GENDER-SPECIFIC PREDICTORS OF VAULT PERFORMANCE IN GYMNASTICS: A MACHINE LEARNING APPROACH

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Original article *DOI: 10.52165/sgj.17.2.243-258*

Abstract

This study investigated gender-specific predictors of vault performance in gymnastics by applying machine learning techniques to analyse body composition and run-up dynamics. Data were collected from 27 national-level gymnasts (17 female, 10 male) during the Slovenian Cup competition. The focus on gender-specific predictors stems from fundamental physiological and biomechanical differences between male and female athletes, which influence force production, movement kinematics, and execution mechanics. A deeper understanding of these distinctions enhances the precision of performance modelling and supports the development of targeted, evidence-based training interventions.

Spatiotemporal parameters of the run-up were recorded using the OptoGait system, while body composition was assessed with the Tanita DC-360. Principal Component Analysis (PCA) and Boosting regression models were used to identify key predictors of vault execution scores. These methods were selected for their ability to reduce dimensionality and capture complex, nonlinear relationships in performance data. The results revealed clear gender-specific patterns. For female gymnasts, the model explained 74.4% of the variance in execution scores, with Overall Lean Body Mass emerging as the most influential predictor (47.12% relative influence), followed by Overall Contact Phases (25.28%). For male gymnasts, the model demonstrated exceptionally high predictive power, explaining 97.8% of the variance, with Body Fat as the primary predictor (48.44% relative influence), followed by Flight and Contact Dynamics (35.22%). These findings suggest that training strategies should be tailored to gender-specific needs. For women, emphasis on lean muscle development, stride optimisation, and the coordination of rhythm and timing may be beneficial. For men, managing body fat levels, optimising flight and contact dynamics, and adopting an integrated approach to stride mechanics appear essential. Given the potential for misinterpretation of body composition metrics, a holistic approach to athletic conditioning is recommended. However, the study's limitations, including the small sample size and cross-sectional design-warrant cautious interpretation. This research provides a foundation for future investigations into gender-specific factors affecting vault performance. Larger and longitudinal studies are needed to validate these findings and support the development of more precise training interventions.

Keywords: run-up characteristics, body composition, execution score, principal component analysis.

INTRODUCTION

Vaulting performance in gymnastics is influenced by multiple factors, particularly run-up characteristics and body composition. While previous studies have laid a foundation for understanding these influences, gaps remain in fully identifying the specific variables that significantly impact vault execution.

Sands and McNeal (1995) demonstrated that faster run-up speeds are associated with longer flight durations and higher vault scores, indicating that speed training can enhance performance. This finding was reinforced by Bradshaw and Sparrow (2001) and Bradshaw (2004), who emphasised the importance of higher approach velocities, optimal step length regulation, and well-coordinated, high-speed run-ups for successful vault execution.

Building on these insights, Atiković and colleagues (2011, 2012) developed regression models to predict vault performance based on biomechanical variables such as force, angle, and velocity. Their models revealed significant relationships between these parameters and vault difficulty values, offering a foundation for the biomechanical optimisation of vault performance.

A consistent body of research has confirmed that higher run-up velocities are linked to improved outcomes. Studies by Krug et al. (1998), Čuk et al. (2007), and more recent work by Fernandes et al. (2016), Fujihara et al. (2017), Milčić et al. (2019), Naundorf et al. (2008), Tang et al. (2019), Wang et al. (2010), and Zhao et al. (2022) documented significant increases in run-up speeds over time, correlating with enhanced vault performance. Furthermore, Velickovic et al. (2011) and Bayraktar et al. (2021) highlighted the importance of run-up characteristics, age, and technical proficiency in distinguishing performance levels.

More recently, studies by Yingjun et al. (2023) and Tan et al. (2023) have underscored the critical role of run-up velocity and pedalling power in vault performance, emphasising the significance of these physical attributes in executing complex vaults. In addition, Dallas and Theodorou (2020) demonstrated that targeted hurdle placement can significantly improve approach velocity and technique, supporting the implementation of specific training aids to enhance vault execution.

The importance of reliable measurement techniques in vault training has been emphasised by Bradshaw et al. (2010), who investigated the reliability and day-to-day variability of vault training metrics. Their findings indicated that approach velocity and board contact time are reliable indicators for tracking training progress and performance improvements, offering valuable tools for coaches and researchers when designing effective training programmes.

While existing research has identified several isolated factors influencing vault performance, a more holistic approach is necessary to construct a robust predictive framework. Such an approach would enable a deeper understanding of how stride characteristics and individual attributes interact to influence vault outcomes. In this context, stride length and cadence are particularly important in gymnastics for establishing rhythm and timing during the run-up. An optimal stride length facilitates momentum generation for a powerful take-off, while cadence ensures consistent pacing, contributing to fluid transitions. Contact time is equally critical, as shorter durations support quicker, more controlled movements, promoting efficient power application. Flight time also plays a pivotal role, as it directly affects height and control, which are essential for technical precision during vault execution. Collectively, these variables may significantly impact a gymnast's ability to perform complex vaults with greater speed, power, control, and accuracy.

In addition, monitoring body composition can help identify areas for improvement and ensure that gymnasts maintain a physique aligned with the sport's physical demands. Such metrics are key to understanding an athlete's capabilities and tailoring training interventions aimed at enhancing strength, agility, and overall vault performance.

Progress toward this integrated analysis has been made by Velickovic et al. (2011), who employed the OptoTrack (Microgate) system to measure the speed of the final 10 steps in the vault run-up. Their study revealed significant differences in velocity progression between top- and middle-class gymnasts, although it focused exclusively on speed, leaving other key variables unexamined. Expanding on this, Schärer et al. (2019) used the Optojump (Microgate) system to assess a broader range of factors, including maximal run-up speed, step frequency, step length, and ground contact time during the final four steps of the approach. They also incorporated basic body composition metrics such as height and weight. Despite these advancements, a comprehensive analysis that includes stride length, contact and swing time, cadence, and other run-up phase indicators remains necessary to fully leverage the predictive potential of these parameters in vault performance optimisation.

This study builds on previous research by incorporating additional variables and extending the analysis over a longer segment of the run-up, thereby offering a more comprehensive evaluation of the interactions between running characteristics and body composition in relation to vault performance. This expanded approach aims to inform the development of targeted training programmes that optimise run-up speed and contribute to improved vault execution. By addressing existing gaps in the literature, this study provides researchers and coaches with a more nuanced understanding of the key factors influencing vault performance. Ultimately, this may lead to the design of evidence-based interventions that enhance gymnasts' vaulting capabilities.

The primary aim of this study is to comprehensively analyse the interplay between run-up dynamics and body composition in gymnastics vault performance, with the objective of identifying gender-specific predictors that can guide the development of tailored training strategies.

METHODS

The study analysed data from 27 national-level gymnasts, comprising 17 female and 10 male athletes. The female gymnasts had a mean age of 16.79 ± 2.09 years (range: 13–21 years), with a mean height of 160.54 ± 6.57 cm and a mean weight of 54.99 ± 5.07 kg. The male gymnasts had a mean age of 16.00 ± 3.89 years (range: 10–22 years), with a mean height of 162.94 ± 12.05 cm and a mean weight of 55.71 ± 14.84 kg. Training volume was systematically recorded, with females training an average of 18.3 ± 3.5 hours per week and males 19.1 ± 4.1 hours per week. The aim and procedures of the study were clearly explained to the gymnasts and their coaches, all of whom provided informed consent to participate. The study was approved by the Ethics Committee of the University of Niš, Faculty of Sport and Physical Education (Project number: 04-779/2).

The research was conducted during the Slovenian Cup competition in May 2024, with approval from the Slovenian Gymnastics Federation. Execution scores (E scores) and difficulty scores (D scores) were recorded for all vaults performed, along with detailed measurements of running characteristics. Only E scores were used in the present analysis. When a gymnast performed two vaults, both were included, resulting in a total of 41 vaults.

Spatiotemporal parameters of the run-up were recorded using the OptoGait photoelectric cell system (Microgate, Bolzano, Italy), a reliable and valid tool for measuring spatiotemporal gait characteristics during running (García-Pinillos et al., 2022). The system operated at a sampling frequency of 1000 Hz over a 17-meter distance (Figure 1). The analysis focused on the last 10 steps of the approach, targeting variables that play a direct role in determining the efficiency of the vault run-up:

• *Temporal parameters*: contact times (Tcont [s], Pcont [%]), flight times (Tflight [s], Pflight [%]), swing time (Tswing [s]), stride time (Tstride [s])
• *Spatial parameters*: elevation (Elevation [cm]), step length (Lstep [cm]), stride length (Lstride [cm])
• *Velocity parameters*: speed (Speed [m/s]), acceleration (Acc [m/s²])
• *Gait characteristics*: duty factor (Dutyfactor), cadence (Pacesteps [steps/s], Pacestepm [steps/m]), angle of vertical deviation (Alpha [deg]), step imbalance (Imb [%])
• *Foot contact phases*: contact phase (Tcontactphase [s], Pcontactphase [%]), foot flat phase (Tfootflat [s], Pfootflat [%]), propulsive phase (Tpropulsivephase [s], Ppropulsivephase [%]).

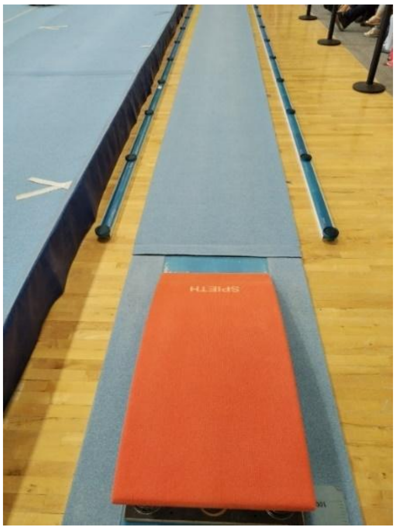

Figure 1. Experimental set-up

Body composition was assessed using the Tanita DC-360 analyser (Tanita Corporation, Tokyo, Japan). The measurements included fat mass (Fat [kg], Fat [%]), fat-free mass (FFM [kg]), muscle mass (Muscle [kg]), total body water (TBW [kg], TBW [%]), and Body Mass Index (BMI). These variables were included in the analysis due to their significant influence on athletic performance (Maughan & Shirreffs, 2010; Santos et al., 2014).

Principal Component Analysis (PCA) with Varimax rotation was employed to reduce the dimensionality of the datasets related to body composition and running characteristics, while retaining the majority of the variance present in the original variables. Varimax rotation was chosen for its ability to maximise interpretability and provide a clear distinction between extracted components. Prior to PCA, Spearman's correlation analyses were conducted to explore the relationships between body composition and running variables, offering insight into inter-variable correlations.

The adequacy of the sample for PCA was assessed using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity. The factor loadings were carefully evaluated to ensure that each extracted component accurately represented the underlying structure of the data. Additionally, the communalities of the variables were examined to determine the proportion of variance explained by the components.

Boosting regression was used to model the relationship between gymnasts' vault performance scores (E Scores) and various predictors. This method was selected for its superior predictive capacity compared to linear regression, as it effectively captures complex, nonlinear interactions among multiple variables. Unlike linear regression, which assumes a strictly linear relationship between independent and dependent variables, boosting regression iteratively improves its predictions by correcting errors from previous weak learners (i.e., decision trees). This sequential process reduces bias, minimises variance, and enhances overall predictive accuracy, making it particularly suitable for modelling performance metrics influenced by interdependent physiological and biomechanical factors. As an ensemble method, boosting combines multiple decision trees to form a robust model that generalises well across different datasets.

The analysis followed these steps:

1. Multiple PCA models were generated, each producing a distinct set of components capturing varying proportions of variance in the original data.
2. The dataset was split into training (75%), validation (12.5%), and test (12.5%) sets.
3. Separate boosting regression models were trained for each set of PCA-derived components using the training set. A Gaussian loss function was applied, with the number of trees automatically adjusted and a shrinkage rate set at 0.1.
4. Model hyperparameters were optimised using the validation set by minimising the out-of-bag mean squared error.
5. Final models were evaluated on the test set using performance metrics including Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and R-squared (R^2).
6. The accuracy and predictive performance of each model were compared to determine the optimal set of PCA components for retention.

All statistical analyses were conducted using SPSS version 29.0 (IBM Corp., Armonk, NY) and JASP version 0.17.2 (JASP Team, Amsterdam, Netherlands).

RESULTS

The PCA identified six components for the female gymnasts and five components for the male gymnasts, accounting for a cumulative variance of 91.84% and 92.28%, respectively (Table 1 and Table 2). The adequacy of the data for PCA was confirmed by the Kaiser-Meyer-Olkin (KMO) measure, with all values exceeding the acceptable threshold of 0.5. Additionally, Bartlett's Test of Sphericity was significant ($p < 0.001$) in both cases, indicating that the correlations among variables were sufficiently strong to justify the application of PCA.

The structural differences observed between the male and female PCA results reflect fundamental physiological and biomechanical distinctions that influence vault execution. In male gymnasts, Overall Lean Body Mass (33.29%) explained the greatest proportion of variance (Table 2), indicating a strong interrelation among body composition variables such as muscle mass, weight, height, BMI, and total body water. This dominant component suggests that movement efficiency in men is closely linked to body composition, likely due to their greater absolute strength and reliance on force production during take-off. Conversely, in female gymnasts, Flight and Contact Dynamics (34.26%) emerged as the most influential component (Table 1), highlighting the interdependence of run-up characteristics such as stride regulation, flight time, and contact phases. This pattern implies that women may rely more on controlled energy transfer, precise cadence, and step sequencing to optimize vault execution, rather than on pure power output alone.

Table 1.
The results of PCA for female gymnasts, identifying six principal components that together explain 91.84% of the total variance. The table lists each component, the percentage of variance it accounts for, and the variables that load most strongly onto it.

Component (% of variance)	Variable	Loading
C1: Flight and Contact Dynamics (34.26)	PFlight	0.975
	Pcont	-0.975
	Dutyfactor	-0.928
	Lstep	0.862
	Lstride	0.821
	TFlight	0.794
	Elevation	0.749
	Tcont	-0.721
	Alpha	0.716
	Speed	0.711
	Acc.	-0.557
C2: Cadence and Timing (23.90)	Pacesteps	-0.952
	Pacestepm	-0.951
	Tstride	0.949
	Tswing	0.810
C3: Overall Lean Body Mass (13.54)	TBW	0.973
	Muscle	0.965
	FFM	0.965
	Weight	0.836
	Height	0.641
C4: Body fat (9.10)	Fat %	0.890
	Fat	0.859
	TBW	-0.841
	BMI	0.752
C5: Propulsion and Foot Flat Dynamics (6.71)	Ppropulsivephase	0.957
	Pfootflat	-0.882
	Tpropulsivephase	0.652
	Tfootflat	-0.594
	Imb	-0.584
C6: Overall Contact Phases (4.35)	Tcontactphase	0.863
	Pcontactphase	0.811

Table 2:
The results of PCA for male gymnasts, identifying five principal components that together explain 92.28% of the total variance. The table lists each component, the percentage of variance it accounts for, and the variables that load most strongly onto it.

Component (% of variance)	**Variable**	**Loading**
C1: Overall Lean Body Mass (33.29)	TBW	0.978
	Weight	0.972
	FFM	0.970
	Muscle	0.970
	Height	0.964
	BMI	0.914
C2: Stride and Step Dynamics (27.30)	Pacesteps	-0.988
	Pacestepm	-0.988
	Tstride	0.980
	Tswing	0.969
	Elevation	0.875
	Alpha	0.864
	TFlight	0.849
	Acc.	-0.584
	Lstride	-0.467
C3: Flight and Contact Dynamics (15.88)	Dutyfactor	-0.934
	Pcont	-0.909
	PFlight	0.909
	Tcont	-0.704
	Lstep	0.525
	Imb	-0.503
	Speed	0.488
C4: Propulsion and Foot Flat Dynamics (9.34)	Ppropulsivephase	0.966
	Pfootflat	-0.955
	Tfootflat	-0.862
	Tpropulsivephase	0.742
	Tcontactphase	0.551
	Pcontactphase	0.478
C5: Body fat (6.46)	TBW	-0.905
	Fat %	0.836
	Fat	0.621

Furthermore, Stride and Step Dynamics (27.30%) emerged as a distinct component in men (Table 2), emphasizing their greater focus on stride efficiency and velocity progression. In contrast, Cadence and Timing (23.90%) formed a separate component in women (Table 1), underscoring the critical role of rhythmic coordination in their vault approach. These findings highlight gender-specific structuring of vault performance, with men relying more on force production and stride efficiency, while women demonstrate greater integration of movement sequencing and regulation of contact phases.

Predictive model for women: The Boosting regression model for women demonstrated strong predictive performance, with an R^2 value of 0.744, indicating that 74.4% of the variability in E scores is explained by the model. This high R^2 reflects a good fit between the model and observed data, suggesting it captures a significant portion of the variance in vault execution scores. The model was optimized to include 15 trees, a number automatically determined during analysis by minimizing validation error.

Predictive accuracy metrics further support the model's reliability: the Test Mean Squared Error (MSE) was 0.917, Root Mean Squared Error (RMSE) 0.958, Mean Absolute Error (MAE) 0.850, and Mean Absolute Percentage Error (MAPE) 10.81%. The MAPE indicates that predictions deviate from actual scores by about 10–11% on average, a moderate level of accuracy considered sufficient for practical applications in training and performance assessment.

Table 3. *Boosting regression model performance for women.* This table presents the performance metrics of the Boosting regression model for female gymnasts. The model explains 74.4% of the variance in execution scores (E Scores), demonstrating good predictive accuracy. Key evaluation metrics, including Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE), are reported, providing insight into the model's precision in estimating execution scores.

Metric	**Value**
Test MSE	0.917
Root Mean Squared Error (RMSE)	0.958
Mean Absolute Error (MAE)	0.850
Mean Absolute Percentage Error (MAPE)	10.81 %
R-squared (R^2)	0.744

Among the key predictors, Overall Lean Body Mass was the most influential, contributing 47.12% of the model's predictive power (Figure 2). This finding underscores the critical role of lean body mass in predicting E scores. A positive correlation between fat-free mass (FFM) and E scores was observed (Spearman's rho = 0.595, $p < .01$), indicating that higher lean body mass is associated with better performance outcomes. This relationship highlights the importance of developing and maintaining lean muscle mass in gymnasts to optimize vault performance.

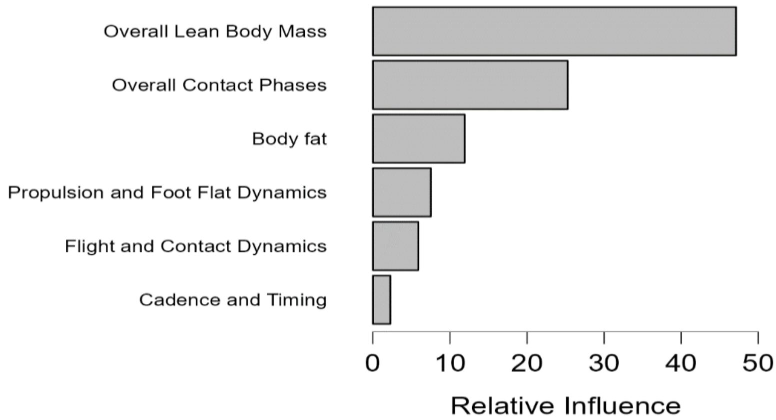

Figure 2. Relative Influence Plot. This figure illustrates the relative influence of predictors in the Boosting regression model for female gymnasts. Overall Lean Body Mass is the most influential predictor, followed by Overall Contact Phases and Body Fat. The plot visualizes the contribution of each predictor to the model's variance explanation, helping to identify the most relevant factors for execution score estimation.

Contact Phases contributed 25.28% to the model's predictions, highlighting their significant role in determining E scores. The negative correlation between contact phases and E scores (Spearman's rho = -0.248) suggests that shorter contact times are associated with higher performance scores, emphasizing the importance of quick and efficient ground interactions during movements. Training programs should therefore focus on techniques that minimize contact time while maintaining control and power.

Body Fat also emerged as a notable predictor, accounting for 11.92% of the model's influence. However, the correlation between body fat percentage and E scores was weaker (Spearman's rho = -0.137), indicating a modest relationship where lower body fat tends to associate with better performance, but not as strongly as other factors. This suggests that while body composition remains relevant, its impact is more nuanced alongside other physical attributes.

Propulsion and Foot Flat Dynamics contributed 7.52% to the model's predictive power. The negative correlation between the propulsive phase and E scores (Spearman's rho = -0.255) implies that shorter propulsive phases may be linked to better performance, underscoring the importance of efficient propulsion during gymnastic routines.

Flight and Contact Dynamics accounted for 5.90% of the model's relative influence. Within this category, stride length emerged as the most important factor. The positive correlation between E scores and stride length (Spearman's rho = 0.410, $p < .05$) indicates that longer strides are associated with better performance outcomes. This finding highlights the importance of emphasizing stride length in training, as it appears to be a key determinant of successful vault execution.

Finally, Cadence and Timing contributed 2.26% to the model's predictive power. Although correlations between cadence-related variables and E scores were relatively weak, their inclusion in the model suggests that maintaining proper rhythm and timing still plays a supportive role in performance, albeit less critical than other factors.

Predictive model for men: The Boosting regression model for men demonstrated exceptional predictive performance, with an R^2 value of 0.978, indicating that 97.8% of the variability in E scores is explained by the model. This very high R^2 value reflects an excellent fit between the model and the observed data, capturing nearly all the variance in E scores.

Table 4.
Boosting regression model performance for men. This table presents the performance metrics of the Boosting regression model for male gymnasts. The model demonstrates exceptional predictive accuracy, explaining 97.8% of the variance in execution scores. Reported metrics, including MSE, RMSE, MAE, and MAPE, confirm the model's ability to closely predict execution scores with minimal error.

Metric	**Value**
Test MSE	0.005
Root Mean Squared Error (RMSE)	0.071
Mean Absolute Error (MAE)	0.063
Mean Absolute Percentage Error (MAPE)	0.7%
R-squared (R^2)	0.978

The model's predictive accuracy, reflected by a Test MSE of 0.005, RMSE of 0.071, MAE of 0.063, and MAPE of 0.7%, indicates that predictions align extremely closely with actual performance scores. The very low MAPE of 0.7% demonstrates that the model's predictions are, on average, within less than 1% of the true values, highlighting a high level of precision suitable for practical performance prediction applications.

Body Fat emerged as the most influential predictor, contributing 48.436% to the model's predictive power (Figure 3). The negative correlation between body fat percentage and E Scores (Spearman's rho = -0.321, $p < .01$) suggests that higher body fat levels are associated with lower performance scores, underscoring the importance of maintaining low body fat to optimize performance.

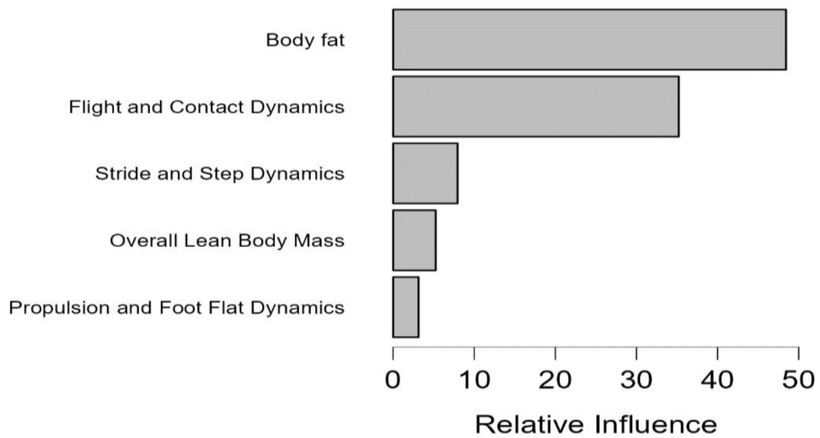

Figure 3. Relative influence plot for men. This figure illustrates the relative influence of predictors in the Boosting regression model for male gymnasts. Body Fat is identified as the most influential factor, followed by Flight and Contact Dynamics. The plot visualizes the contribution

of each predictor to the model's variance explanation, helping to identify the most relevant factors for execution score estimation.

Figure 3 also highlights the significant contribution of Flight and Contact Dynamics, accounting for 35.221% of the model's predictive power. Within this category, several correlations—such as the negative relationship between contact phase duration and E Scores (Spearman's rho = -0.299)—indicate that shorter contact phases are beneficial for vault performance. These findings emphasize the importance of optimizing flight and contact mechanics to improve vault scores.

Stride and Step Dynamics contributed 7.948% to the model's influence. The positive correlation between stride length and E Scores (rho = 0.365, $p < .05$) suggests that longer strides are associated with better performance, underscoring the potential value of training interventions aimed at enhancing stride length to boost vault outcomes.

Overall Lean Body Mass accounted for 5.251% of the model's predictive power. Interestingly, the negative correlation between lean body mass and E Scores (Spearman's rho = -0.232), though not statistically significant, points to a complex relationship where greater lean body mass may not always translate into improved vault performance.

DISCUSSION

The comparative analysis of PCA and Boosting regression models between women and men reveals both shared and distinct factors influencing body composition, gait dynamics, and performance outcomes. These differences extend beyond statistical variation, carrying important practical implications for training and performance optimization.

While PCA showed a comparable amount of total variance explained by the extracted components for women (91.84%) and men (95.18%), the Boosting regression models highlighted a marked difference in predictive accuracy. The model for women explained 74.4% of the variability in E scores ($R^2 = 0.744$), whereas the model for men demonstrated exceptional precision, accounting for 97.8% of the variance ($R^2 = 0.978$). This discrepancy suggests that the predictors for men are more consistently linked to vault performance outcomes, possibly reflecting more homogeneous physiological and biomechanical characteristics within the male gymnast group.

In women, PCA identified Flight and Contact Dynamics as the most influential component, explaining 34.26% of the variance, whereas in men, Overall Lean Body Mass was predominant, accounting for 33.29% of the variance. This pattern is reflected in the Boosting regression models, where Overall Lean Body Mass was the most influential predictor for women (47.12% of the model's power), while Body Fat was the key predictor for men (48.44% contribution). These findings indicate that lean body mass development and stride optimization are crucial for women's vault performance, while body fat reduction and efficient flight/contact dynamics play a more critical role for men.

Practically, this suggests that training for female gymnasts should emphasize muscle development, efficient use of lean body mass, and stride optimization. Exercises targeting single-leg power, stride efficiency, and controlled energy transfer—such as weighted step-ups, single-leg plyometric hops, and Bulgarian split squats—can enhance lower-body strength and stability, reinforcing force application during take-off while preserving flexibility. Plyometric bounding drills over hurdles are effective for improving stride length and explosive propulsion, ensuring a powerful and efficient approach. To refine step efficiency, acceleration drills with stride-length markers help gymnasts optimize stride length and frequency, maximizing approach speed without unnecessary deceleration before take-off.

For male gymnasts, the focus should be on body fat management alongside optimizing movement phases, particularly flight/contact dynamics and stride mechanics, which directly influence performance outcomes. Training strategies to improve the power-to-weight ratio while maintaining explosive acceleration include sprint intervals and resisted sled runs. Incorporating flying sprints with gradual acceleration reinforces velocity maintenance throughout the run-up, ensuring efficient energy transfer from the approach into the take-off phase. These drills emphasize stride consistency and controlled acceleration, critical for maximizing vault performance in male athletes.

The PCA for women identified Cadence and Timing as a distinct component, explaining 23.90% of the variance and highlighting the importance of temporal aspects of gait. In contrast, men's PCA grouped these variables with Stride and Step Dynamics (27.30% variance), suggesting a more integrated relationship between spatial and temporal running characteristics. Practically, this implies that female gymnasts may benefit from training that focuses on rhythm and timing separately from stride mechanics to improve running efficiency during the vault approach.

For women, bounding drills with rhythmic cues—such as external beats or claps—can help develop a controlled, repeatable stride pattern that ensures efficient cadence regulation. Hurdle rhythm runs, where gymnasts sprint over evenly spaced low hurdles, are also effective in training consistent stride timing and cadence control, helping prevent overstriding or erratic step placement.

For men, a more holistic training approach that integrates both timing and spatial stride mechanics may better optimize performance. Flying sprints with gradual acceleration allow gymnasts to progressively build velocity while naturally integrating stride length and frequency. Runway stride-length variability drills, in which athletes alternate between increasing and decreasing stride lengths within a single sprint, enhance dynamic stride control and adaptability during vault approaches. Additionally, acceleration sprints combined with audible timing cues encourage gymnasts to adjust step frequency based on external auditory signals, reinforcing spatial-temporal control and ensuring efficient step regulation under varying approach conditions.

Both genders show significant components related to Propulsion and Foot Flat Dynamics, though the variance explained and their predictive contributions differ. For women, this component accounted for 6.71% of the variance and contributed 7.52% to the model's predictive power, indicating that propulsion efficiency has a direct and consistent impact on vault execution. In men, propulsion dynamics explained a slightly higher variance of 9.34%, but only contributed 3.15% to the model's predictive power. This suggests that while propulsion influences approach mechanics for men, its effect on overall performance is more indirect and interacts with other key factors like body fat and flight/contact dynamics.

This difference implies that propulsion dynamics play a more supportive yet consistent role in women's vault performance by ensuring efficient energy transfer throughout the run-up and take-off. For men, propulsion is more isolated but becomes critical when combined with other biomechanical variables.

For female gymnasts, bounding drills that transition immediately into sprints can enhance propulsion and step efficiency, promoting fluid energy transfer from stride into take-off. Quick-step hurdle runs help refine foot placement and reduce excessive ground contact time, facilitating smoother propulsion mechanics leading into take-off. Additionally, low-box depth jumps can be integrated to strengthen push-off power while maintaining movement fluidity, reflecting the consistent role of propulsion in women's vault performance.

For male gymnasts, resisted sprint drills improve power application during acceleration phases, while plyometric bounding with alternating take-off surfaces enhances neuromuscular adaptation in propulsion mechanics. Single-leg depth jumps followed by forward sprints can refine force application strategies, ensuring gymnasts generate sufficient propulsion without compromising stride efficiency or flight phase execution.

Gender differences in vault performance are shaped not only by physiological and biomechanical factors but also by cultural and coaching biases. Female gymnasts often experience pressure to maintain a “thin” body ideal, which can sometimes come at the expense of developing adequate strength. This focus on aesthetics may lead training to emphasize flexibility and elegance over explosive power. In contrast, male gymnasts are typically encouraged to prioritize strength development. Such biases can contribute to performance disparities that extend beyond natural physiological differences. Therefore, it is crucial to frame strength training as a means to enhance athletic performance rather than simply a way to alter body composition. By cultivating training environments that prioritize functional capability over appearance, coaches and practitioners can support holistic athlete development and promote a positive body image. Addressing these biases with evidence-based coaching strategies ensures that both male and female gymnasts receive training that effectively develops their strength, power, and technical skills necessary for optimal vault performance.

Despite the strengths of the present study, several limitations should be acknowledged. First, although the sample size was sufficient for initial analyses, it may restrict the generalisability of our findings to a broader population of gymnasts, especially at the international level. Future research should aim to include larger and more diverse samples across different competitive levels and age groups to validate these results more broadly.

Second, the cross-sectional design provides only a snapshot of the relationships between body composition, running characteristics, and vault performance. This approach does not capture changes over time or the effects of long-term training interventions. Longitudinal studies would be valuable to track the development of these variables and their influence on performance across multiple training cycles.

Third, the heterogeneous nature of our sample — encompassing gymnasts of varying ages, competitive categories, and vault difficulties — introduces variability that may influence the predictors of performance. Since the physical and technical demands differ across vault types, key performance predictors might vary accordingly. As we did not stratify gymnasts by competitive level or vault type, our findings should be interpreted as general predictors of vault performance rather than specific determinants for particular vaults. Future research should investigate distinct competitive levels and vault difficulty categories to identify whether performance predictors differ across vault types.

Fourth, despite using state-of-the-art equipment for biomechanical and body composition assessments, potential measurement error cannot be entirely ruled out. Future studies should consider employing multiple measurement techniques to cross-validate results and conduct reliability analyses to quantify potential errors.

Despite these limitations, our findings provide a solid foundation for future research and offer valuable insights for coaches and practitioners aiming to optimise gymnastics biomechanics and performance.

CONCLUSION

The combined analysis of PCA and Boosting regression models reveals important gender-specific factors influencing vault performance in gymnastics. For female athletes, lean body mass, stride characteristics, and the coordination of rhythm and timing emerge as critical contributors, suggesting that strength training, stride optimisation, and focused rhythm development may enhance vault execution. In contrast, for male athletes, body composition—particularly body fat management—alongside optimisation of flight/contact dynamics and an integrated approach to stride mechanics play more prominent roles. Although propulsion dynamics are important for both genders, they appear to support women's overall performance more consistently, while for men, propulsion has a more isolated but crucial impact when combined with body fat and flight/contact factors.

This study advances existing knowledge by providing a data-driven understanding of how gender-specific physiological and biomechanical factors shape vault performance. By integrating PCA with Boosting regression, the findings highlight both structural and predictive differences in performance determinants, offering a nuanced perspective beyond prior research focused mainly on general vault mechanics. The identification of key gender-specific contributors—such as lean body mass and stride optimisation for women, and body fat management and flight/contact dynamics for men—enables the development of more precise, tailored training interventions.

These insights should inform the design of targeted training programmes; however, they must be considered preliminary in light of the study's limitations. Coaches and practitioners are encouraged to view these findings as a foundation for further exploration rather than definitive prescriptions. Training adjustments should be applied judiciously, taking into account individual athlete differences, varying skill levels, and the specific demands of different vault types.

Future research should aim to validate these findings through longitudinal studies involving larger and more diverse gymnast populations. Additionally, investigating the influence of these gender-specific factors across various competitive levels would provide a more comprehensive understanding of their role in vault performance.

In conclusion, this study offers valuable preliminary insights into gender-specific predictors of vault performance; however, further research is necessary to confirm and expand upon these findings before they can be confidently applied in training contexts. To bridge this gap effectively, close collaboration among coaches, gymnasts, and researchers is essential to refine these insights and develop more balanced, evidence-based training approaches that optimize performance while supporting athlete well-being.

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Article received: 28. 8. 2024
Article accepted: 17. 3. 2025