plates, Vault One Mark I does not return calibrated force values. Instead, it outputs relative force measurements—capturing changes in pressure distribution without a direct physical force mapping.

This limitation prevents the calculation of absolute force-based metrics such as peak force (in newtons) or rate of force development (RFD) in standard units. However, many biomechanical indicators can still be derived from relative signal profiles using indirect or physics-informed models. The central question of this study is: can Vault One Mark I produce force plate-equivalent insights into vertical jump performance, despite lacking absolute force calibration?

To answer this, we compare Vault One's output against a laboratory-grade force plate using impulse-momentum and flight-time methods for estimating jump height. We also evaluate the accuracy of key timing metrics (e.g., takeoff and landing) and assess whether relative force signatures are sufficient for performance tracking and diagnostic use.

This validation effort is part of Vault Kinetics' broader mission to make comprehensive ground reaction force (GRF) data collection accessible to everyone. We believe the rich information embedded in GRFs can help explain a wide range of human performance and movement patterns. Vault One Mark I is the first in a series of evolving systems. Future versions will support larger sensing areas, higher spatial resolution, and full force calibration—while remaining optimized for consumer hardware through GPU-accelerated real-time processing.

Our vision is to democratize elite biomechanics and enable deep, high-fidelity movement analysis anywhere – on the field, in the gym, or during live competition. We invite researchers, clinicians, and performance specialists to join this effort as we open-source our research methods and algorithms. We see especially promising use cases: injury prediction, high-risk movement detection, training optimization, and rehabilitation support.

1.1 Vault Raw Data for Machine Learning

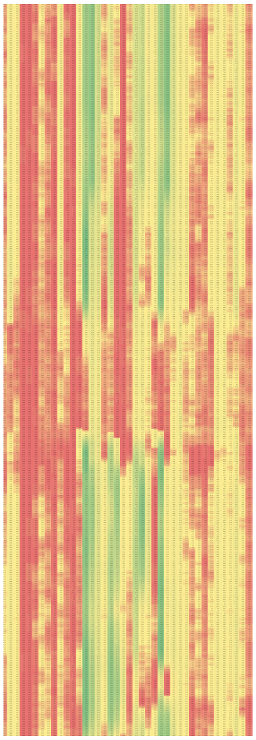
When large datasets capturing human movement across many individuals and timepoints are collected, subtle patterns begin to emerge. We believe high-quality performance data, combined with modern AI methods, can reveal critical insights such as the moments leading up to injury or the factors underlying elite performance.

In this framework, injury prediction and performance optimization can be viewed as machine learning problems—where the quality and dimensionality of input data are paramount.

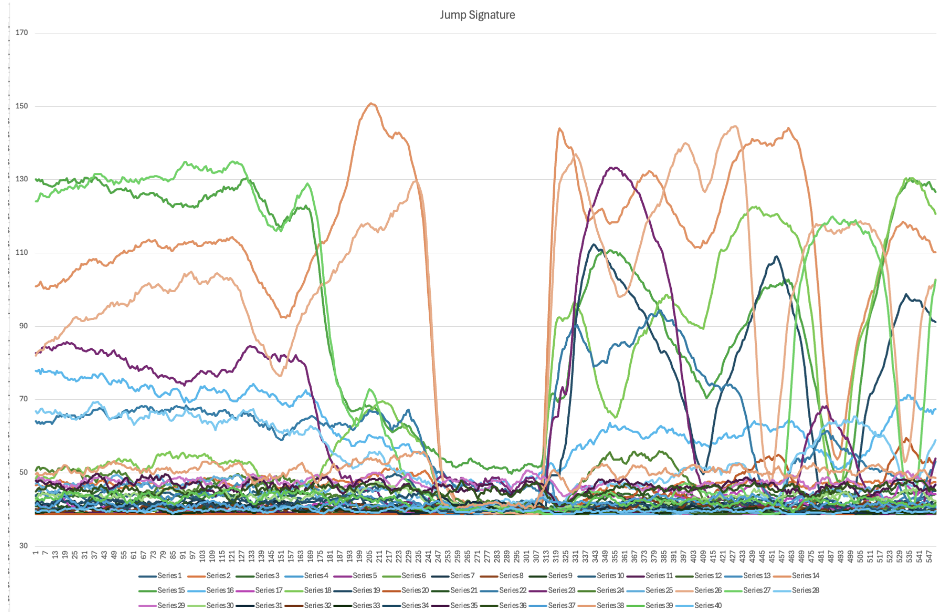
Traditional vertical jump assessment tools, such as contact mats, rely on binary signals: contact is either true or false. These systems reduce the complex biomechanical jump movement to a pair of timestamps (e.g., takeoff and landing), which, in the language of embeddings, can be encoded as a 1×2 vector. Force plates improve upon this by capturing continuous force values over time. $1 \times t$ vectors can be constructed for trainig problems, where t is the number of timepoints during the jump.

Vault One advances this by outputting an nt matrix per jump, where n is the number of spatially distributed sensors and t is the time horizon. This high-dimensional structure significantly increases the raw, linearly independent information per trial—providing a deep foundation for training machine learning models.

Both internal and academic research show that pressure-based locomotion data exhibits high dimensionality and preserves meaningful variance across individuals. From a mechanical perspective, the feet are the sole point of contact with the ground during most athletic movements. Thus, every motion throughout the kinetic chain must ultimately be resolved as a force pattern beneath the feet. In theory, detailed GRF data encodes the entire biomechanical story of a movement. Notably, prior work—such as the IntelliCarpet project at MIT CSAIL—has demonstrated the feasibility of reconstructing full-body posture above the ground using only pressure data captured from below (https://intcarpet.csail.mit.edu/).



(a)



(b)

Figure 1: Two complementary visualizations of Vault One's vertical jump data. (a) Heatmap view of force distribution during a vertical jump. (b) Ribbon plot showing vertical force signature over time.

2 Validation Method

To validate our novel mat system for measuring vertical jump height, we required precise reference data from a laboratory-grade force plate. A Vernier Scientific force plate provided calibrated vertical force measurements with an accuracy of ± 1 N at 1000 Hz. To estimate jump height via the impulse-momentum method, we developed a custom algorithm that extracted jump signatures and integrated net force from movement onset to takeoff. Unlike standard commercial methods, which use fixed thresholds to identify movement events, our approach detects onset using the derivative of force (rate of change) and shifts the detection point 0.2 seconds earlier to capture the full preparatory phase.

100 Jumps performed by members of the Vault team (athletes) were collected. To obtain the most accurate impulse-momentum estimates, we avoided estimating body mass from noisy or unstable resting periods—which are often affected by slight pre-jump movements. Instead, we directly measured each subject's body weight before testing and used this value to normalize the force data.

Each jump was characterized using a 3-second signature window centered on the midpoint between takeoff and landing. We validated each jump by confirming that the entire push-off phase occurred within this window, ensuring complete capture of the preparatory and propulsion phases.

Jump height was then calculated using the impulse-momentum method, which considers the actual force generated during the push-off phase:

$$v = \frac{I}{m}, \quad h = \frac{v^2}{2g}$$

where I is net impulse and m is the subject's mass.

This approach yields the most accurate reference measurements for validating our mat system by accounting for the complete force-time profile of each jump—including preparation, push-off, flight, and landing—while also filtering out invalid or unrealistic trials automatically.

A similar jump extraction algorithm was applied to the Vault One sensor data. To accurately detect takeoff and landing events, the signals from all 40 capacitive sensors were pooled into a composite force trace. Event detection was performed using dual thresholding—applying separate high and low cutoffs to reduce noise sensitivity and minimize hysteresis effects.

Each node on the Vault mat reports an averaged value from four internal readings per scan. The entire 40-sensor array is sampled at a rate of 120 frames per second, resulting in:

$$120 \text{ frames/sec} \times 40 \text{ sensors/frame} \times 4 \text{ readings/sensor} = 19{,}200 \text{ sensor readings per second.}$$

The four readings per sensor are acquired within a 2 ms window to minimize measurement noise while preserving temporal resolution for accurate detection of critical jump events.

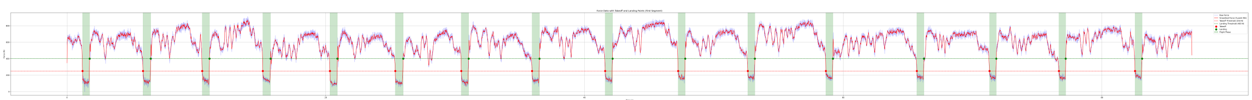


Figure 2: Jump signatures extracted from pooled Vault One sensor data across all trials.

3 Results

We evaluated the accuracy of Vault One Mark I by comparing its vertical jump height estimates to those obtained from a laboratory-grade force plate sampling at 1000 Hz. Each jump trial was analyzed using both a flight-time-based method and an impulse-momentum-based method. The results demonstrate strong agreement between the two systems, with a consistent linear relationship and high repeatability across 100 trials.

3.1 Raw Vault One Output vs. Force Plate Measurements

Figure 3 displays a scatter plot of raw Vault One vertical jump height estimates against corresponding force plate measurements. Each point represents an individual jump trial. Vault One's estimates were derived from uncalibrated force data and processed using flight-time detection from contact transitions.

A simple linear regression model was fit to the uncorrected data:

$$\text{Force Plate Height (in)} = 0.8939 \times \text{Vault Height (in)}$$

The regression yielded an R^2 value of 0.9899, indicating that nearly 99% of the variance in the force plate measurements can be explained by the Vault One estimates. This demonstrates that Vault One produces consistent, tightly clustered jump height readings. However, the slope of less than 1.0 suggests a **systematic underestimation** of jump height by Vault One relative to the force plate.

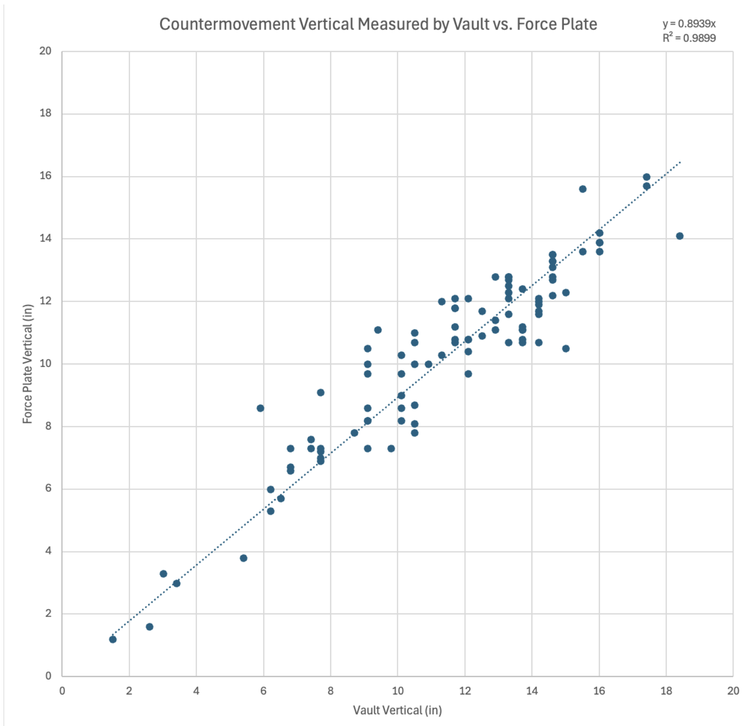


Figure 3: Scatter plot comparing uncorrected Vault One jump height estimates to force plate measurements. The dotted line shows the best-fit regression with $R^2 = 0.9899$.

3.2 Indice Transformation

To account for the observed bias, a linear correction was applied to Vault One's outputs by scaling each jump height estimate by the inverse of the regression slope:

$$\text{Corrected Vault Height} = \frac{\text{Vault Height}}{0.8939}$$

This transformation aligns the scale of Vault One's data with that of the force plate, enabling direct comparison. Figure 4 shows the results of this correction. The corrected data closely follows the identity line ($y = x$), confirming that the transformation eliminated the scale bias.

A post-correction regression yielded a slope of 1.0 with the same $R^2 = 0.9899$, demonstrating that the transformation preserved the strength of the original correlation while achieving near-perfect alignment with the force plate values.

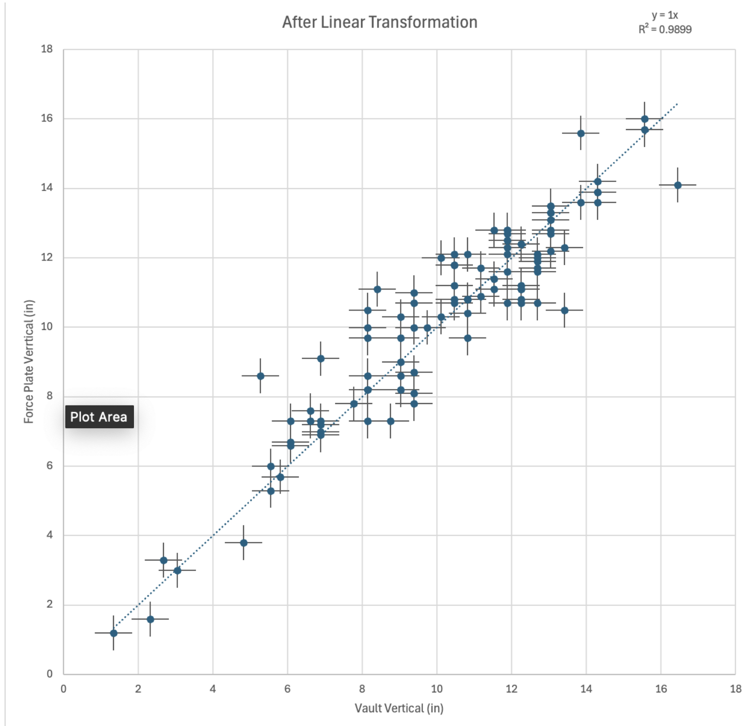


Figure 4: Corrected Vault One jump height estimates plotted against force plate measurements. Post-correction, the data aligns with the identity line ($y = x$), with an $R^2 = 0.9899$.

3.3 Measurement Repeatability and Practical Utility

Vault One exhibited minimal scatter across repeated trials and a high degree of consistency in detecting key timing events such as takeoff and landing. The system's high resolution and stable signal make it capable of tracking relative changes in jump height with excellent fidelity. This supports its use in training environments, especially when tracking intra-athlete trends over time or conducting comparisons within a consistent measurement framework.

Furthermore, for users interested in benchmarking Vault jump statistics against gold-standard systems such as Vertec or force plates, simple linear correction factors (such as the one derived in this study) can be applied to align results. The robustness of Vault One's output after transformation underscores its potential as a practical and portable alternative to force plates in field settings.

4 Calibration

While Vault One currently reports uncalibrated, relative force measurements, future iterations aim to produce calibrated outputs comparable to laboratory-grade force plates. To assess this potential, we conducted a preliminary calibration study using a single capacitive sensor node from the Vault One array.

The sensor was subjected to incremental loading while simultaneously recording ground-truth vertical force from a calibrated force plate. As shown in Figure 5, the raw capacitive output tracks the general trajectory of the force plate data, particularly in the low to mid-force ranges. At higher loads, the sensor signal exhibits a plateauing effect, likely due to physical saturation in the capacitive material—suggesting the need for further dielectric tuning or hardware optimization.

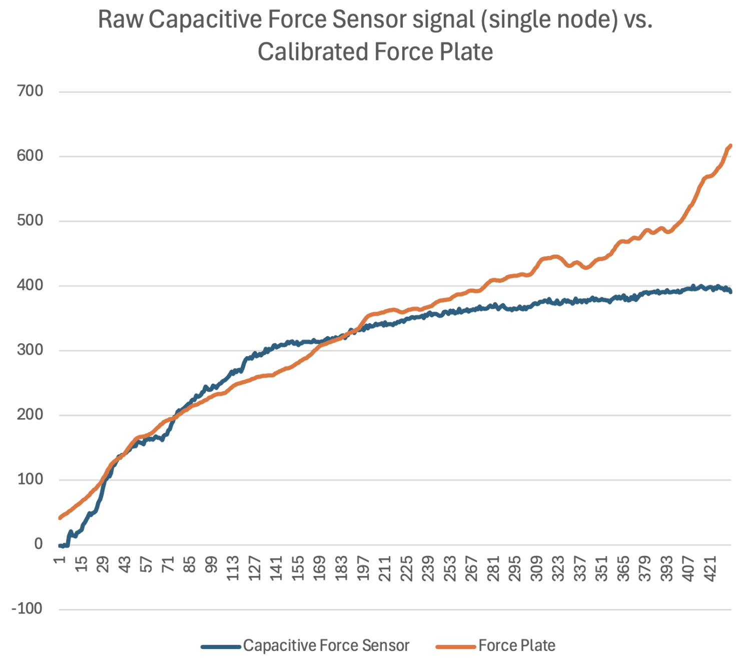


Figure 5: Comparison of raw capacitive sensor output and ground-truth force plate data over time. The signals follow similar trends with divergence at higher forces due to sensor saturation.

To evaluate the possibility of mapping the raw signal to physical force, a nonlinear regression was applied. As shown in Figure 6, the resulting calibration curve reveals a clear relationship between raw sensor output and applied force. This indicates that while the signal is inherently nonlinear, it can be systematically transformed into meaningful physical units.

To explore the relationship between raw output and true force, we applied a nonlinear curve fit of the form:

$$f(x) = a - \frac{c}{x - h} + sx$$

where $a = 30$, $c = 3700$, $h = 420$, and $s = 0.8$. This model captures the nonlinear rise in sensor output and the asymptotic behavior observed near sensor saturation. As shown in Figure 6, the resulting curve provides a smooth, monotonic mapping from raw sensor values to estimated force, supporting the feasibility of applying individualized calibration functions to each node.

These findings demonstrate that even with a non-linear response, raw capacitive signals can be systematically transformed into meaningful physical units. With refined sensor design and per-node calibration curves, Vault One could extend its utility beyond relative force to calibrated force measurement. This would enable more advanced biomechanical metrics—such as peak force or rate of force development (RFD)—broadening Vault One's applications in both elite athletic performance and clinical rehabilitation.

These findings support the feasibility of per-node calibration in future versions of Vault One. With refined sensor design and individualized calibration curves, the platform could transition from binary contact detection to continuous force estimation. This would enable more advanced biomechanical metrics—such as impulse, peak force, and rate of force development (RFD)—broadening Vault One's utility across both elite sports performance and clinical rehabilitation domains.

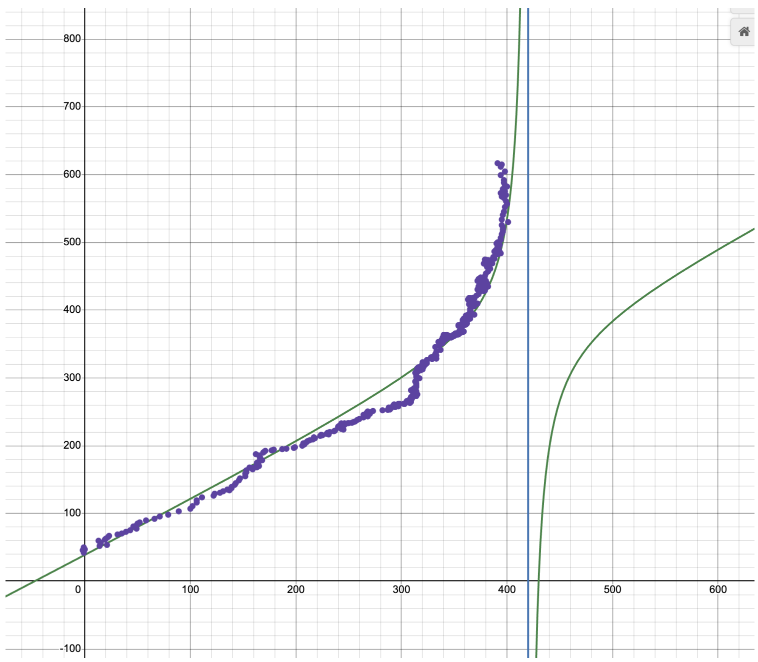


Figure 6: Nonlinear curve fit between raw sensor output and calibrated force plate readings. The exponential relationship supports the viability of per-node calibration.

5 Conclusion

Vault One Mark I offers a novel approach to capturing vertical jump data through high-resolution, uncalibrated pressure measurements. Despite its current limitations, the system demonstrates force plate-level accuracy in estimating jump height and provides a scalable platform for future sensor-based biomechanics research. With continued development, Vault aims transform how athletic performance, movement quality, and injury risk are measured in real-world environments.

6 Appendix: Detailed Data Extraction and Processing Methodology

The force plate data was processed using a multi-step algorithm to identify and analyze vertical jumps. Each stage of the algorithm is described below.

1. **Initial Data Processing**

   Raw force plate data was collected at 1000 Hz and processed using Python (NumPy, Pandas). Force values were normalized by subtracting the subject's body weight (770 N), isolating the net force. To reduce high-frequency noise while preserving force-time patterns, a 10-point moving average was applied.

2. **Movement Detection**

   Movement onset was determined using a derivative-based method:

   - The rate of change of force was computed using the forward difference method:

   $$\frac{dF}{dt} = \frac{F_{t+1} - F_t}{\Delta t}$$

   - This derivative was smoothed using the same 10-point moving average.
   - A threshold of ± 400 N/s was defined to distinguish dynamic from stable phases.
   - Regions where $|dF/dt|$ remained below threshold for at least 0.5 seconds were marked as stable.
   - The transition from stability to instability marked movement onset.
   - To ensure initial force changes were captured, movement start time was shifted back by 0.2 seconds.

3. **Jump Signature Definition**

   Each jump was defined by a 3-second signature window:

   - The center of the window was the midpoint between takeoff and landing.
   - The window extended 1.5 seconds before and after this center point.
   - This captured the full jump cycle: preparation, push-off, flight, and landing.

4. **Flight Phase Detection**

   Takeoff and landing were detected using force thresholds:

   - Takeoff was when force dropped below 50 N.
   - Landing was when force rose above 50 N.
   - Flight time t was used to calculate jump height:

   $$h = \frac{1}{8}gt^2$$

- Jumps with $h > 60$ inches were excluded as unrealistic.

5. **Push-off Phase Analysis**

   The push-off phase—from movement onset to takeoff—was analyzed using impulse-momentum:

   - Impulse:
   $$I = \int_{t_{\text{start}}}^{t_{\text{takeoff}}} F(t)\, dt$$
   Calculated via numerical integration with 0.001 s resolution.
   - Takeoff velocity:
   $$v = \frac{I}{m}$$
   - Jump height:
   $$h = \frac{v^2}{2g}$$

6. **Validation and Quality Control**

   Several constraints ensured data quality:

   - Push-off phase had to be fully contained within the 3-second window.
   - Temporal alignment of movement start, takeoff, and landing was verified.
   - Takeoff landing pairs that indicated stepping on or off the plate, rather than a jump, were discarded.

7. **Peak Force Analysis**

   For each jump:

   - **Pre-takeoff peak force:** Max force during push-off.
   - **Post-landing peak force:** Max force during landing.
   - Both normalized by body weight for comparison.

8. **Data Output and Visualization**

   Data visualization used a dual-plot format:

   - **Top plot:** Force-time curve with annotations.
   - **Bottom plot:** Force rate of change with stable regions highlighted.
   - For each valid jump, the following metrics were displayed:
     - Impulse (N·s)
     - Takeoff velocity (m/s)
     - Jump height (in)
     - Phase timing breakdown

This comprehensive extraction pipeline integrates robust validation and multiple analysis techniques to ensure accurate measurement of vertical jump performance.