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Acceleration Rhythm and Horizontal Velocity Retention Differentiate World-Class, Elite, and Sub-Elite Female Pole Vaulters: A Three-Dimensional Kinematic Analysis

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ABSTRACT:

Background: The approach run and take-off phases critically determine pole vault performance, yet the kinematic and temporal characteristics distinguishing world-class from sub-elite female vaulters remain incompletely characterized, particularly in ecological competition settings.

Methods: This cross-sectional study compared three-dimensional kinematics of the approach and take-off phases between world-class (n = 6), Chinese elite (n = 8), and Chinese sub-elite (n = 9) female pole vaulters during competition. Field-based video analysis at 100 Hz was employed, with effect sizes and 95% confidence intervals reported to address small-sample limitations.

Results: World-class athletes exhibit a "slow-fast" acceleration rhythm during the final two approach steps, while Chinese athletes show a "fast-slow" deceleration. At take-off, world-class vaulters have a higher horizontal velocity (7.02 m/s) compared to elite (6.44 m/s) and sub-elite groups (6.04 m/s). Additionally, these athletes exhibit lower take-off angles (19.1°) negatively correlated with performance.

Conclusion: World-class female pole-vaulting performance is distinguished by efficient velocity preservation during the approach and take-off phases, rather than merely higher absolute speeds. These findings provide evidence-based targets for technical optimization in elite training programs.

INTRODUCTION

The approach run, take-off and flight are among the most biomechanically complex events of track and field, where the sequence of actions has to be carefully coordinated to ensure that the pole is bent to its maximum potential energy and the bar is cleared, during the approach run and take-off phase, respectively, while in flight (Gross et al., 2020; Schade et al., 2004; Sudlow et al., 2025). The approach run and take-off are the most important performance elements since the horizontal velocity at the take-off determines the energy for the vertical lift (Hanley et al., 2022; Yang et al., 2021). Therefore, the kinematic and temporal characteristics of these phases are of key importance to enhance elite athletic performance and continue to be the focus of many biomechanical studies.

The key biomechanical components of approach run in pole vaulting are similar to those of sprinting, such as acceleration rhythm, force-velocity profile, velocity retention strategies, etc. (Edwards et al., 2021; Gleadhill and Nagahara, 2021; Samozino et al., 2016; Talukdar et al., 2021). It is known that elite sprinters have certain kinetic and kinematic characteristics that allow them to produce maximum horizontal velocity with minimum deceleration during the acceleration phase of running (Haugen et al., 2019; Runacres et al., 2024; Slawinski et al., 2017; Theodorou et al., 2023; Yang et al., 2021). Likewise, pole vaulters need to carefully control the frequency, length and velocity of center of mass of the approach steps in preparation for the energetically challenging take-off (Loturco et al., 2018; Rabita et al., 2015; Theodorou et al., 2023). In addition, high ground reaction forces during this transition are critical in achieving vaulting performance and associated with increased risk of lower-limb injuries. Thus, the take-off pattern must be technically efficient and also be biomechanically appropriate (Edouard et al., 2019).

Recent biomechanical studies have shown the approach velocity and take-off angle during the pole-plant phase to be closely related to vaulting performance as well as a temporal coordination between the plant and pole phases (Gross et al., 2020; Hanley et al., 2022; Schade et al., 2004; Sudlow et al., 2025). Furthermore, there have been important biomechanical gender differences identified (Cassirame et al., 2017; Panoutsakopoulos et al., 2021; Sudlow et al., 2025) and therefore a need for separate analysis of male and female athletes to fully understand the technical demands imposed on elite female athletes. The last two stages of the process have been shown to be particularly critical, especially in the defining of spatial and temporal parameters that enable efficient pole-plant mechanics and energy transfer (Loturco et al., 2018; Theodorou et al., 2023). The physiological basis of the different kinematic strategies between top-level and sub-elite female vaulters, however, is not fully understood, especially regarding: acceleration rhythm and horizontal velocity retention.

Traditional biomechanical analysis on pole vaulting has been limited in many cases by using a laboratory-based motion capture system, which has limited ecological validity, with a potential for disrupting the athletes' natural motor functions during competition. In recent years, some innovative methods have been developed, such as marker-less motion analysis and highly accurate three-dimensional (3D) kinematic analysis, which have allowed the evaluation of competitive movements in real world settings with high accuracy (Baker et al., 2025; Bissas and Cronin, 2026; Cronin et al., 2023). Field-based technologies have been found to be very useful in analysing multi-action sports such as take-offs for the high jump, sprinting and middle distance running without interfering with pre-competition routines and provide unprecedented access to world-class performance data (Burns et al., 2021; Cronin et al., 2023; Nicholson et al., 2024) Even with these advancements in technology, there is still a significant lack of comparative 3D kinematic analysis in the approach and take-off phases of world class and sub-elite female pole vaulters using ecological settings. In addition, elite sports research is often limited due to the small number of athletes in the study population (Hecksteden et al., 2022). To overcome these methodological issues, it is necessary to employ rigorously statistical methods and advanced modeling techniques to prevent the confidence crisis that is so often seen in biomechanics research, with the aim of being able to interpret the results of an effect size as well as a practical significance (Hecksteden et al., 2022; Knudson, 2017; Newans et al., 2022).

This is, to the best of our knowledge, the first study to compare the approach and take-off phases of world class and sub-elite female pole vaulters using ecological competition data, in a comprehensive field-based 3D kinematic analysis. Thus, the aim of the study is to investigate the key kinematic and temporal characteristics that distinguish elite from sub-elite performance for the evaluation of stride rhythm, horizontal velocity retention, and take-off angles. The hypothesis was that world-class female pole vaulters would exhibit a unique "slow-fast" acceleration phase rhythm and longer horizontal velocity retention during the pole-plant and take-off phases, which would allow more efficient energy transfer. The results of this study will be able to offer practical, evidence-based suggestions to improve technical execution and competitive results for female pole vaulters.

MATERIALS AND METHODS

Study Design

The nature of the study was cross-sectional, observational and biomechanical in an ecological competition environment. Although STROBE was originally developed for epidemiological research, its core principles for reporting observational study design, participant selection, and variable measurement are directly applicable to cross-sectional observational designs more broadly; the present study therefore adapted the STROBE guidelines as a general framework to ensure the research protocol, data collection, and reporting were methodologically transparent, reproducible, and rigorous.

Participants

A total of 23 elite female pole vaulters performed in this cross-sectional biomechanical analysis. The participants were split into three groups according to their performance, the World-Class group (WC, n = 6, mean competition height: 4.80 ± 0.10 m, PB: 4.94 ± 0.07 m), Chinese Elite group (CG-A, n = 8, competition height 4.30 m to 4.72 m, PB: 4.51 ± 0.16 m), and Chinese Sub-Elite group (CG-B, n = 9, competition height 4.00 m to 4.15 m, PB: 4.16 ± 0.09 m), representing the global elite population, national-level athletes and Chinese athletes. The CG-A and CG-B athletes were selected from the three major national events: 14th Chinese National Games, China Athletics Championship 2023, and China Athletics Indoor Championship 2023.

The inclusion criteria were: (a) female pole vaulters, aged between 18 and 35 years, who were active in international (World Championships) and/or national (Chinese National Games and National Championships) competitions; (b) a minimum of five years of competitive pole vaulting experience; (c) successful multi-camera video capture of the final approach and take-off phases in competitive pole vault; and (d) competitive level reached at the international (World Championships) or national (Chinese National Games, National Championships) level.

Exclusion criteria were: (a) any musculoskeletal injury that occurred during the videoed competition that could have interfered with movement patterns; (b) incomplete filming of the critical phases; (c) unsuccessful trials (e.g., knocking the crossbar, fouling the take off, or not reaching the bar); and (d) use of performance-enhancing substances or modifications to equipment not allowed by the IAAF regulations. Before data collection all Chinese participants signed informed consent forms and a history of training was confirmed by official competition registration records, along with details of age, height, and body mass. The data for the world-class athletes were drawn from publicly available broadcast video from the 2018 IAAF World Indoor Championships and the athletes' names were anonymized during the data analysis to adhere to data protection regulations. This study received approval from the Ethics Committee of the authors' affiliated institution (IRB-2023-047), which explicitly covered the use of publicly available broadcast footage for the World-Class group alongside directly consented data collection for the Chinese groups, and adhered to the Declaration of Helsinki and international standards for conducting biomechanical research with human subjects. The sample size (n = 6) is small; these athletes were the world-class vaulters for whom sufficiently high-quality broadcast footage was available for three-dimensional reconstruction, and the sample size matches that used in previous biomechanical studies of elite pole vaulters (Hanley et al., 2022; Rabita et al., 2015). In recent years, methodological recommendations have been made highlighting that small-sample studies in elite sports can provide valuable information even without the use of dichotomous interpretation of the p-value, but by reporting effect sizes with confidence intervals (Hecksteden et al., 2022; Li et al., 2024; Panoutsakopoulos et al., 2021). The present study took this route, with a careful consideration of the limitations of statistical power by using extensive effect size estimation and clear reporting of 95% confidence intervals.

Materials and Instruments

Kinematic data were collected with a multi-camera video system designed to capture valid and reliable spatial-temporal data in field-based biomechanical analysis contexts that does not compromise ecological validity as demonstrated in real world athletic environments (Bissas and Cronin, 2026; Cronin et al., 2023). Two high-definition digital camcorders (Sony AX60, Sony Corporation, Tokyo, Japan) were used to acquire three-dimensional (3D) recordings. In order to minimize the possibility of motion blur when the velocity was high, the cameras were operated at a sampling frequency of 100 Hz and an exposure time of 1/1000 s. A third camera was used to film the approach run in two dimensional (2D) sagittal planes.

Procedure

Data Acquisition: The 3D camera setup was calibrated to acquire the volume that included the athlete's last approach step into the pole completion phase (about 6 m long). Camera 1 was set up in the spectator stand directly in front of the crossbar and Camera 2 was set up in the spectator stand to the left of the runway. The angle between the two 3D cameras (primary optical axes) was kept within the range of 60° to 120°, and the distance from the calibration volume was about 35 m. Camera 3 was placed at a distance of 25-30 m, a distance at which the film was taken of 10 m and a camera height of 1.2 m with the main optical axis perpendicular to the plane of motion.

Calibration: A custom 3D calibration frame was recorded before and after every competition session, to create the global coordinate system. The calibration scale was kept consistently perpendicular to the athletes' direction of motion to minimize errors of reconstruction in the main plane of motion. **Figure 1** shows a schematic diagram of the video acquisition.

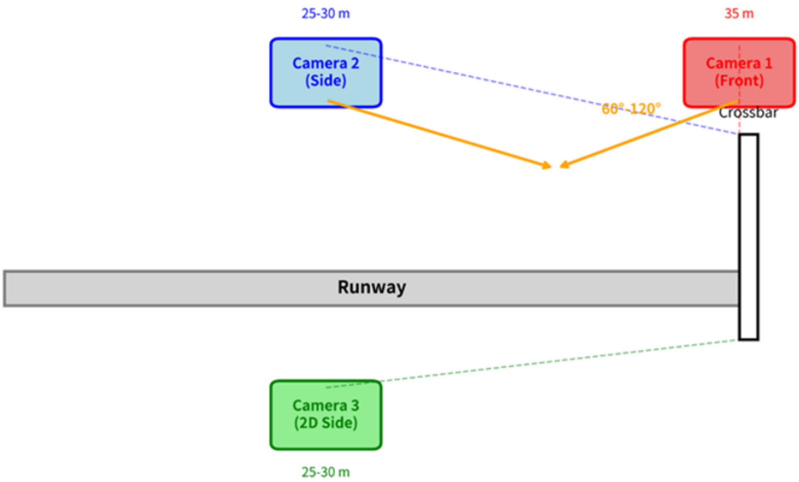

Figure 1: Schematic Diagram of Video Acquisition Process

Data Processing and Kinematic Modeling: Two-dimensional point digitization of anatomical landmarks in each camera view was performed using Kinovea open-source software (Version 0.9.5, Kinovea, France). The resulting 2D coordinates from the two calibrated camera views were then combined via a Direct Linear Transformation (DLT) algorithm to reconstruct the 3D coordinates of the anatomical landmarks, with reconstruction accuracy (RMS error < 8.5 mm; see Limitations) confirmed against the calibration frame. The raw coordinate data were smoothed using a low-pass digital filter with a cutoff frequency of 10 Hz, determined via residual analysis to optimize the signal-to-noise ratio for the specific velocity characteristics of the pole vault take-off. The approach phase was defined by the final two steps (penultimate and final step). The pole plant and take-off phases were delineated based on established biomechanical definitions for the event (Hanley et al., 2022; Loturco et al., 2018). Key dependent variables included step length, step speed, horizontal and vertical center of mass velocities, and take-off angle.

Statistical Analysis

Data were analyzed using SPSS 26.0 and Excel 2019. To address small-sample limitations (Hecksteden et al., 2022; Li et al., 2024), effect estimation was prioritized over dichotomous p-values (Panoutsakopoulos et al., 2021). Following normality and homogeneity checks (Shapiro-Wilk, Levene's tests), group differences were assessed via one-way ANOVA with Tukey's HSD post-hoc tests where assumptions were met, or Kruskal-Wallis tests with Dunn's post-hoc corrections where they were violated. Effect sizes (partial η_p^2, Cohen's d) and 95% CIs were reported. Pearson or Spearman correlations evaluated relationships with performance. Significance was set at $p \leq 0.05$; data are presented as mean ± SD.

RESULTS

Participant Characteristics

The anthropometric and performance characteristics of the participants are presented in **Table 1**. Significant differences were observed among groups for competition height ($F(2, 20) = 48.76$, $p < 0.001$, $\eta_p^2 = 0.83$) and personal best ($F(2, 20) = 52.34$, $p < 0.001$, $\eta_p^2 = 0.84$), with the World-Class (WC) group outperforming both Chinese groups. Moderate differences were found for age ($F(2, 20) = 4.12$, $p = 0.031$, $\eta_p^2 = 0.29$) and height ($F(2, 20) = 3.85$, $p = 0.039$, $\eta_p^2 = 0.28$), while body mass did not differ significantly ($p = 0.144$).

Table 1: Anthropometric and Performance Characteristics of the Participants

Variable	World-Class (WC) n = 6	Chinese Elite (CG-A) n = 8	Chinese Sub-Elite (CG-B) n = 9	ANOVA
Age (years)	28.3 ± 3.2	24.6 ± 2.8^a	22.1 ± 3.5^{a,b}	$F(2,20) = 4.12$ $p = 0.031$ $\eta_p^2 = 0.29$
Height (m)	1.74 ± 0.05	1.71 ± 0.04	1.68 ± 0.06^b	$F(2,20) = 3.85$ $p = 0.039$ $\eta_p^2 = 0.28$
Body Mass (kg)	62.5 ± 4.8	59.8 ± 5.2	57.2 ± 4.5	$F(2,20) = 2.14$ $p = 0.144$ $\eta_p^2 = 0.18$
Competition Height (m)	4.80 ± 0.10^{a,b}	4.47 ± 0.14^a	4.08 ± 0.08	$F(2,20) = 48.76$ $p < 0.001$ $\eta_p^2 = 0.83$
Personal Best (m)	4.94 ± 0.07^{a,b}	4.51 ± 0.16^a	4.16 ± 0.09	$F(2,20) = 52.34$ $p < 0.001$ $\eta_p^2 = 0.84$

Note. Data are presented as mean ± SD. ^a Significantly different from World-Class group ($p < 0.05$). ^b Significantly different from Chinese Elite group ($p < 0.05$).

Approach Phase Kinematics

Step length and horizontal velocity data for the final two approach steps are presented in **Table 2**. No significant group differences were observed for step length ($p > 0.05$), with all groups demonstrating a "long-short" rhythm. Significant differences were found for step speed at the penultimate step ($F(2, 20) = 18.76$, $p < 0.001$, $\eta_p^2 = 0.65$) and at the final step ($F(2, 20) = 22.14$, $p < 0.001$, $\eta_p^2 = 0.69$), as well as speed variation ($F(2, 20) = 9.42$, $p = 0.001$, $\eta_p^2 = 0.49$). The WC group exhibited a "slow-fast" acceleration pattern (+0.14 ± 0.17 m/s), while both Chinese groups showed "fast-slow" deceleration (CG-A: -0.08 ± 0.06 m/s; CG-B: -0.12 ± 0.11 m/s) (Figure 2). The WC group achieved significantly higher speeds than both Chinese groups ($p < 0.05$, large effect sizes). Although CG-A achieved higher step speeds than CG-B across the final two steps, the speed variation between the two groups did not differ significantly ($p = 0.49$).

Table 2: Step Length and Horizontal Velocity During the Final Two Steps of the Approach

Group	Step Length (m)			Step Speed (m/s)		
	Penultimate	Final	Difference	Penultimate	Final	Difference
WC	1.97 ± 0.08	1.87 ± 0.09	-0.10 ± 0.10	8.04 ± 0.26^{a,b}	8.18 ± 0.17^{a,b}	+0.14 ± 0.17^{a,b}
				d = 1.82 [0.52, 3.12]	d = 2.45 [0.98, 3.92]	d = 1.12 [0.14, 2.10]

CG-A	1.91 ± 0.12	1.88 ± 0.09	-0.03 ± 0.07	7.90 ± 0.30^b	7.82 ± 0.30^b	-0.08 ± 0.06
				d = 0.46 [-0.48, 1.40]	d = 0.38 [-0.54, 1.30]	d = 0.32 [-0.72, 0.48]
CG-B	1.84 ± 0.14	1.79 ± 0.20	-0.05 ± 0.14	7.60 ± 0.18	7.48 ± 0.16	-0.12 ± 0.11
ANOVA	F = 1.84	F = 1.62	F = 0.42	F = 18.76	F = 22.14	F = 9.42
	p = 0.184	p = 0.221	p = 0.662	p < 0.001	p < 0.001	p = 0.001
	η_p^2= 0.16	η_p^2 = 0.14	η_p^2= 0.04	η_p^2= 0.65	η_p^2= 0.69	η_p^2= 0.49

Note. ^a Significantly different from CG-A (p < 0.05). ^b Significantly different from CG-B (p < 0.05). d = Cohen's d effect size for WC vs. CG-B comparison; 95% CI in brackets.

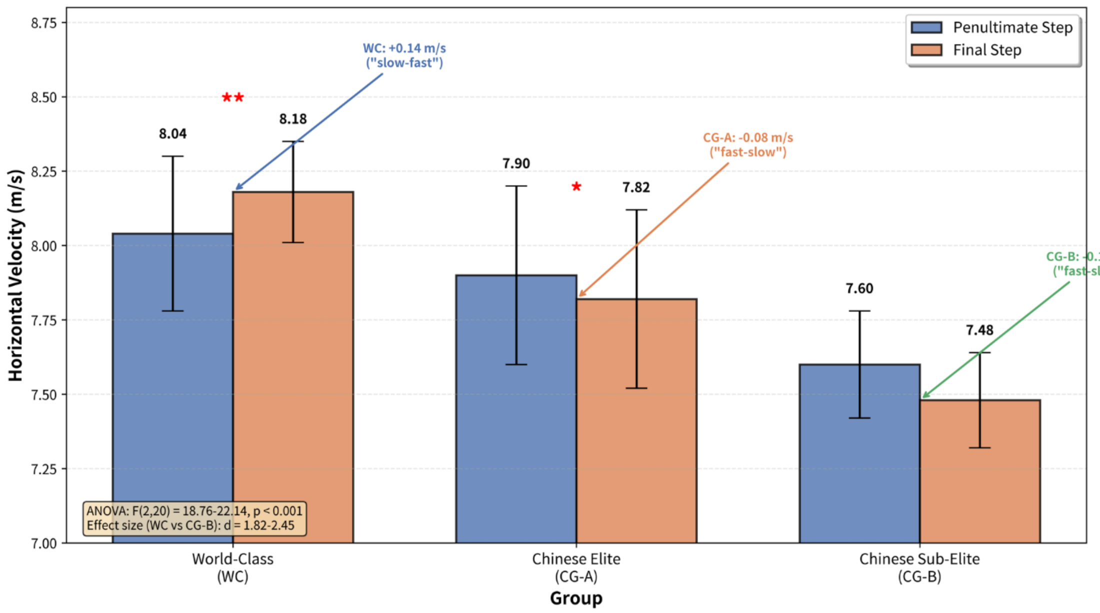

Figure 2: Horizontal velocity profiles during the final two approach steps for World-Class (WC), Chinese Elite (CG-A), and Chinese Sub-Elite (CG-B) female pole vaulters. Error bars represent standard deviations. * Indicates significant difference from CG-B (p < 0.05).

Pole Lowering Kinematics

Pole lowering amplitude and speed data are presented in **Table 3**. No significant group differences were observed for pole lowering amplitude (p > 0.05). However, a significant difference was found for pole lowering speed during the final step ($F(2, 20) = 4.15$, $p = 0.031$, η_p^2= 0.29), with the WC group exhibiting significantly lower speed (44.1 ± 17.4°/s) compared to CG-B (61.7 ± 16.9°/s; p = 0.042, d = 1.03).

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Table 3: Pole Lowering Amplitude and Angular Velocity During the Final Two Steps

Group	**Pole Lowering Amplitude (°)**		**Pole Lowering Speed (°/s)**	
	Penultimate	Final	Penultimate	Final
WC	21.3 ± 3.5	10.3 ± 4.6	87.0 ± 14.0	44.1 ± 17.4^b
				d = 1.03 [0.02, 2.01]
CG-A	22.4 ± 3.4	13.5 ± 3.2	91.2 ± 14.6	61.5 ± 13.6
				d = 0.88 [-0.12, 1.88]
CG-B	24.0 ± 3.6	13.5 ± 4.5	95.3 ± 17.6	61.7 ± 16.9
ANOVA	F = 1.24	F = 1.85	F = 0.68	F = 4.15
	p = 0.310	p = 0.182	p = 0.516	p = 0.031
	$\eta_p^2 = 0.11$	$\eta_p^2 = 0.16$	$\eta_p^2 = 0.06$	$\eta_p^2 = 0.29$

Note. ^b Significantly different from CG-B ($p < 0.05$). d = Cohen's d effect size for WC vs. CG-B comparison; 95% CI in brackets.

Center of Mass Velocity and Take-off Angle

Center of mass velocity components and take-off angle data are presented in **Table 4**. Significant group differences were observed for horizontal velocity (V_x) at both pole-plant ($F(2, 20) = 28.45$, $p < 0.001$, $\eta_p^2 = 0.74$) and take-off ($F(2, 20) = 34.12$, $p < 0.001$, $\eta_p^2 = 0.77$). The WC group maintained higher V_x throughout both phases: at pole-plant, WC's Vx was 0.24 m/s higher than CG-A ($p = 0.08$, not statistically significant) and 0.80 m/s higher than CG-B ($p < 0.05$, d = 2.14); at take-off, WC's Vx was significantly higher (7.02 ± 0.45 m/s), 0.58 m/s greater than CG-A (6.44 ± 0.24 m/s; $p = 0.012$, d = 1.72) and 0.98 m/s greater than CG-B (6.04 ± 0.23 m/s; $p < 0.001$, d = 2.95). No significant differences were found for vertical (V_y) or medio-lateral (V_z) velocity changes ($p > 0.05$).

The WC group demonstrated a significantly lower take-off angle (19.1° ± 1.8°) compared to CG-B (21.3° ± 2.1°; $p = 0.013$, d = 1.42). A significant negative correlation was observed between take-off angle and performance ($r = -0.528$, $p = 0.009$, 95% CI [-0.78, -0.15]) (Figure 3).

Table 4: Center of Mass Velocity Components During the Pole-Plant and Take-off Phases

Group	**Horizontal Velocity, V_x (m/s)**			**Vertical Velocity, V_y (m/s)**			**Medio-lateral Velocity, V_z (m/s)**		
	Pole-plant	Take-off	Loss	Pole-plant	Take-off	Change	Pole-plant	Take-off	Increment
WC	8.33 ± 0.20^b	7.02 ± 0.45^{a,b}	1.30 ± 0.40	-0.12 ± 0.04	0.09 ± 0.12	0.21 ± 0.14	-0.15 ± 0.13	2.41 ± 0.18	2.56 ± 0.17
	d = 2.14	d = 2.95	d = 0.42						

CG-A	8.09 ± 0.22^b	6.44 ± 0.24^b	1.65 ± 0.29	-0.11 ± 0.09	0.06 ± 0.16	0.17 ± 0.21	-0.13 ± 0.10	2.42 ± 0.14	2.55 ± 0.15
	d = 1.58	d = 1.72	d = 0.38						
CG-B	7.53 ± 0.29	6.04 ± 0.23	1.50 ± 0.46	0.00 ± 0.17	0.19 ± 0.14	0.20 ± 0.13	0.05 ± 0.50	2.38 ± 0.22	2.32 ± 0.47
ANOVA	F = 28.45	F = 34.12	F = 2.18	F = 0.24	F = 0.85	F = 0.12	F = 0.11	F = 0.09	F = 0.15
	p < 0.001	p < 0.001	p = 0.138	p = 0.789	p = 0.441	p = 0.888	p = 0.896	p = 0.915	p = 0.862
	η_p^2= 0.74	η_p^2= 0.77	η_p^2 = 0.18	η_p^2= 0.02	η_p^2= 0.08	η_p^2 = 0.01	η_p^2= 0.01	η_p^2= 0.01	η_p^2 = 0.02

Note. ^a Significantly different from CG-A (p < 0.05). ^b Significantly different from CG-B (p < 0.05). d = Cohen's d effect size for WC vs. CG-B comparison.

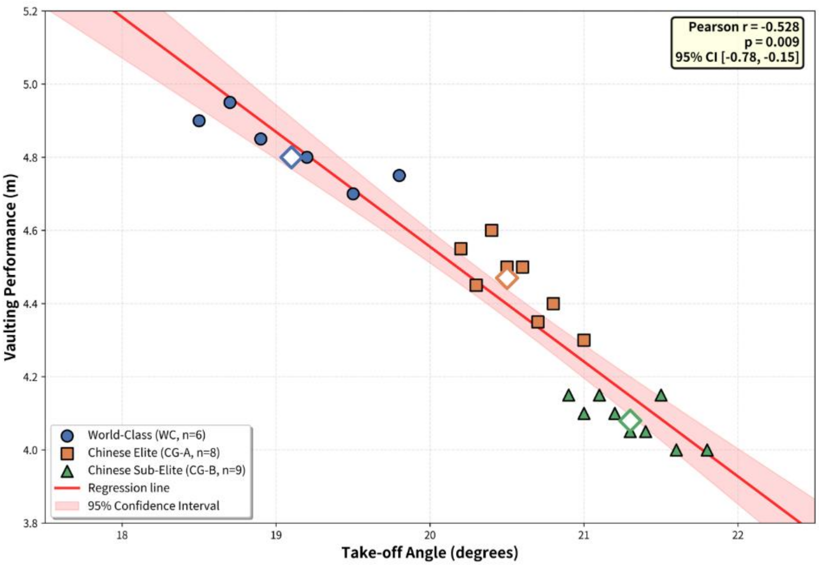

Figure 3: Scatter plot showing the relationship between take-off angle and vaulting performance (height cleared) for all participants (n = 23). The regression line (solid) and 95% confidence intervals (shaded area) are displayed. Pearson correlation coefficient (r) and p-value are shown in the top left corner.

DISCUSSION

The present study identified two primary kinematic determinants that differentiate world-class from sub-elite female pole vaulters: (1) a "slow-fast" acceleration rhythm during the final two approach steps that preserves horizontal velocity, and (2) superior horizontal velocity retention during the pole-plant and take-off phases. These results show that absolute velocities are not the only indication of world-class performance, but rather than that, world class performance is an indication of more efficient energy transfer strategies across the approach-take-off continuum.

Acceleration Rhythm and Velocity Preservation in the Approach

The "slow-fast" acceleration pattern and the "fast-slow" deceleration pattern in the last two approach steps are in line with known sprint mechanics. Elite sprinters have a unique acceleration profile in which they do not sprint too quickly to their maximal velocity, but rather maintain their velocity and apply as much force as possible during the next acceleration phase (Haugen et al., 2019; Samozino et al., 2016; Slawinski et al., 2017). The present study applies these concepts in sprint mechanics to the pole vault approach and demonstrates that the final approach steps are not a sprint speed acceleration phase, but rather a velocity maintenance phase. This interpretation is supported by the correlation of a step speed variation with outcomes. The results showed that the Chinese group reduced their velocity by 0.08–0.12 m/s in final step, whereas the world-class group increased its velocity by 0.14 m/s, indicating their better neuromuscular control and energy management in the critical pre-plant step. The results agree with earlier work identifying the last approach steps as crucial for establishing spatial and temporal conditions for optimal pole-plant mechanics (Loturco et al., 2018; Theodorou et al., 2023). The current study, however, offers novel evidence that the ability to produce a positive acceleration rhythm, rather than relying on absolute step length or speed, is a critical determinant of elite performance in female pole vaulters. The "fast-slow" deceleration pattern seen in sub-elite athletes likely represents a compensatory strategy due to poor approach velocity control, possibly stemming from reaching maximal velocity too early or lacking sufficient technical preparation for the pole plant. This reasoning corroborates previous research demonstrating that velocity loss directly impacts the energy available for pole flexion and vertical clearance (Gross et al., 2020; Jukic et al., 2023; Pareja-Blanco et al., 2020; Yang et al., 2021).

Horizontal Velocity Retention and Energy Transfer Efficiency

The superior energy transfer efficiency from the approach to the pole-athlete system is reflected in the significant differences in horizontal velocity between the world-class athletes and the other groups during the pole-plant and take-off phases (8.33 m/s vs. 7.53 m/s for the pole plant, and 7.02 m/s vs. 6.04 m/s for the take-off). These results are consistent with previous studies identifying approach velocity as the most critical factor determining vaulting performance (Gross et al., 2020; Hanley et al., 2022; Sudlow et al., 2025) but they add an important dimension by quantifying velocity loss during the critical energy transfer phase. The lower horizontal velocity loss of the world-class group (1.30 m/s) compared to the Chinese groups (1.50–1.65 m/s) indicates higher efficiency in transferring kinetic energy into the elastic energy of the pole, with fewer dissipative losses occurring at impact in the Chinese groups. It is consistent with the biomechanical models that flexible pole is an energy storage and release mechanism with the input amount of energy and the speed of input and release strongly influencing its efficiency (Gross et al., 2020; Sudlow et al., 2025). The present findings suggest that world-class athletes are able to reach higher values of energy transfer not only due to their higher approach speeds, but also due to more efficient pole-plant mechanics. This is also backed by the lack of difference between the groups for vertical velocity change; world-class athletes have a performance advantage not only because they are able to produce more vertical velocity but because they have a greater ability to maintain horizontal velocity also. This is contrary to some previous research that indicated that the most significant difference between elite performance and other levels of performance is take-off technique, specifically the vertical impulse (Hanley et al., 2022; Sudlow et al., 2025). This difference could be explained by gender-specific biomechanical patterns since the female pole vaulters may need more time to retain velocity in the horizontal direction because they have less maximal strength capacity than male pole vaulters (Cassirame et al., 2017; Panoutsakopoulos et al., 2021).

Take-off Angle Optimization and Mechanical Efficiency

Take-off angle was lower in the world-class athletes (19.1°) than in the other athletes (21.3°) and was negatively correlated with performance ($r = -0.528$), indicating that better-vaulters are more efficient in energy transfer by optimizing the ratio of horizontal to vertical velocity components. This is consistent with biomechanical data that shows that increases in take-off angle correlate with increases in vertical ground reaction forces but not a corresponding increase in vertical velocity, resulting in greater energy dissipation and increased risk of injury (Edouard et al., 2019). The present results confirm the previous findings that optimum horizontal velocity retention is achieved by lower take-off angles, not only due to different technical styles but due to optimization of mechanical efficiency in the world class group. The world class group had more regular horizontal speeds and lower take-off angles, meaning they had better pole-plant mechanics, which effectively transformed their horizontal momentum to pole flex. The higher take-off angles seen in sub-elite athletes may be a compensatory strategy for the lower approach angles to ensure the bar clearance heights, resulting in a higher vertical impulse to be imparted to the bar. This is not, however, an efficient biomechanical approach, since there is a large negative correlation between take-off angle and performance.

These findings demonstrate that approach velocity training is vital pre-cursor to developing optimal take-off mechanics, not just trying to recalibrate velocity deficits with change in take-off angle.

Practical Implications

From the above results, some suggestions are made for coaches and athletes to optimize pole vault performance. First, training interventions should be directed at the development of "slow-fast" acceleration rhythms in the last approach steps with the intention of holding velocity rather than going too fast. The neuromuscular control and stride regulation exercises performed at the penultimate and final steps may help develop higher quality acceleration patterns. Second, it would be preferable to optimize pole-plant mechanics to obtain high horizontal velocity retention, rather than simply to increase approach velocity. Athletes can use video feedback and biomechanical analysis to recognize and correct any technical faults that will result in excessive velocity loss during pole plant. Thirdly, it is important to optimize take-off angle through approach velocity and pole-plant mechanics, rather than by directly changing take-off technique. Interventions targeting approach velocity development and pole-plant timing could be particularly beneficial for athletes with excessive take-off angles.

Limitations and Future Directions

The present study has some limitations. The field-based video analysis methodology offers a high level of ecological validity over laboratory-based methods, but it has inherent limitations regarding spatial resolution and marker-less tracking accuracy. Although the RMS (root mean square) error of the three-dimensional reconstruction was kept below 8.5 mm, which is satisfactory for large-scale movements, future studies should employ marker-based motion capture systems to confirm the present results with greater precision. Second, the relatively small number of world-class athletes ($n = 6$) is representative of the global elite population but lacks sufficient statistical power for broad generalizability. To address this limitation, the present study followed guidelines for small-sample biomechanical studies by thoroughly reporting effect sizes and performing confidence interval estimation (Hecksteden et al., 2022; Li et al., 2024; Panoutsakopoulos et al., 2021). Future research should aim to reproduce these findings with larger cohorts of elite athletes, potentially through multi-center international collaborations. Third, the cross-sectional design of the present study does not allow for causal inferences regarding the relationship between kinematic and performance variables. Longitudinal studies tracking technical development over time, or intervention studies manipulating specific kinematic parameters, would provide more convincing evidence of the causal influence of the identified determinants. For future work, the authors suggest incorporating kinetic analyses, such as measuring ground reaction forces and calculating joint moments, to gain a more comprehensive understanding of the mechanical factors influencing elite pole vaulting.

CONCLUSION

Two main biomechanical criteria were found to distinguish world-class from sub-elite female pole vaulters: a "slow-fast" approach step acceleration rhythm, and higher horizontal velocity retention during the pole-plant and take-off phases. The results indicate that elite performance is driven by strategies of efficient energy transfer, rather than merely higher absolute velocities or altered take-off angles. The practical applications of these findings are clear: coaches and athletes should prioritize the development of velocity preservation strategies during the final approach steps, optimize pole-plant mechanics to minimize horizontal velocity loss, and refine the timing of the pole plant to ensure rapid and efficient energy transfer. Technical interventions aimed at improving acceleration rhythm and pole-plant efficiency should focus on achieving optimal take-off mechanics, rather than attempting to compensate for velocity deficits by altering take-off angles or prolonging force application times.

Take-home message: World-class female pole-vaulting performance is distinguished not by how fast athletes run, but by how efficiently they preserve and transfer that speed through precisely coordinated approach-take-off mechanics.

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Author Contributions

Author contributions: Md. Zillur Rahman: Data Curation, Formal Analysis, Writing Main Draft, Review and Editing. Md. Eman Ali: Data Curation, Validation, Review and Editing. Md. Zafiroul Islam: Visualization, Resources, Validation, Writing

Main Draft, Review and Editing. Rezwan Hossain: Conceptualization, Methodology, Data Curation, Formal Analysis, Supervision, Visualization, Validation, Writing Main Draft, Review and Editing.

Conflicts of Interest

Authors declare no conflicts of interest.

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Data Availability

Data supporting the approach-phase, velocity, and take-off angle analyses reported in this manuscript are available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used AI editing services in order to improve language structure and text conciseness. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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