Review Article

Movement Science Analysis of Pole Vault Performance: A Systematic Review of Run-Up and Airborne Phases

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ABSTRACT

The systematic review is anticipated to significantly advance scientific knowledge of pole vault complexities through its comprehensive scope and detailed examination of the approach and aerial phases. Pole vaulting, as a technically demanding athletic discipline, serves as the central focus of this systematic investigation aimed at enhancing understanding of pole-vaulting biomechanics and performance dynamics. Through systematic review methodology, multiple biomechanical, kinetic, and kinematic factors have been identified as crucial determinants of athletic performance in pole vaulting, with landing technique representing a critical biomechanical element designed to minimize post-vault impact stress through precise body positioning, optimal joint angles, and coordinated muscle activation patterns. Our systematic review employed a comprehensive search strategy across multiple databases including PubMed, Scopus, Google Scholar, Medline, and Web of Science using varied search terminology, with inclusion criteria encompassing English-language publications from the past decade involving human subjects while excluding non-English publications and studies without human participants. Quality assessment adhered to PRISMA guidelines and incorporated bias risk evaluation to maintain internal validity through stringent selection criteria and dual evaluation processes ensuring methodological rigor. The selected studies collectively provide comprehensive insights into pole vaulting performance, examining kinetic and kinematic variables across diverse athlete populations, with take-off velocity emerging as a significant performance factor highlighted by multiple studies examining variations in touchdown speed and horizontal hand-foot distance relationships, while research additionally demonstrates a positive correlation between maximum pole flexion and achieved jump height.

Keywords: *Biomechanics, Kinetic, Kinematic, Run-Up, Takeoff.*

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INTRODUCTION

Pole vaulting represents one of the most technically sophisticated athletic disciplines, requiring athletes to efficiently convert horizontal momentum into vertical displacement during the approach phase to successfully clear the crossbar.[1] This approach velocity is fundamental as it generates the kinetic energy necessary for barrier clearance and rapid execution. Contemporary research demonstrates that approach technique is paramount in pole vaulting and directly correlates with enhanced jump performance.[2] Athletes and coaches must concentrate on numerous biomechanical elements, including kinetic and kinematic variables, to optimize performance throughout the run-up and flight phases.[3] Previous literature emphasizes the critical importance of approach velocity, indicating that each 1 m/s velocity increase corresponds to a 0.5 m height gain for males and 0.6 m for females.[4]

Multiple studies have validated this relationship by demonstrating strong linear correlations (r-values ranging from 0.69–0.86) between approach phase velocity and vault height.[5] Take-off speed significantly influences vault height performance, accounting for 74% of variance in male athletes and 58% in female competitors.[6] The International Association of Athletics Federations (IAAF) emphasizes pole vaulting's biomechanical complexity, highlighting how specific markers contribute to a vaulter's maximum height potential.[6]

Researchers typically measure approach velocity during the final approach phase, particularly within the last three steps of the transition period.[6] Biomechanical investigations reveal that athletes distribute energy across various phases, including acceleration during take-off and implementing subtle adjustments throughout the approach to achieve optimal positioning.[7] These velocity modifications and movement adaptations depend on specific technical cues, which serve as critical indicators for various biomechanical factors and responses that determine successful or failed attempts. Research has identified additional movement patterns of interest in previous investigations.[8] However, the specific factors contributing most significantly to performance remain unclear. While functional flexibility provides benefits, technical execution changes appear more influential. Documentation shows that pole vaulters exhibit variable gait control patterns, with improvement occurring more frequently following unsuccessful attempts rather than successful ones, emphasizing the importance of error identification and gait modulation refinement.[9]

This systematic review aims to provide comprehensive understanding of biomechanically critical elements while emphasizing fundamental performance components. Such analysis will serve as a foundational resource for enhancing training methodologies and improving overall athletic performance in pole vaulting by systematically addressing existing research gaps. Beyond synthesizing current knowledge, this systematic review will establish clear directions for future investigations. Furthermore, this comprehensive analysis will make significant contributions through rigorous examination, enabling readers to better comprehend the sport's technical complexities and advance performance to new levels.

METHODOLOGY

Search Strategy

Intensive search techniques has been used in order to find studies using keywords from data bases including PubMed, Scopus, Google Scholar, Medline and Web of Science. The search phrases used were “pole vault”, “biomechanics”, “kinetics”, and “kinematics”. AND or OR were the Boolean operators used. Synonyms and similar phases were also included. Language included was English and subjects were included as “Human” with the filter of year “10 years”. Studies included were based on assessment of biomechanical, kinetic, and kinematic characteristics in the pole vaulting setting was one of the inclusion criteria.

Inclusion and Exclusion Criteria

Human subjects were included, studies written in English were included only, published within the previous 10 years. Researches based on Kinetic, Kinematic and Biomechanics were the part from data bases; PubMed, Scopus, Google Scholar, Medline, and Web of Science.

Exclusion criteria included all studies not following the time limits, any articles published in language other than English and any subjects other human. Furthermore, all researches those didn’t include kinematic, kinetic, or biomechanical aspects unique to pole vaulting were also disqualified. Rigorous selection was the guarantee the specific factors.

Data Extraction

Data extraction was done using organized method in a standardized form pattern that created methodologically to collect the information. Data extraction was carried out using two reviewers, third reviewer was present to solve any queries present. Information included research features, participant demographics, methods, and quantitative results pertaining to pole vaulting biomechanics. Consistency, precision, and thoroughness was maintained through rigorous methods.

Quality Assessment

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) criteria had been used in order to assess the quality of the papers that were considered eligible. Evaluation was through risk of bias to ensure the internal validity. PRISMA considers the research design, participant selection, data collecting, and statistical analysis. Potential source of bias was evaluated through risk of bias.

RESULTS

The critical determinants affecting the athletic performances are based on numerous biomechanical, kinetic, and kinematic aspects. In order to reduce the stress on athlete body, landing technique is important. Which also includes exact body alignment, joint angles, and muscle activation. Also, the impact of bending and flexibility of the pool also impact strategically in biomechanical factors. Among kinetic factor takeoff velocity is a key component that is known to be correlated with increased jump height. To address kinematic factors in the systematic review, the run-up approach was thoroughly examined. This includes an evaluation of the athlete's overall performance, step length, and frequency, all of which affect athlete's efficiency to reach the target. Effective run-up kinematics are seen as essential components that provide the framework for an effective pole vault performance.

Initially, 1058 articles were obtained from five databases, with deduplication resulting in 870 unique articles. Further, 789 items were excluded due to title filtering, reducing the selection to 81. Another 47 publications were rejected after a thorough review of their abstracts. The remaining 34 publications were subjected to full-text analysis, which resulted in the elimination of 26 more. As a result, 12 articles met the inclusion requirements. These researches contribute to a better knowledge of the biomechanical, kinetic, and kinematic factors that influence pole vault performance, with a focus on the run-up and flight. It is noteworthy that 8 articles stand out as being very relevant to the subject at hand following this exhaustive evaluation procedure. The following 8 studies offer insightful analyses of the biomechanical nuances of pole vaulting, illuminating the complex interactions between variables that impact performance during the run-up and flight phases (Figure-1).

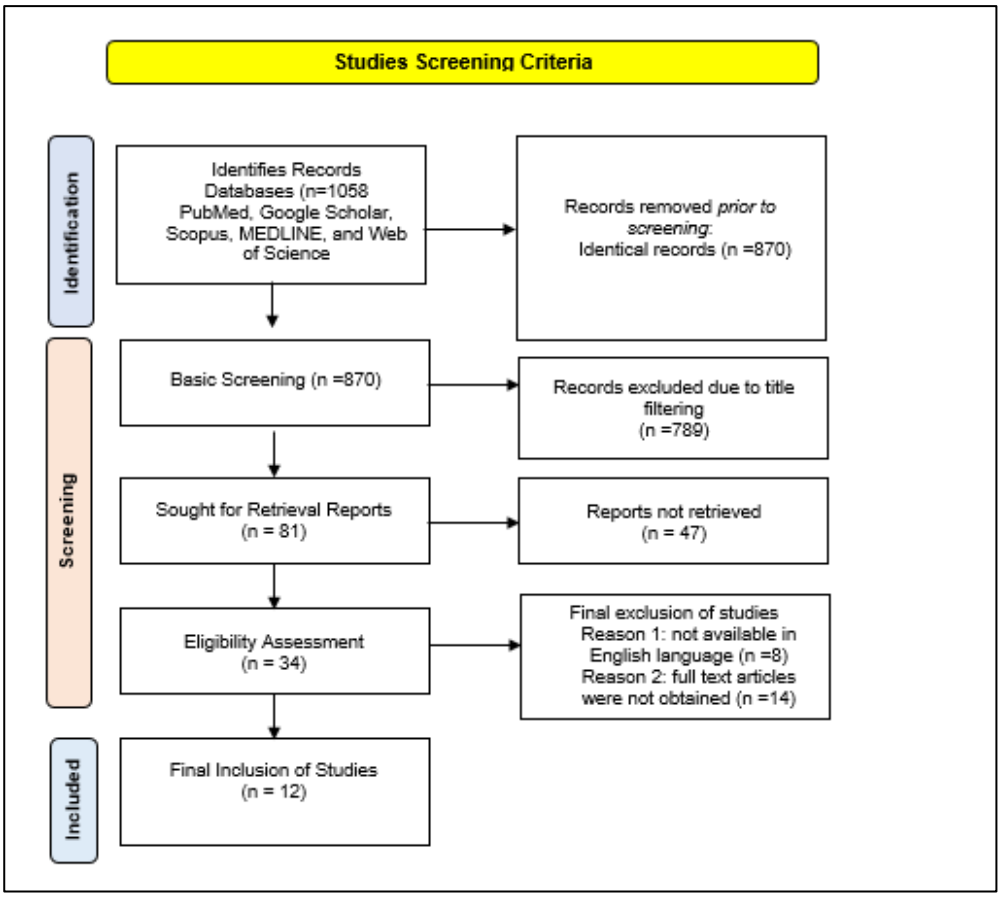

Figure-1 PRISMA Flow Chart of Studies Inclusion

Characteristics of Included Studies

The characteristic of studies included in the paper was depicted in Table-1 that suggested the impact of kinetic and kinematic variables on pole vaulter performance. The effects of various kinetic and kinematic variables like velocity, stride length, frequency, maximum height, horizontal distance covered etc. on pole vault performance were analyzed in depth and summarily provided in the below given Table-1.

Table 1. Characteristic of Included Study

Author/Year of Publication	Target population	Factors Analyzed	Outcome Measures	Findings
Theodorou et al., 2023[9]	Elite pole vaulters	Kinematic parameters	Step length, frequency, average velocity, inter-limb asymmetry	No significant differences was reported ($p>0.05$) in step length and step velocity between successful and failed attempts. For unsuccessful tripping footsteps more frequently were recorded ($p<0.05$) rather than the pole-carrying leg in successful trials. In sagittal plane there were not any statistically significant differences ($p>0.05$) between the asymmetry values for step length, frequency and average velocity for successful and unsuccessful attempts.
Enoki et al., 2023[10]	Male pole vaulters	Kinematic parameters	Center of gravity and height, approach velocity, takeoff, distance, push height and maximum vertical velocity	Grip height showed the strongest link, followed by push height and takeoff velocity. It is recommended that pole vaulters aim for higher approach and grasp velocities since these greatly increased their mechanical energy.
Hanley et al., 2022[11]	Men and women pole vaulters from IAAF world indoor championship	Kinematic of final approach	Running speed, step length, time and take-off angle	‘ Men showed faster run-ups, higher hand grip positions, and enhanced take-off velocities in order to reach greater clearance heights (all $p<0.001$). In absolute terms, males took longer steps (all $p<0.001$) in the last three steps, however there were no differences in terms of height. Interestingly, no differences were found in take-off angles, step times, run-up pole angles, take-off contact times, or the duration from pole plant to take-off. On the other hand, women differed in how they approached and took off depending on their size and strength; for example, they took fewer run-up steps, shorter takeoff lengths, and lower grasp heights. The adoption of a lighter, shorter pole was blamed for these lower grips, and the drawback exceeded the effect of slower run-up speeds.
Yang et al., 2021[12]	Male pole vaulters	Kinetic parameters	Sprint running velocity and speed, pole running speed, pole vault approach speed and maximum average velocity	The investigation found a statistically significant positive relationship between the maximum pole running (PR) segment speed and both PV performance and the last 5 meters approach of PV (PVA). Moreover, the correlation between the PVA velocity utilization rate and the relation between the distance to the PR's peak speed and the distance traveled during the PVA proved to be negative and significant.

Outinen et al., 2021[13]	Male and female pole vaulter from Birmingham World Indoor Championship	Kinetic and kinematic characteristic	Run-up and take off	The two factors that showed the biggest favorable impacts in the general regression model (R^2=0.639) were maintaining horizontal velocity during takeoff (b = 0.728) and using a takeoff strategy that favors early plant (b = 0.662). The general model's coefficients were shared by the men's models (R^2 = 0.752), although they gave more weight to a comparable takeoff maneuver (b = 0.834) than to velocity preservation (b = 0.799). On the other hand, step length (b = -1.673) and step rate (b = -1.280) were shown to have the most significant negative impacts of running variables in women, according to the model (R^2 = 0.984)
Kageyuki et al., 2020[14]	Japanese male vaulters from the intercollegiate entry level to the top international level	Kinetic parameters	Epole at maximal pole bending (MPB), maximal height of vaulter's center of gravity, maximal bending rate and amount of pole bending, translational energy and angular momentum	At maximal pole bending, Epole was shown to be a more significant factor than the maximum bending rate and the maximum pole bending as their values were (r=0.94; r=0.86; r=087, respectively). Moreover, there was a drop in translational energy, an increase in potential energy at the moment of the pole bending phase, a greater moment of inertia around the CG, and a contact grip at the very instant the negative peak angular momentum around the CG occurred identified themselves as the significant contributors to higher Epole at the instants of the MPB.
Gross et al., 2020[15]	International female pole vaulters	Kinetic and kinematic variables	Approach speed, height, explosive strength	Reduced stride length, as opposed to a drop in step frequency, is the main cause of the speed differences between the vault approach and flying sprint.
Pavlović[1] et al., 2019[16]	Finalists of Pole Vault World Championship	Kinematics and biomechanical parameters	Total run-up distance, number of steps, average step length, VA (m/s), AP (m)	Statistically significant discrepancies of the critical kinematic markers with reference to the men and the women pole finalists. The below mentioned factors showing differences in total distance, number of steps, average step length, vertical acceleration (VA), horizontal acceleration (AP) and average last step length, had a pronounced violations between genders. More importantly, Ratios% seemed to show no statistical differences between them.
Cassirame et al., 2019[17]	Pole vaulters from six different categories: cadet men and women; junior men and women and elite men and women	Kinetic and kinematic parameters of run up and Flight	Run-up speed, soot distance, number of successful and un-successful jump (height clearance)	When comparing successful and unsuccessful pole vaulting performances, there was a statistically significant but little variation in the final touchdown's speed. More specifically, successful leaps were seen to have a higher takeoff speed (+0.15 m/s). Furthermore, a noteworthy marginal distinction was seen in the horizontal hand-foot distance between female athletes during successful and failed leaps; the former showed gains of +0.05 m and +0.06 m during pole plant and take-off, respectively.
Gudelj et al., 2019[18]	Single athlete (Case Study)	Kinematic parameters	Stride Length, Horizontal Distance, Maximum Pole Bend (%), Maximum Height	The finding revealed that of all the kinematic variable and jump height by pole vaulter maximum pole bending is the

				only parameter that reflected strong positive correlation R^2=0.98 (p=0.05).
Cortes et al., 2016[19]	Trainee Pole Vaulters from Portugal	Kinetic and Kinematic Variables	Frequency and velocity of last four stride	The study looked at the amplitude and frequency of pole vaulters' best leaps in the last four strides. The findings showed that, in comparison to world-class pole-vaulters competing in the Olympic Games in Seoul, Portuguese elite athletes had slower pre-jump velocities. The study showed differences in each athlete's average and standard deviation by taking into account the amplitude (A) and frequency (Fr) in the final four strides. Kinetic energy and angular kinematic parameters were also examined. Compared to top athletes, Portuguese athletes notably had more variability and lower kinetic energy levels during take-off.

Risk of Bias Assessment

The analyses of risk of bias was performed on the guidelines of Cochrane risk of bias assessment tool. The parameters that were used for assessment includes:

Random Sequence Generation

The random sequence generation suggested that all eight studies had low risk of bias.

Allocation Concealment

As kinetic and kinematic parameters were determined on pole vault performance no study suggested any risk of allocation concealment.

Outcome Assessment Blinding

As per author's judgment all included studies had maintained outcome assessment blinding.

Reporting Selection Bias

Reporting Selection bias were also at low in all included studies.

The result of qualitative analyses of the study as per author's judgment were provided in Table-2.

Study Findings

Together, the included studies offer thorough insights into a variety of pole vaulting-related topics, including kinetic and kinematic characteristics and variables affecting performance across diverse athlete types. Cassirame et al.[17] discussed the relevenacy of take-off phase and found somewhat variability in both horizontal and vertical speed. In another case study Gudelj et al.[18] discussed a single athlete imposing a positive association between both the jump and pole bending. The between symmetry and gender variations in the step length and velocity also during the final 8 steps were noted by Panoutsakopoulos et al.[20] Outinen et al.[13] outlining gender specific findings, targeted the need of using maximum horizontal velocity and an early plant strategy in a regression model. According to Gross et al. the speed discrepancy in vault approach and flying sprinting are mostly caused by shorter taken strides rather than fewer steps taken. The visibility of the grip height, push height, and takeoff velocity in augmenting mechanical energy was emphasized by Enoki et al.[10] Cortes et al.[19] also found that the elite trainers of Portuguese showed very slow pre-jump velocities had slower pre-jump velocities than Olympic participants. Hanley et al. also look into the gender specific data, describing the impact of variables such as grip height and pole choice. Kageyuki et al.[14] acknowledge Epole as a difficult factor at maximum pole bending, such other factors such as translational energy, potential energy, moment of inertia, and contact grip, which, if increased, can cause higher Epole. Distinctive results had been detected by Pavlović et al.[15] in the purpose of some kinematic markers between men and women pole vault finalists, including total distance, number of steps, average step length, vertical acceleration, horizontal acceleration, and average last step length, while the ratio values showed no statistical differences between genders. Yang et al. also found that increased running pole speed positively correlated with pole vault performance and a strong inter-correlation between the utilization of different

velocities and distance travelled in the approach phase. Finally, Theodorou et al.[9] visualized that the step length and velocity did not differ significantly in successful and failed trials. However, the frequency of the tripping footstep was more frequent than the pole-carrying leg in successful trials, while the asymmetry values in the sagittal plane did not show significant statistical differences between successful and unsuccessful tackles.

Table-2 Cochrane Collaboration's Tool for Assessing Risk of Bias of Included Studies

Studies	"Random Sequence Generation"	"Allocation Concealment"	"Outcome Assessment Blinding"	"Selective Reporting"
Theodorou et al., 2023	+	+	+	+
Enoki et al., 2023	+	+	+	+
Hanley et al., 2022	+	+	+	+
Yang et al., 2021	+	+	+	+
Outinen et al., 2021	+	+	+	+
Kageyuki et al., 2020	+	+	+	+
Gross et al., 2020	+	+	+	+
Pavlović[1] et al., 2019	+	+	+	+
Cassirame et al., 2019	+	+	+	+
Gudelj et al., 2019	+	+	+	+

−, bias at high risk
+, bias at low risk
? , unknown risk of bias

DISCUSSION

The pole vault, a complex track and field event, necessitates a distinct set of abilities that combines aspects of sprinting, jumping, and gymnastics. The constant quest of world records in this difficult discipline has fueled ongoing study, mainly on the biomechanics of the pole vault. Scholars have studied the kinematics, kinetics, and energy components of top-tier pole vault performances to better understand the complexities underlying top-tier pole vault achievements. Kinematics research has highlighted broad biomechanical aspects, examined the symmetry of the left and right legs throughout the run-up, and investigated the subtle control mechanisms used during this phase. On the kinetic front, studies include ground reaction forces, joint torques for pole vaulters, the angular momentum of the vaulter, and athlete forces and torques applied to the pole during the vaulting maneuver. Apart from these well-established domains of investigation, a methodical examination of the run-up and flight phases surfaces as a crucial emphasis for comprehending the biomechanical complexities that regulate pole vault performance.

According to a 2019 research by Cassirame et al.[17] that examined 207 pairs of leaps at the same height in an effort to identify biomechanical differences between successful and failed pole vault jumps during competition. Athletes in three age groups, both male and female, with bar clearances ranging from 2.81 to 5.91 metres were included in the study. The Optojump Next system and Stalker Pro II radar gun were used for run-up parameter acquisition. A 2D kinematic study produced a set of take-off parameters, most of which were negligible and inconsequential. The speed at the last touchdown showed a statistically significant modest difference, with successful jumpers having a greater take-off speed (+0.15 m/s) than unsuccessful counterparts. In calculation, female athletic personnel also showed a striking difference in the horizontal hand-foot distance during successful leaps; during pole plant and take-off, they registered enhancements of +0.05 m and +0.06 m, respectively. These findings encompasses the presence of preserving faster run-up velocities and preventing speed reduction prior to takeoff. According to the study, just a few minor changes in posture will improve an athlete's overall performance by adding or transferring the energy to important muscles thus helping in clearing heights. Numerous other investigations on the biomechanics of pole vaulting have also showed significant knowledge regarding the variables impacting performance. Maximum pole bending has a crucial effect, as Gudelj et al.[18] noted, showing a substantial positive association with jump height. The effectiveness of carrying the pole on performance was underscored by Panoutsakopoulos et al.[20] inquired of inter-limb asymmetry and gender variations in stride length and average step velocity. As previously mentioned, This importance of maintaining horizontal velocity during takeoff and implementing an early plant approach was noted by Outinen et al.[13]. According to Gross et al.[16] the main reason of such speed variations in the vault approach was shorter strides rather than fewer steps. In order to maximize mechanical energy, Enoki et al.[10] made a suggestion that greater approach and grab velocities, with grip height demonstrating a strong correlation. Finally, Hanley et al.[11] noted that approach and takeoff techniques varied according to gender, with male gender exerting quicker run-ups and greater takeoff velocities and women adjusting according to size and strength, which had been impacted by things like pole length.

Still, the data on spot light provides a detailed synopsis of diverse research on pole vault biomechanics, it is crucial to recognize possible constraints in this systematic review. First off, the majority of the research papers are now in the debate which may have minimize the range of viewpoints on the biomechanics of pole vaulting. The neglection of more word to word reviews or meta-analyses might lead to an insufficient synthesis of the body of research. Furthermore, the studies that have been mentioned are from a variety of years, and changes in technology and methodology throughout time may bring about differences in the way data is gathered and analyzed. Furthermore, because the synthesis focuses mostly on kinematic and kinetic elements, it's possible that connections with physiological or psychological elements that affect pole vault performance haven't been thoroughly checked. The review's scope might be loop on the broader aspect to provide a more thorough grasp of the biomechanical problems controlling pole vaulting by taking into account a more holistic integration of varied research methodologies. By incorporating recent research, Yang et al.[12] highlighted the fact that maximum interval velocity in pole running is a crucial factor to be assessed in determining a potential pole vaulter's worth, advocating for the improvement of maximum velocities in sprint running, pole running, and in the final part of the approach phase of pole vault. More importantly, Kageyuki et al.[14] indicated that the strain elastic energy effectively evaluated the ability to bend the pole and knew that technique improvements during the pole drop phase and pole planting were highly recommended to show your velocity potentials fully and finally improve competition performance. Pavlović et al.[15] understood significant kinematic parameter differences between male and female pole vault finalists. These findings illustrate the multi-sided nature of success in pole vault jumping that is determined by various components such as the morphological parameters of the athletes, specific motor abilities, the specific characteristics of the pole, the technique the athletes use, and biomechanics. Theodorou et

al.[9] also picturize the biomechanical factors of pole vaulting: the symbiosis between the step and their effects on jump results. It is revealed that while speed is crucial, it alone is not the sole consideration for a high jump win. The research shows the importance of stability in the relationship between the athlete and the pole when jumping, which concerns stable dropping, and the last phase is approach training. Besides, this study is one the investigations that focuses on the domain of other persons variations in step parameters, including various leg moments of inertia and explosive strength, to add more knowledge on their role in the process. Therefore, incorporating that data into training routines can help pole vaulters bring out the best in their competitive performances.

CONCLUSION

In the short end, the combined knowledge from the examined research offers a thorough catch of the biomechanical complexity factors affecting pole vault performance in a range of athletic profiles. The factors that have been stressed, which include gender-specific nuances as well as kinematic and kinetic aspects, provide significant information to the subject. The investigations, in particular, highlight the significance of variables like takeoff speed, maximal pole bending, and the complex interaction between stride length and frequency. The effects of grip height, push height, and takeoff velocity on mechanical energy that have been identified highlight important factors that athletes should take into account in order to maximize their performance. The results also emphasize the need of applying tactical techniques, such early plant maneuvers, and sustaining horizontal velocity during takeoff. Although these discoveries contribute to our growing knowledge of pole vault biomechanics, more research is needed to fully understand the interactions between different biomechanical components and the manner in which they interact with physiological and psychological factors. Only then will we be able to offer a more comprehensive approach to improving pole vaulting skills.

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None.

Author Contributions

Amanullah Khan contributed to the study design, methodology development, and initial drafting of the manuscript. **Dua Fatima Sajid** assisted in data collection, literature review, and preparation of the results**. Farhan Waqar Khan** contributed to data analysis, interpretation of findings, and critical revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

Ethical Approval

Not applicable

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None.

Conflict of Interests

None.

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