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Ahmed Abdulameer Abdulradha Shubbar

ahmed.shubbar@qu.edu.iq

University of Al-Qadisiyah

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Ahmed Abdulameer Abdulradha Shubbar

College of Physical Education and Sport Sciences, University of Al-Qadisiyah, Al-Diwaniyah, Iraq

Corresponding author: Ahmed Abdulameer Shubbar

Email: ahmed.shubbar@qu.edu.iq

ORCID: <https://orcid.org/0000-0002-1868-2957>

Abstract

Peak summaries can obscure the temporal organization of plantar loading during the volleyball spike jump. This study examined whether phase-anchored Gaussian decomposition could characterize bilateral in-shoe plantar-loading waveforms during the final plant and whether derived loading features were associated with performance and kinematic outcomes. Twenty male players, comprising five eligible players from each of the four clubs that qualified for the final stage of the Iraqi Elite Volleyball League, completed three standardized spike-jump trials. For each participant, the DYNAFOOT® software averaged the three valid trial recordings into a single participant-level waveform, from which the final-plant interval was extracted before model fitting. Baseline-offset single- and double-Gaussian models were compared using corrected Akaike information criterion. Nineteen participants (95%) were better represented by a double-Gaussian model and one by a single-Gaussian model. Median model fit was $R^2 = 0.966$ [0.954–0.986], with a median RMSE of 7.56 [5.60–8.47] kgf. Bilateral peak plantar load averaged 1.76 ± 0.51 body weights, and mass-normalized load impulse averaged 2.53 ± 0.79 N·s·kg⁻¹. Fifteen double-component fits met all identifiability criteria. Exploratory association testing identified no relationship between the loading or Gaussian-derived features and the kinematic or performance outcomes that remained significant after false-discovery-rate correction (all $q \geq 0.192$). Results were unchanged in the post hoc influence analysis excluding P04, in which no association met the multiplicity-adjusted significance threshold. Phase anchoring provided a compact representation of how final-plant loading was organized over time, while observed performance associations remained exploratory.

Keywords: volleyball; instrumented insoles; plantar loading; wearable sensing; Gaussian decomposition; waveform modeling

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1. Introduction

The spike jump is a decisive offensive action in volleyball and requires an approach, conversion of horizontal momentum, rapid bilateral braking, propulsion, ball contact, and controlled landing. Three-step approach velocity, lower-limb coordination, and the arm swing contribute to spike-jump height, but the same sequence also exposes the lower extremity to substantial and often asymmetric loading [1–4]. Studies using force platforms and three-dimensional motion analysis have shown that approach-jump strategy, expertise, and limb-use pattern alter take-off and landing mechanics [3–9].

Force platforms remain the reference for external ground-reaction-force measurement, whereas instrumented insoles provide bilateral, in-shoe load histories under footwear conditions and can retain each foot's contribution when foot placement is unconstrained [10, 11]. Insole-derived signals should nevertheless be described as plantar load or kgf-equivalent output unless system-specific validation supports equivalence to laboratory force [10–13]. Wearable pressure-sensing systems have also been applied to quantify sport-specific plantar loading during dynamic athletic tasks, supporting their broader use in performance-oriented biomechanical assessment [14]. Volleyball plantar-pressure research has largely emphasized regional pressure, training adaptations, or peak measures rather than the shape of the final-plant waveform [13, 15]. To our knowledge, the phase-anchored Gaussian representation of bilateral in-shoe plantar-loading waveforms has not been evaluated during the final-plant phase of the volleyball spike jump.

A single peak collapses a time-varying signal into one value and may miss distinct braking and propulsion features. Computational modeling approaches, including artificial neural networks, have also been applied in volleyball biomechanics to integrate multiple biomechanical variables and characterize sport-specific performance [16]. Gaussian basis functions have been used to represent force time courses and reconstruct full force curves while quantifying component amplitude, timing, and width [17–19]. Applying this approach to a short, phase-anchored volleyball final plant could provide an interpretable waveform representation while avoiding unconstrained high-dimensional curve analysis.

Accordingly, the primary aim was to evaluate whether a phase-anchored Gaussian framework could compactly represent bilateral in-shoe plantar-load waveforms during the final plant of the volleyball spike jump. Baseline-offset single- and double-Gaussian models were compared using an information-theoretic criterion, and the resulting bilateral and component-level features were summarized. A secondary exploratory aim was to examine associations of selected loading and model-derived features with vertical hip-marker displacement, resultant hip-marker velocity, execution time, and spike accuracy. We expected the double-Gaussian model to be selected for most waveforms because the final plant may contain temporally distinct loading features associated with the approach-to-take-off transition.

2. Methods

2.1 Study design and participants

A cross-sectional biomechanics design was used, and the study was reported in accordance with the relevant STROBE recommendations [20]. Data collection was conducted in April 2026 at the indoor sports hall of the Iraqi Volleyball Federation. Participants were recruited from the four clubs that qualified for the final stage of the Iraqi Elite Volleyball League. All players from

these clubs who met the prespecified eligibility criteria and agreed to participate were included. Five eligible players were recruited from each club, resulting in a total sample of 20 male competitive volleyball players, all of whom used the right arm as their hitting arm. Participants were eligible if they were registered with a club competing in the Iraqi Elite Volleyball League, had at least five years of competitive experience, participated regularly in training and competition, were free from any current musculoskeletal injury that could limit maximal performance, and reported no pain during the spike-jump testing session. Players were excluded if they presented with a current injury or reported pain during testing, were unable to complete three valid spike-jump trials, had incomplete video or DYNAFOOT recordings because of technical failure, or failed to comply with the standardized spike-jump protocol. No a priori statistical sample-size calculation was performed because the study used complete enumeration of the eligible players available from the four qualifying clubs. Given the resulting sample size ($n = 20$), the study was framed as an exploratory proof-of-concept investigation. Mean age was 22.60 ± 1.23 years, height was 189.55 ± 1.10 cm, body mass was 86.55 ± 1.54 kg, and playing experience was 10.55 ± 1.28 years. The study protocol was approved by the Scientific Research Ethics Committee of the College of Physical Education and Sport Sciences, University of Al-Qadisiyah (approval no. UOQ-COPE-ETH-2026-016; 22 March 2026). All participants provided written informed consent before participation.

2.2 Standardized spike-jump protocol

The volleyball net was set at the regulation men's height of 2.43 m. Players wore their own volleyball shoes with the socks and instrumented insoles required by the DYNAFOOT® system. They completed their usual coach-directed warm-up, which the researcher did not prescribe or modify, and testing began after the coach confirmed readiness. Across all clubs and trials, the same designated individual delivered the ball to the club's specialist libero, who passed it to the specialist setter for a set to position 4. The researcher visually standardized set trajectory, height, and proximity to the net. The same libero and setter were used within each club, although they differed between clubs.

A trial was valid when the player completed the prescribed approach, contacted and directed the ball toward the designated accuracy zones without a net-contact or execution fault, and produced complete synchronized video and DYNAFOOT recordings permitting identification of final-plant onset, take-off, and landing. Trials with a non-compliant reception or set would have been repeated; none required repetition. Each participant completed three valid trials separated by approximately 2–3 min. Heart rate was monitored using a fingertip pulse oximeter, and the next trial began when it had decreased to ≤ 120 beats·min⁻¹. The DYNAFOOT® software averaged the three recordings into a single 5-s participant-level waveform. The final-plant interval was extracted for plantar-loading and Gaussian-model analyses and normalized to 0–100% for group visualization. Video-derived outcomes were also averaged across trials. Vertical hip displacement was calculated as the difference between the initial and highest hip-marker positions.

2.3 Instrumentation and synchronization

Dynamic plantar loading was recorded using a DYNAFOOT® dynamic pressure-mapping system (Techno Concept, Mane, France) comprising flexible instrumented insoles with resistive pressure sensors. Data were sampled at 100 Hz and recorded using the dedicated DYNAFOOT acquisition and analysis software. The analysis used the plantar-load channels exported directly by the manufacturer's software; no independent conversion or reconstruction from individual sensor-level pressure values was performed.

The exported load-channel values were treated as kgf-equivalent plantar-load outputs, consistent with the unit representation provided by the DYNAFOOT software. For body-weight normalization, plantar load expressed in kgf-equivalent units was divided by participant body mass in kilograms, yielding dimensionless body-weight units (BW).

Two Sony $\alpha 7S$ III cameras recorded Full HD video at $240 \text{ frames} \cdot \text{s}^{-1}$ from lateral and posterior views. Each camera was tripod-mounted, with the lens center approximately 3.8 m from the player and 1.45 m above the floor; lighting was held constant. Spatial calibration in Kinovea 2025.2.0 was performed using a perspective grid applied to the recording field to establish a calibrated two-dimensional reference plane for kinematic tracking. Video and DYNAFOOT recordings were synchronized post hoc using final-plant onset as a common biomechanical event. Final-plant onset was identified as the first foot-ground contact in the video and the corresponding onset of increased plantar loading in the insole signal, and the two recordings were temporally aligned to this event. Camera shutter speed and lens-distortion calibration parameters were not retained in the archived records.

2.4 Phase anchoring and outcome definitions

The analyzed interval extended from final-plant contact onset to take-off. Final-plant onset was the first foot-ground contact of the final plant. Propulsion onset was the lowest hip-marker position immediately before upward motion. These event definitions were applied consistently across participants, recognizing that the reliability of biomechanical phase identification can vary across volleyball-specific jump-landing tasks [21]. Braking duration extended from final-plant onset to propulsion onset; propulsion duration extended from propulsion onset to take-off; and final-plant duration equaled braking plus propulsion. Time was re-expressed from 0% to 100% of each player's final-plant phase for group visualization. Left, right, and bilateral peak plantar loads were extracted. Bilateral plantar-load impulse was calculated as the trapezoidal integral of the bilateral kgf-equivalent load signal over the final-plant phase. The resulting kgf·s values were converted to N·s using $1 \text{ kgf} = 9.80665 \text{ N}$ and subsequently normalized to body mass, yielding $\text{N} \cdot \text{s} \cdot \text{kg}^{-1}$. Signed peak asymmetry was calculated as $200 \times (\text{right} - \text{left}) / (\text{right} + \text{left})$, and the absolute value represented asymmetry magnitude.

Video-derived outcomes were vertical hip-marker displacement (cm), resultant hip-marker velocity ($\text{m} \cdot \text{s}^{-1}$), execution time (s), braking duration, propulsion duration, final-plant duration, flight duration, and spike-target accuracy. Resultant hip-marker velocity was calculated as $v_{\text{hip}} = \sqrt{v_x^2 + v_y^2}$. It reflects the planar resultant speed of a single retroreflective hip marker in the calibrated 2D lateral field and was treated as a localized indicator of proximal-segment kinematics rather than a whole-body center-of-mass motion vector. Kinematic analysis used the final player-level velocity values extracted from the tracked hip marker. Execution time extended from the first movement of the approach steps to the first foot-ground contact at landing. Flight duration extended from loss of ground contact at take-off to the first foot-ground contact at landing. Durations were calculated from frame differences divided by $240 \text{ frames} \cdot \text{s}^{-1}$.

Spike accuracy was evaluated using a prespecified target-zone scoring system on the opposite court. Two $1 \times 1 \text{ m}$ target mats were positioned in playing zones 1 and 5. For each mat, the edge nearest the end line was positioned 1 m from the end line, and the edge nearest the adjacent sideline was positioned 1 m from that sideline. The spaces between each target mat and the corresponding end line and adjacent sideline were marked with parallel strips in colors contrasting with those of the target mats. The rear-court space between the two target mats was divided equally into zones A and B, with zone A located toward playing position 1 and zone B toward playing position 5. The front-court scoring area comprised playing positions 2, 3, and 4. Four points were awarded

when the ball landed on a target mat, three points for the striped areas, two points for zones A or B, one point for the front-court area, and zero points for an unsuccessful or out-of-bounds spike.

$$D = [40 / (3 \times 4)] \times \sum_{i=1 \text{ to } 3} S_i = (10 / 3) \times \sum_{i=1 \text{ to } 3} S_i$$

where S_i represents the raw score obtained in the i -th trial, with $S_i \in \{0, 1, 2, 3, 4\}$. This transformation converted the summed scores from the three analyzed trials to a 0–40-point scale, with 40 representing the maximum possible score. All participants completed three valid trials, and no unsuccessful or out-of-bounds spikes occurred in the analyzed dataset. The observed final accuracy scores were either 20 or 40 points.

2.5 Gaussian waveform models

The bilateral waveform $F(t)$ was modeled with a non-negative baseline-offset single Gaussian:

$$F(t) = F_0 + A \cdot \exp \left[-0.5 \left(\frac{t - \mu}{\sigma} \right)^2 \right]$$

The alternative model contained two components:

$$F(t) = F_0 + A_1 \cdot \exp \left[-0.5 \left(\frac{t - \mu_1}{\sigma_1} \right)^2 \right] + A_2 \cdot \exp \left[-0.5 \left(\frac{t - \mu_2}{\sigma_2} \right)^2 \right]$$

Nonlinear least squares used bounded parameters and deterministic multiple starting values for the double model, followed by temporal sorting of component centers. The baseline and amplitudes were constrained to be non-negative, and σ was bounded below by the greater of 0.005 s and half the sampling interval. The double model was selected only when its corrected Akaike information criterion (AICc) was more than two units lower than that of the single model; otherwise, the single model was retained. AICc was calculated as $n \ln(\text{RSS}/n) + 2k + [2k(k+1)/(n-k-1)]$, where n was the number of samples in the participant-specific final-plant interval and k was the number of estimated parameters ($k = 4$ for the single model and $k = 7$ for the double model). Model selection was based on the information-theoretic principle of balancing model fit against model complexity [22]. Fit quality was descriptively classified using prespecified thresholds as good ($R^2 \geq 0.90$), acceptable (0.75--0.899), or poor ($R^2 < 0.75$). For component-level interpretation, a selected double model additionally required both centers to be at least 0.01 s from a phase boundary, each width to be no more than 50% of the phase duration, and center separation to be at least 10% of the phase. The full theoretical area of each Gaussian basis function was calculated as $A\sigma\sqrt{2\pi}$, excluding the baseline term; for double-Gaussian fits, the two component areas were summed. Because this quantity represents the unbounded integral of the fitted Gaussian components rather than the observed integral restricted to the final-plant window, it was treated solely as a model-derived waveform descriptor and not as a substitute for the measured plantar-load impulse. For participant-level summaries, selected-model amplitude was defined as A for single-Gaussian fits and as $A_1 + A_2$ for double-Gaussian fits. First-center timing represented μ for the single-Gaussian fit and the earlier of μ_1 and μ_2 for double-Gaussian fits. Center separation and early-component area share were summarized only for identifiable double-component fits.

2.6 Statistical analysis and quality control

Continuous variables were summarized using mean $\pm$ SD and median [interquartile range]. Spearman rank correlations related seven loading/model predictors to four outcomes: vertical hip-marker displacement, resultant hip-marker velocity, execution time, and spike accuracy. Percentile bootstrap 95% confidence intervals used 5,000 valid resamples with the prespecified random seed 20260819. Two-sided p values were obtained from the Spearman rank-correlation test, whereas bootstrap resampling was used only to estimate the confidence intervals. The 28 p values were

adjusted using the Benjamini–Hochberg false-discovery-rate procedure [23], with $q < .05$ as the multiplicity-adjusted significance threshold. Given $n = 20$ and the number of comparisons, associations were interpreted as exploratory, with emphasis on effect size, interval width, and multiplicity-adjusted inference. Because P04 exhibited an extreme but technically retained absolute peak-load asymmetry (150.0%), a post hoc influence sensitivity analysis repeated the same 28 correlations after temporarily excluding P04 ($n = 19$; $n = 14$ for predictors restricted to identifiable double fits). This sensitivity analysis used 5,000 bootstrap resamples with seed 20260821 and a separate BH correction across its 28 tests; it did not replace the primary $n = 20$ analysis.

Complete 5-s plantar-load and pressure arrays were audited for between-player signal similarity using pairwise correlations and exact non-zero agreement. No pair met the prespecified critical-similarity criteria; consequently, all 20 distinct player recordings were retained. The highest observed pairwise similarity was P18–P20 (plantar-load $r = 0.704$; pressure $r = 0.663$; exact non-zero fraction = 0.036). Analyses were performed in Python using NumPy, pandas, SciPy, and Matplotlib.

3. Results

3.1 Participant, performance, and loading characteristics

All 20 participant-level averaged plantar-load waveforms contained a usable final-plant window. Vertical hip displacement averaged 91.05 ± 5.63 cm, resultant hip-marker velocity 3.53 ± 0.43 m·s⁻¹, and execution time 2.685 ± 0.195 s. Mean braking, propulsion, final-plant, and flight durations were 0.164 ± 0.025 s, 0.089 ± 0.016 s, 0.253 ± 0.033 s, and 0.348 ± 0.019 s, respectively. Accuracy averaged 32.0 ± 10.1 points. Bilateral peak plantar load averaged 1.76 ± 0.51 BW and mass-normalized load impulse 2.53 ± 0.79 N·s·kg⁻¹. Absolute peak-load asymmetry was right-skewed (median 8.94% [5.59–21.81%]; mean $22.13 \pm 33.55\%$), largely because P04 displayed a markedly unilateral peak pattern (Tables 1 and 2; Figure 1).

Table 1 Participant characteristics and video-derived performance outcomes

Variable	Mean $\pm$ SD	Median [IQR]; Range
Age (years)	22.60 $\pm$ 1.23	23.00 [21.75–23.25] / 21–25
Height (cm)	189.55 $\pm$ 1.10	190.00 [189.00–190.00] / 187–191
Body mass (kg)	86.55 $\pm$ 1.54	87.00 [86.00–88.00] / 83–89
Playing experience (years)	10.55 $\pm$ 1.28	11.00 [9.75–11.00] / 9–14
Hip vertical displacement (cm)	91.05 $\pm$ 5.63	90.50 [87.75–95.50] / 81–99
Resultant hip-marker velocity (m·s ⁻¹)	3.53 $\pm$ 0.43	3.60 [3.20–3.83] / 2.8–4.2
Execution time (s)	2.685 $\pm$ 0.195	2.750 [2.500–2.825] / 2.3–2.9
Braking duration (s)	0.164 $\pm$ 0.025	0.171 [0.141–0.180] / 0.104–0.196
Propulsion duration (s)	0.089 $\pm$ 0.016	0.092 [0.082–0.097] / 0.050–0.125
Final-plant duration (s)	0.253 $\pm$ 0.033	0.263 [0.234–0.275] / 0.188–0.288

Variable	Mean $\pm$ SD	Median [IQR]; Range
Flight duration (s)	0.348 $\pm$ 0.019	0.350 [0.338–0.350] / 0.313–0.413
Spike accuracy score (points; 0–40)	32.00 $\pm$ 10.05	40.00 [20.00–40.00] / 20–40

Values are presented as mean $\pm$ SD and median [IQR] / range. Participant-level performance outcomes were derived from the mean of three valid trials per player ($n = 20$).

Table 2 Phase-anchored plantar-loading and asymmetry outcomes

Outcome	Mean $\pm$ SD	Median [IQR]
Left peak plantar load (BW)	0.99 $\pm$ 0.26	1.00 [0.93–1.15]
Right peak plantar load (BW)	1.05 $\pm$ 0.18	1.02 [0.91–1.19]
Bilateral peak plantar load (BW)	1.76 $\pm$ 0.51	1.87 [1.41–2.05]
Absolute peak-load asymmetry (%)	22.13 $\pm$ 33.55	8.94 [5.59–21.81]
Mass-normalized load impulse (N·s·kg ⁻¹)	2.53 $\pm$ 0.79	2.48 [1.98–3.20]

BW = body-weight units. Mass-normalized load impulse is expressed as N·s·kg⁻¹.

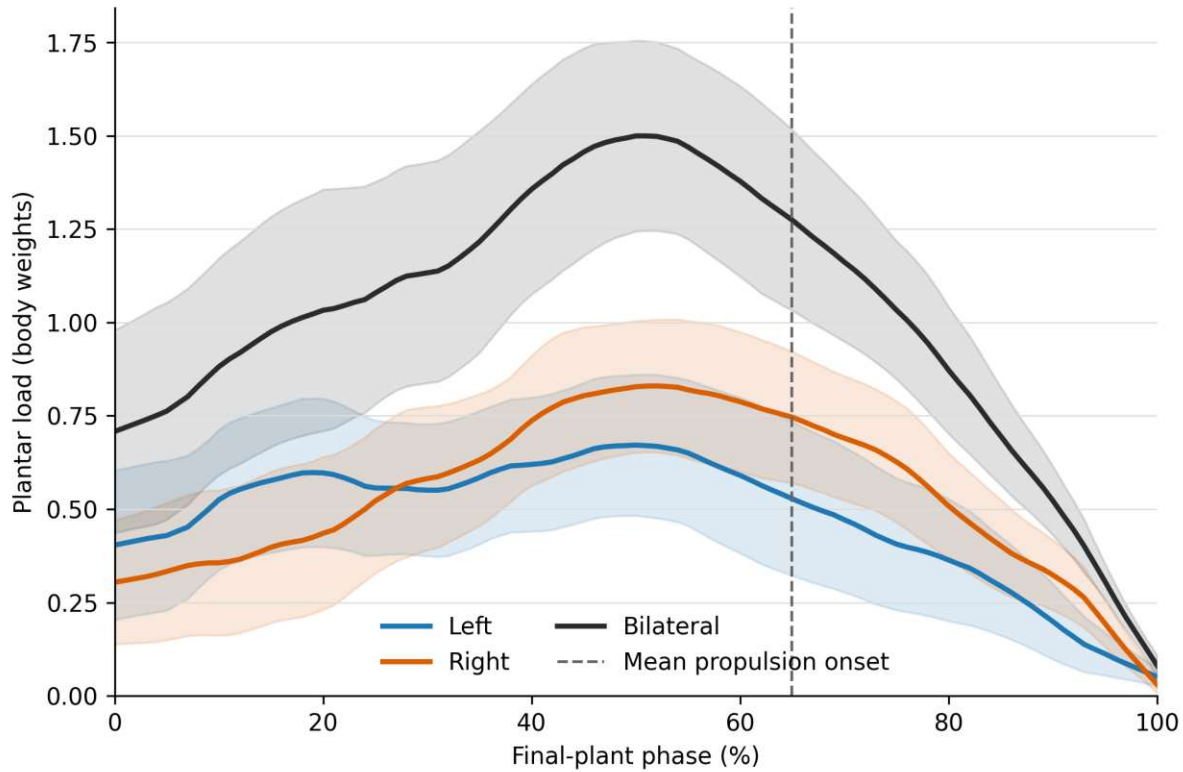


Fig. 1 Phase-normalized left, right, and bilateral plantar loading across the final plant. Lines show sample means and shaded bands show 95% confidence intervals ($n = 20$); the vertical marker denotes mean propulsion onset

3.2 Gaussian model selection and fit

AICc selected the double-Gaussian model for 19 players (95%) and the single-Gaussian model for one player (P07; 5%). All 20 selected fits met the prespecified good-fit threshold ($R^2 \geq 0.90$). Median selected-model R^2 was 0.966 [0.954–0.986], and median RMSE was 7.56 [5.60–8.47] kgf. Fifteen of the 19 double-Gaussian fits met all component-identifiability criteria; center-separation and early-area-share summaries were therefore restricted to these 15 identifiable

participant-level fits. For identifiable fits, mean center separation was $41.06 \pm 12.57\%$ of the final-plant phase and mean early-component area share was $51.17 \pm 29.17\%$ (Table 3; Figure 2).

Table 3 Gaussian model selection, decomposition characteristics, and fit quality

Metric	Estimate	n
Single Gaussian selected, n (%)	1 (5%)	20
Double Gaussian selected, n (%)	19 (95%)	20
Good fit ($R^2 \geq 0.90$), n (%)	20 (100%)	20
Identifiable double-Gaussian fit, n	15	20
Sum of selected Gaussian component amplitudes (BW)	2.32 ± 0.71	20
Full Gaussian-component area ($N \cdot s \cdot kg^{-1}$)	2.84 ± 0.96	20
First-center timing (% final-plant phase)	18.52 [6.43–39.82]	20
Center separation (% phase; identifiable)	41.06 ± 12.57	15
Early-component area share (%; identifiable)	51.17 ± 29.17	15
Selected-model R^2	0.966 [0.954–0.986]	20
Selected-model RMSE (kgf)	7.56 [5.60–8.47]	20

Values are mean $\pm$ SD except first-center timing, selected-model R^2 , and selected-model RMSE, which are median [IQR].

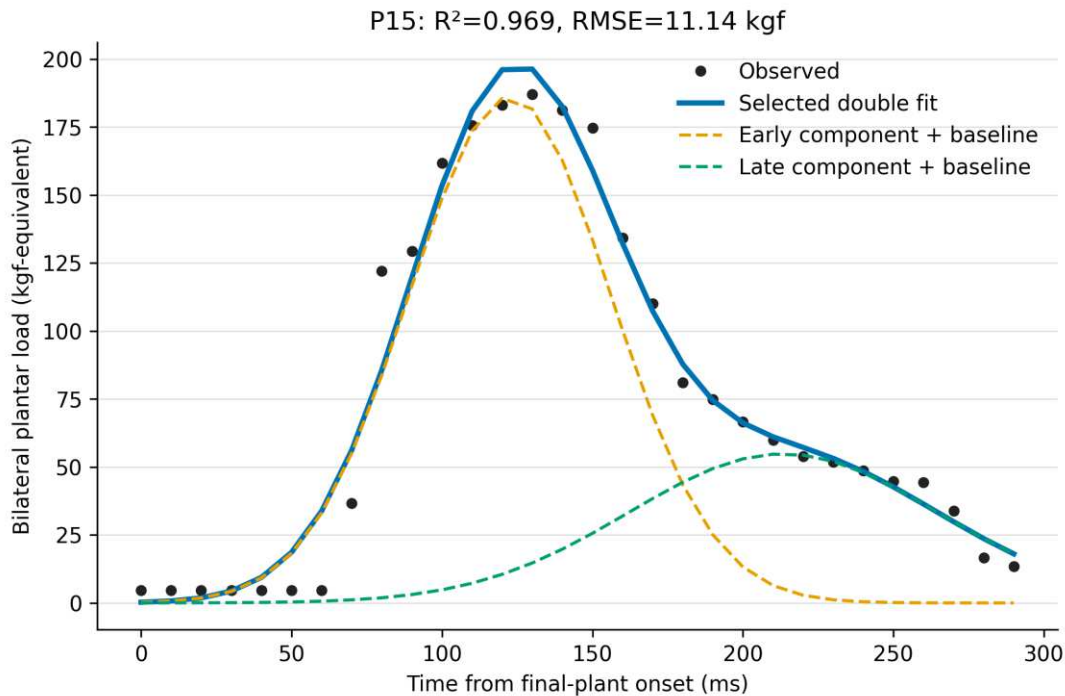


Fig. 2 Representative observed bilateral plantar-load waveform and the AICc-selected double-Gaussian fit for P15, whose selected-model fit quality was closest to the sample median ($R^2 = 0.969$; RMSE = 11.14 kgf)

3.3 Exploratory associations and quality-control findings

The strongest unadjusted association was between absolute peak-load asymmetry and spike accuracy ($\rho = 0.584$, bootstrap 95% CI 0.228 to 0.819, $p = 0.0069$), followed by mass-normalized

load impulse and spike accuracy ($\rho = -0.531$, 95% CI -0.797 to -0.159 , $p = 0.0160$). Neither survived correction across 28 comparisons (BH $q = 0.192$ and 0.224 , respectively). Load impulse also showed a moderate negative association with vertical hip displacement ($\rho = -0.400$, 95% CI -0.677 to -0.002 , $p = 0.080$, $q = 0.561$), whereas absolute asymmetry showed a moderate positive association with resultant hip-marker velocity ($\rho = 0.403$, 95% CI 0.011 to 0.694 , $p = 0.078$, $q = 0.561$). No association met the $q < .05$ multiplicity-adjusted significance threshold (Table 4; Figure 3).

The signal-similarity audit identified no critical between-player matches, so all 20 records were retained in the primary analysis. In the post hoc P04 sensitivity analysis, the asymmetry–accuracy association changed only from $\rho = 0.584$ ($n = 20$) to $\rho = 0.564$ ($n = 19$; bootstrap 95% CI 0.174 to 0.832 ; $p = 0.0118$; sensitivity BH $q = 0.331$). The impulse–accuracy association changed from $\rho = -0.531$ to $\rho = -0.506$ (95% CI -0.805 to -0.098 ; $p = 0.0271$; $q = 0.379$). The asymmetry–hip-marker-velocity association was similarly stable ($\rho = 0.403$ to 0.395 ; 95% CI -0.029 to 0.711 ; $p = 0.0940$; $q = 0.632$). No sensitivity-analysis association met $q < .05$. Thus, P04 influenced the descriptive asymmetry mean but did not materially determine the principal rank-correlation estimates.

Table 4 Selected exploratory associations between plantar-loading and Gaussian predictors and performance outcomes

Predictor	Outcome	n	ρ	95% bootstrap CI	p / BH q
Absolute asymmetry (%)	Spike accuracy	20	0.584	0.228 to 0.819	0.0069 / 0.192
Load impulse ($N \cdot s \cdot kg^{-1}$)	Spike accuracy	20	-0.531	-0.797 to -0.159	0.0160 / 0.224
Absolute asymmetry (%)	Resultant hip-marker velocity	20	0.403	0.011 to 0.694	0.0777 / 0.561
Load impulse ($N \cdot s \cdot kg^{-1}$)	Hip displacement	20	-0.400	-0.677 to -0.002	0.0802 / 0.561
Bilateral peak load (BW)	Execution time	20	0.340	-0.122 to 0.712	0.1426 / 0.570
Bilateral peak load (BW)	Spike accuracy	20	-0.354	-0.722 to 0.087	0.1257 / 0.570
Gaussian amplitude (BW)	Execution time	20	0.261	-0.185 to 0.644	0.2663 / 0.678
Gaussian amplitude (BW)	Spike accuracy	20	-0.283	-0.695 to 0.192	0.2263 / 0.667
Bilateral peak load (BW)	Resultant hip-marker velocity	20	-0.036	-0.491 to 0.428	0.8791 / 0.912
Gaussian amplitude (BW)	Resultant hip-marker velocity	20	0.120	-0.338 to 0.516	0.6132 / 0.896
Load impulse ($N \cdot s \cdot kg^{-1}$)	Execution time	20	0.077	-0.385 to 0.527	0.7459 / 0.896
Gaussian amplitude (BW)	Hip displacement	20	-0.009	-0.431 to 0.398	0.9698 / 0.970

CI = confidence interval; BH = Benjamini–Hochberg. The complete 28-comparison analysis is provided in Supplementary Table S2. No BH-adjusted q value was below .05. Additional participant-level model-fit diagnostics and the post hoc sensitivity analysis are provided in the Supplementary Material (Supplementary Figures S1–S2 and Supplementary Table S1).

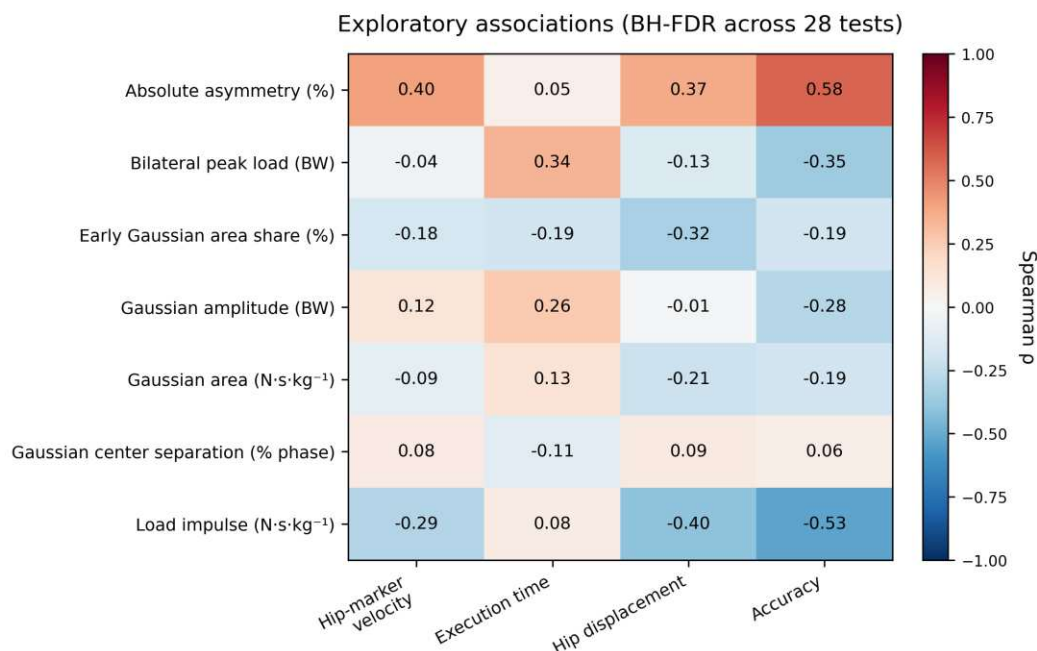


Fig. 3 Spearman correlations between seven plantar-loading/Gaussian predictors and four outcomes, including resultant hip-marker velocity. Values are exploratory; no association survived Benjamini–Hochberg correction across 28 tests

4. Discussion

The main finding was that a parsimonious Gaussian framework described bilateral in-shoe plantar loading over the volleyball spike-jump final plant with consistently high fit quality. AICc favored two components in 95% of players, supporting the working hypothesis that the approach-to-take-off transition frequently contains more than one dominant loading feature. The results do not prove that each Gaussian component represents a discrete biological mechanism; nevertheless, the strong waveform reconstruction and phase anchoring provide an interpretable representation of within-phase loading organization.

The predominance of double-Gaussian fits is mechanically plausible. During a spike approach, the final contacts must brake horizontal momentum and redirect it vertically before take-off. Force-platform studies have demonstrated that approach speed, single- versus double-leg strategy, lower-limb flexion, and coordination alter the magnitude and timing of spike-jump kinetics [1–5, 8, 9]. Fuchs and colleagues emphasized optimized approach-to-vertical energy conversion and arm-swing coordination as central to jump height [1, 2], while Tai et al. documented distinct kinetic strategies between one- and two-leg approach jumps [3]. More recent evidence indicates that the contribution of the lower limbs may also differ according to their functional role during the spike-jump approach, reinforcing the importance of retaining bilateral information when interpreting take-off mechanics [8]. The present in-shoe curves extend that literature by retaining left and right plantar-load contributions in the athletes' footwear.

The Gaussian approach also addresses a limitation of isolated peak reporting. Full-curve decomposition can represent temporal features that share a similar maximum but differ in timing or duration. Gaussian representations have previously been used to characterize force-pattern time

courses and reconstruct complete vertical ground-reaction-force curves [17, 19], while Nixon et al. used a double-Gaussian description to distinguish running-related waveform features [18]. The present study used fewer components because the analyzed interval was restricted to the short final plant rather than a full gait cycle. AICc penalization and explicit identifiability criteria were essential: although 19 double models were selected, only 15 were suitable for component-level interpretation [22].

Mean bilateral peak plantar load was 1.76 BW, but individual peak magnitude and inter-limb asymmetry varied substantially. Absolute asymmetry had a median of 8.94%, whereas its mean was inflated to 22.13% by a markedly unilateral pattern in P04. This variability may reflect genuine differences in penultimate/final-foot strategy, foot placement relative to the sensor field, or uncertainty in identifying biomechanical event boundaries across the synchronized video and insole signals. Volleyball studies have linked take-off and landing strategies to patellar-tendon loading and injury-relevant joint mechanics [4–7], while plantar-pressure redistribution and foot-pressure characteristics have also been examined in volleyball jump and spike-jump tasks [13, 15]. However, because the present signals were in-shoe kgf-equivalent outputs rather than laboratory ground-reaction forces, the asymmetry findings require cautious interpretation [10, 11].

4.1 Practical implications

From an applied perspective, phase-anchored Gaussian decomposition provides a compact method for summarizing the timing and relative prominence of loading features from in-shoe recordings collected during a sport-specific spike jump. The approach may support within-athlete monitoring and descriptive comparison of final-plant strategies when conventional force platforms are unavailable. However, because no association remained significant after false-discovery-rate correction and the insole outputs were not validated against a force platform in this study, the derived components should not yet be used for player selection, injury-risk classification, or clinical decision-making.

4.2 Limitations

Several limitations should be considered. First, the small and homogeneous sample ($n = 20$) limited generalizability and statistical power; association tests were therefore exploratory. Second, resultant hip-marker speed was not whole-body center-of-mass velocity, and the absence of frame-wise coordinates, project files, and filtering and differentiation settings prevented independent reconstruction. Third, the perspective-grid calibration remained two-dimensional because the camera views were not integrated into a calibrated three-dimensional volume; out-of-plane motion was therefore not captured. Event-based synchronization also depended on identifying final-plant onset and was constrained by the video and insole sampling intervals (4.17 and 10 ms, respectively). Fourth, insole kgf-equivalent load is not interchangeable with laboratory ground-reaction force, and sensor saturation, footwear interaction, or partial foot contact may affect peak, impulse, and asymmetry estimates. Fifth, the DYNAFOOT software retained only a participant-level mean waveform from the three valid trials. Without separate trial-level waveforms, within-participant variability and test–retest reliability could not be quantified; the findings therefore do not establish trial-to-trial reliability. Sixth, the two observed accuracy levels (20 and 40 points) reduced statistical resolution and support using continuous spatial error in future studies. Seventh, warm-up was coach-directed rather than researcher-standardized. Eighth, club-specific liberos and setters were used, while set height and proximity to the net were standardized visually, potentially introducing between-club variation. Finally, AICc and R^2 were applied to

temporally ordered mean-waveform samples without modeling residual serial dependence; model selection and fit indices are therefore descriptive rather than confirmatory. The P04 sensitivity analysis was post hoc, and Gaussian component labels remain mathematical descriptors pending validation against independently measured braking and propulsion mechanics.

5. Conclusion

Phase-anchored single- and double-Gaussian models reconstructed bilateral in-shoe plantar loading during the volleyball spike-jump final plant with high fit quality. A double-Gaussian model was preferred for the vast majority of players (19 of 20), although 15 of these fits met all stringent component-identifiability criteria. While initial unadjusted associations were observed, no loading or Gaussian feature remained significantly associated with vertical hip displacement, resultant hip-marker velocity, execution time, or spike accuracy after false-discovery-rate correction. The framework may be useful for exploratory waveform characterization; however, larger samples, laboratory force validation, and higher-resolution continuous spatial performance metrics are required before definitive inferential or applied conclusions can be drawn.

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433 institutional ethical standards.

434 **Consent to participate**

435 Written informed consent was obtained from all participants before participation.

436 **Author contributions**

437 Ahmed Abdulameer Shubbar was responsible for the study conceptualization and design,
438 methodology, investigation, data collection, formal analysis, data curation, visualization, and
439 preparation, review, and editing of the manuscript. The author read and approved the final
440 manuscript.

441 **Data availability**

442 De-identified derived data, model curves, analysis definitions, quality-control outputs, and figure-
443 source data are archived in Zenodo at <https://doi.org/10.5281/zenodo.22104092> and are also
444 provided in the accompanying supplementary workbook. Access to the archived repository is
445 restricted to protect participant confidentiality and may be granted upon reasonable request, subject
446 to institutional approval and applicable confidentiality requirements. Raw instrument exports may
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448 **Declaration of generative AI and AI-assisted technologies in the writing process**

449 During the preparation of this work, the author used ChatGPT (OpenAI) to support English-
450 language editing and improve manuscript clarity and organization. The author reviewed and edited
451 the output as needed and takes full responsibility for the content of the manuscript.

Supplementary Files

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