Original Article

Multivariate regression modeling of Chinese artistic gymnastic handspring vaulting kinematic performance based on judges scores

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Abstract

Introduction: Vault kinematic variables have been found to be strongly correlated with vault difficulty (DV) values and judges' scores. However, the Fédération Internationale de Gymnastique Code of Points (COP) was updated after every Olympic Games rendering previous regression models inadequate. Therefore, the objective of this study was to develop a prediction model for vault performance based on judges' scores.

Methods: Handspring vaults (n = 70) were recorded during the Men's Artistic Gymnastic qualifying round of the 2017 China National Artistic Gymnastics Championship using a video camera placed 50 m perpendicular to the vault table. Kinematic data were coded and correlated with judges' official competition final scores (FSs). The vault samples were used to develop a mathematical model (n = 65) and to verify the scores against the predicted model (n = 5). Partial least squares regression was established using the statistical software to calibrate and cross validate the model.

Results: The goodness-of-fit of a 3-factor model was utilised (R^2_{cal} = 90.13% and R^2_{val} = 87.30%) and a significant and strong relationship was observed between predicted Y (FS) and reference Y (FS) in both the calibration and validation models (r_{cal} = 0.949, r_{val} = 0.932) with Y-calibration error (RMSEC = 0.1727) and Y-prediction error (RMSEP = 0.1990). Maximum height, 2nd-flight-time and DV were the key variables against FS. Using JSPM, 40% of new samples were within the acceptable range.

Conclusion: Kinematic variables and known DV seem adequate to form a JSPM that could offer coaches an alternative scientific approach to monitor vault training.

Key Words: Multivariate regression analysis, kinematic variables, difficulty value, vault performance, gymnastics

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INTRODUCTION

Performing vaults in artistic gymnastics require a gymnast to perform a run-up sprint of <25 m towards a springboard, execute a take-off, flip over a table, complete a series of acrobatic movements in the air, and then land in a stable manner within the designated landing area. The entire vault performance will then be accorded a score which is the summation of a difficulty value (DV) and an E-score. According to the Fédération Internationale de Gymnastique (FIG 2016), the DV is a summation value of a series of rotations in the longitudinal or transverse axes that comprises acrobatic movements registered in the Code of Points

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(COP). This contrasts with the E-score which starts with a gymnast having 10 points, with deductions of 0.1–0.5 points made when errors related to the severity of compositional requirements, esthetics, technique, and body position are made, as the gymnast approached the springboard. Hence, E-score judges scored vault performance using mostly visual judgments related to the changes in kinematic variables such as time, angle, and displacement (Heinen et al. 2012).

Vault kinematic variables such as approach velocity (AV), maximum speed on the springboard, 1st and 2nd flight times, in addition to contact duration on the support table of the artistic gymnastic vault have previously been found to be strongly correlated with vault DV (Atiković 2012) and judges' scores (Bradshaw and Sparrow 2001; Gervais 1994). Of the five vault performance prediction models examined by Atiković (2012), the 2nd flight-phase model was established as the model that was most highly related to DV. Bradshaw and Sparrow (2001), however, found that AV and 2nd post-flight distance were related to judges' scores. Increased AV may lead to an increase in round-off velocity and higher board take-off velocity as it has been previously reported that a reduction of both approach and take-off velocity in elite female artistic gymnasts may be detrimental to post-flight distances (Dainis 1981). Of the two factors, a reduction in AV seemed to have a larger effect as can be deduced from studies which suggested that increased vertical center of mass take-off velocity from the vault table was essential for optimal 2nd flight height and distance during a Yurchenko vault (Koh and Jennings 2007). In addition, jump height and relative power of the countermovement jump (CMJ) also correlated with the DV in men's artistic gymnastic movements (Veljković et al. 2016). In general, greater horizontal running velocity translates to better angular velocity, shorter vault table contact times, and longer 2nd flight times which in turn, permits more complex and better quality acrobatic movements to be produced. This emphasizes the importance of the role of physical fitness for vault performance scores.

Previous vault performance modeling studies had procedural and experimental limitations such as focusing only on specific parts of the vault technique, using simple regression techniques to analyze complex inter-correlated variables to determine performance optimization, utilizing small sample sizes, and acquiring data in noncompetitive settings without judges' scores (Atiković 2012; Bradshaw and Sparrow 2001; Dainis 1981; Gervais 1994; King and Yeadon 2005; Koh and Jennings 2007; Koh et al. 2003). To date, only one published study applied judges' scores to develop a prediction model for the Hecht vault performance in elite male artistic gymnasts during the 1995 World Gymnastics Championships utilizing one to six kinematic parameters that accounted for 27%–57% of performance variances (Takei et al. 2000). The low to moderate accuracy of prediction of previous models have limited practical use for providing training focus and monitoring. Furthermore, the COP is updated every 4 years after each Olympic Games, and the existing prediction model would need to be discarded. Based on these assertions, the purpose of the study was to develop a prediction model for vault performance based on judges' scores. It was hypothesized that two-dimensional (2D) video analysis kinematic parameters were sufficient to develop a performance model and would be able to predict performance scores when DVs were specified.

METHODS

Sampling and data collection

The selected sample ($n = 70$) was vaults performed by male gymnasts during the 2017 China National Artistic Gymnastic Championships qualifying round which adopted the 2017–2020 COP. The vault performances generated data that included the independent variable which was the official final score (FS), and 20 dependent variables comprising the DV and 19 vault kinematic variables from the three vault performance phases – the approach phase, 1st flight phase, and 2nd flight phase. In addition, all samples included successful vault landings in the standing position that did not obtain penalty deductions from Vault groups I and II performing the handspring with 1/4 or 1/2 twist during the 1st flight in all body positions with twists. The technical apparatus utilized during the competition was produced by TaiShan® (China). A 50Hz (JVC PX100, Japan) video camera was placed perpendicular to the vault table at a distance of 50 m. Five calibration markers were placed 1 m apart from the edge of the springboard along the runway, and two calibration markers were placed vertically on the vault table throughout the competition.

Data reduction

A 2D video analysis was performed by an experienced coder ($r = 0.91 - 0.96$) using Dartfish (Fribourg, Switzerland) video analysis software. The selection of 2D analysis been deemed adequate for use when the use of 3D analysis was not possible as during competition and has been found to match the accuracy of 3D analysis adequately (Schurr et al. 2017). Three phases of vault analysis were performed. The approach phase consisted of 13 variables comprising time, displacement, velocity of the 3rd-last step, 2nd-last step, single leg take-off, springboard take-off, and AV. The 1st flight phase comprised three variables including springboard contact-time, table contact-time, and table-springboard contact-time ratio. Finally, the 2nd flight phase involved maximum height (MH), time to MH, and time to landing (TL).

Performance score

The organizers of the championship employed a judging panel consisting of two D-judges, five E-judges, two reference judges, and one Line judge as provided by FIG rules. The D-judges notated and evaluated the entire vault performance based on the DV and awarded penalties if any violation of COP rules occurred. The E-judges awarded E-scores (ES) and evaluated the vault performance from the springboard take-off until the landing in an upright standing position. The ES was the average of remaining scores after the highest and lowest sums of total error deductions were eliminated. The FS is a summation of DV and ES. The gymnasts' FS ranged from 12.40 to 14.90, while DV ranged from 4.00 to 6.00 during this championship.

Data analysis

The sample of 70 vaults were assigned to two datasets, Set 1 ($n = 65$) and Set 2 ($n = 5$). The Set 1 dataset was used to develop the judges' scores prediction model, whereas the Set 2 dataset was used to authenticate the predicted score against the model. A statistical software (CAMO Unscrambler® X 10.3v, Norway) was used to perform Partial Least Squares Regression (PLSR) to calibrate and cross validate the model. PLSR was used as there were many factors that were likely to be strongly related. The PLSR modeled both the x- and y- matrices simultaneously to determine the latent variables in X that best predicted the latent variables in Y. These two PLSR components are similar to the principal components but are referred to as factors. PLSR maximizes the covariance between X and Y. The X and Y variables were set as equal weights. A full cross validation or leave-one-out method was used to validate the calibrated judges' scores prediction model. A non-linear Iterative Partial Least Squares (NIPALS) algorithm was selected. By referring to the known kinematic variables and DV of the remaining vaults, the validated model was used to predict and compare with the judges' scores ($p < 0.05$). Four outliers were identified and excluded during the model development process according to Hotelling's T^2 statistic.

RESULTS

In this section, the robustness of the judges' scores prediction model is presented first, followed by the correlation between the parameters and the judges' scores prediction model according to vault performance phases. Finally, the predicted value is matched against the reference (FS).

Partial least squares regression model

Calibration and cross validation were carried out on Set 1 dataset. The optimum number of factors was chosen on the basis of explained variances closest to 100% (peak) before a plateau [Figure 1a]. Thus, in this study, a 3-factor model which determined calibration variance, R^2_{cal} to be 90.13% and validation variance R^2_{val} to be 87.30% was chosen. A significantly strong relationship was found between predicted Y (FS) and reference Y (FS) in both calibration and validation models ($r_{cal} = 0.949$, $r_{val} = 0.932$). The Y-calibration error was expressed by Root Mean Square Error of Calibration (RMSEC) and the Y-prediction error by Root Mean Square Error of Prediction (RMSEP) with values of 0.1727 and 0.1990, respectively [Figure 1b]. These numbers suggest that although the calibration data were well-fitted, the model described the calibrated dataset only moderately well.

Table 1 explains the x- and y- loading of variances in factor 1 (45%, 67%), factor 2 (11%, 20%), and factor 3 (9%, 3%). The independent variable of the study (FS) correlated significantly and strongly with factor 1 ($r = 0.816$), moderately with factor 2 ($r = 0.452$), and poorly with factor 3 ($r = 0.178$). Meanwhile, the DV correlated significantly and strongly with factor 1 ($r = 0.836$) and moderately with factor 2 ($r = 0.503$).

Approach phase

Time domain variables such as the 3rd-last-step and springboard take-off correlated poorly ($r = 0.297$) with factor 1 and moderately ($r = 0.550$) with factor 2. Displacement domain variables such as the 3rd-last-step, 2nd-last-step, take-off and springboard take-off were poorly correlated with factor 1. Other analyses indicated that the 3rd-last-step springboard and take-off correlated poorly and moderately with factor 2, respectively, whereas the 2nd last-step obtained moderate significance with factor 3. The velocity domain variables such as AV strongly correlated with factor 1 but other velocity domain variables such as the 3rd last step, 2nd last-step, take-off and springboard take-off correlated only moderately with factor 1. The 3rd last step, 2nd last-step, and AV correlated poorly with factor 2 while the 2nd last-step correlated moderately with factor 3 [Table 2].

First flight phase

The time domain variables were springboard contact time, table contact-time, and table springboard ratio. There was no

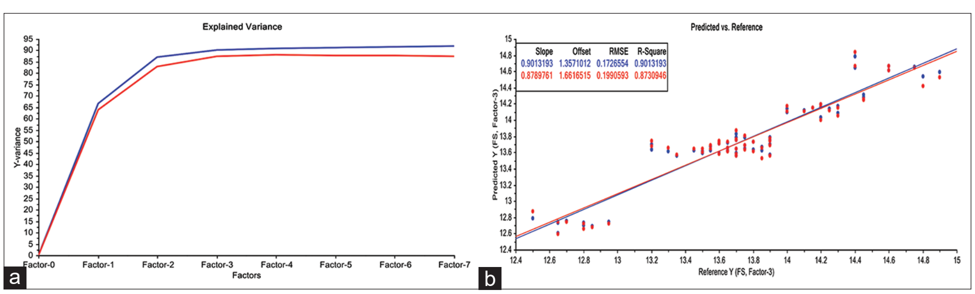

Figure 1: (a) Explained calibration and validation variances plot; (b) preferred versus reference final score regression plot

Table 1: Descriptive statistics and correlations (*r*) of official judges score with the prediction model

Variables	Mean±SD	Minimum	Maximum	Factor 1 (*r*)	Factor 2 (*r*)	Factor 3 (*r*)
Score						
Difficulty value	4.90±0.46	4.00	6.00	0.836**	0.503**	0.179
E score	8.84±0.28	7.70	9.30	-	-	-
Final score	13.73±0.57	12.40	14.90	0.816**	0.452**	0.178*

*$p<0.05$, **$p<0.01$. SD: Standard deviation

significant correlation between springboard contact time and all three factors while table contact time registered a negative and weak significance with factor 1. Table springboard ratio correlated negatively and moderately with factor 2 [Table 3].

Second flight phase

Of the two time domain variables, only TL correlated moderately and poorly with factor 1 and factor 2, respectively. The displacement domain (MH) correlated poorly with both factors 1 and 2 [Table 4].

The inter relationships between DV and FS with MH, TL and AV are shown in Figure 2a-c. What can be observed is that the higher the DV, the higher the FS awarded. This suggests that the influence of MH was mild when DV was between 4.0 and 5.2 with the exception of a DV of 5.6. However, Figure 2b indicates that TL with a DV of 4.0 achieved the shortest duration, while DVs of 4.8 and 5.2 obtained moderate duration, with the DV of 5.6 acquiring the longest duration. Furthermore, Figure 2c indicates that a DV of 4.0 elicited the slowest AV, a DV of 4.8 achieved moderate AV, while DVs of 5.2 and 5.6 obtained the highest AV. However, AV did not seem to be a good discriminator between DVs of 5.2 and 5.6. In summary, the 4.0 DV kinematic vault performance achievement was low for AV, MH and TL; 4.8 DV kinematic vault performance achievement was moderate for AV, low for MH and moderate for TL; 5.2 DV kinematic vault performance achievement was high for AV, low for MH and moderate for TL; 5.6 DV kinematic vault performance achievement was high for AV, MH and TL.

Predicted versus reference score

Set 2 dataset ($n = 5$) was used as a new sample to predict FS and is shown in Figure 3. The deviation of the predicted judges' scores was <0.5 (0.257–0.430) points as indicated by the box plots, and this is within an acceptable range according to FIG scoring rules. As only two out of five (40%) predicted judges' scores were within the deviation, this suggests that the predicted judges' scores model over-predicted when compared to the reference scores, but the model is deemed moderately acceptable.

DISCUSSION

Based on the results, it is proposed that the 2D video analysis kinematic parameters in this study were sufficient to develop a vault performance judges' scores prediction model (JSPM) which was able to predict vault performance judges' scores when DV scores are known. Although the 19 kinematic parameters and the DV explained variances are similar to those from previous studies

Table 2: Descriptive statistics and correlations (r) between the approach phase with the prediction model

Variables	Mean±SD	Minimum	Maximum	Factor 1 (r)	Factor 2 (r)	Factor 3 (r)
Time (s)						
3rd-last-step	0.21±0.02	0.18	0.24	−0.297*	0.253	−0.374
2nd-last-step	0.21±0.01	0.18	0.26	−0.166	−0.289	0.149
Take-off	0.18±0.02	0.14	0.22	−0.215	0.033	−0.276
Springboard take-off	0.28±0.03	0.22	0.36	−0.094	0.550*	−0.189
Displacement (m)						
3rd-last-step	1.55±0.08	1.37	1.74	0.382**	− 0.131**	−0.239
2nd-last-step	1.63±0.11	1.39	1.91	0.299*	−0.143	−0.456*
Take-off	1.51±0.13	1.24	1.87	0.330*	−0.191	−0.156
Springboard take-off	2.81±0.21	2.34	3.31	0.326*	0.508**	−0.216
Velocity (ms^{-1})						
3rd-last-step	7.33±0.47	6.38	8.45	0.689**	−0.419*	0.235
2nd-last-step	7.60±0.41	6.59	8.55	0.572**	0.184*	−0.735**
Take-off	8.27±0.57	7.11	9.44	0.667**	−0.258	0.138
Approach velocity	7.69±0.34	7.02	8.38	0.918**	−0.251**	−0.144
Springboard take-off	9.93±0.53	8.53	11.32	0.625**	−0.265	0.028

*p<0.05, **p<0.01. SD: Standard deviation

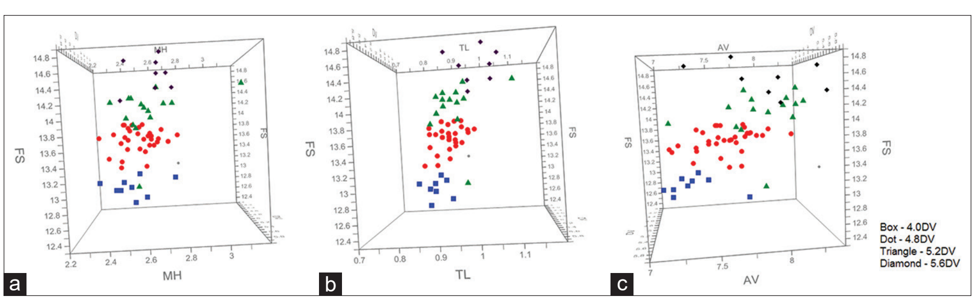

Figure 2: (a) Three-dimensional scatter plot for MH, FS and DV; (b). Three-dimensional scatter plot for TL, FS and DV; (c) Three-dimensional scatter plot for AV, FS and DV. The DV categories were indicated by 'Box' = 4.0 DV,' Dot' = 4.8 DV, 'Triangle = 5.2 DV and 'Diamond = 5.6 DV. MH: Maximum height, FS: Final score, DV: Difficulty value, AV: Approach velocity, TL: Time to landing

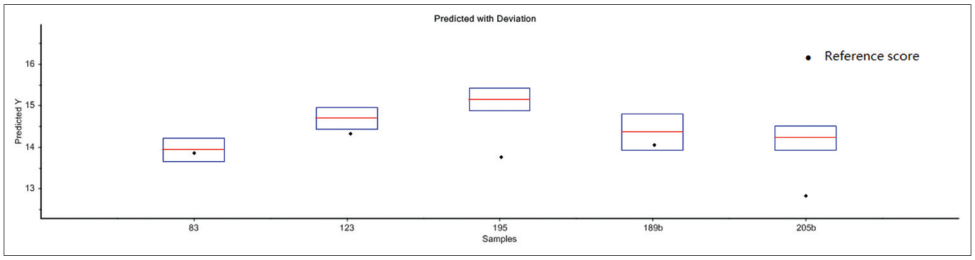

Figure 3: Predicted versus reference final scores

Table 3: Descriptive statistics and correlations (r) of 1st flight phase with the prediction model

Variables	Mean±SD	Minimum	Maximum	Factor 1 (r)	Factor 2 (r)	Factor 3 (r)
Time (s)						
Springboard contact-time	0.11±0.01	0.10	0.14	−0.097	−0.285	−0.007
Table contact-time	0.27±0.04	0.14	0.36	−0.293*	−0.313	−0.030
Table-springboard ratio	0.95±0.19	0.50	1.50	−0.190	−0.514*	0.061

*$p<0.05$, SD: Standard deviation

Table 4: Descriptive statistics and correlations (r) of 2nd flight phase with the prediction model

Variables	Mean±SD	Minimum	Maximum	Factor 1 (r)	Factor 2 (r)	Factor 3 (r)
Time (s)						
Time to maximum height	0.60±0.03	0.52	0.66	0.114	−0.114	−0.024
Time to landing	0.91±0.06	0.76	1.10	0.680**	0.361**	0.058
Displacement (m)						
Maximum height	2.56±0.15	2.20	3.16	0.410**	0.321*	−0.033

*$p<0.05$, **$p<0.01$. SD: Standard deviation

(Takei et al. 2000), the forecast scores were consistently over-predicted but were within an acceptable range. The MH, TL, and DV are important variables in this JSPM, as similarly established previously (Atiković and Smaljovic 2011; Takei 2007). The tempo domain vault kinematic variables also displayed results that are similar with previous studies that observed AV lasting about 2 s, springboard contact duration of 0.1 s, table contact duration of 0.2 s, and TL of 1s (Dillman et al. 1985). However, the current results reveal that the product of displacement and time variables described vault performance better during pre-flight then any single variable within both domains, and tempo domain variables better described vault performance during the post-flight phase.

According to biomechanical principles of artistic gymnastic vaulting, the AV toward the springboard sets the momentum for the 1st and 2nd flight phases (Dainis 1981; Koh and Jennings 2007; Veličković et al. 2011; Fernandes et al. 2016). This study found that gymnasts had to set a DV of at least 5.2, and have an AV of at least 7.75 ms^{-1} to achieve a FS mark greater than 14 points. Further improvement in AV did not seem to positively influence the FS for DVs between 5.2 and 5.6. It could be that other factors such as optimum take-off distance, timing and duration of contact time on the springboard, body posture during springboard contact, angle of hand placement, upper-body strength during vault table contact time, competition psychological stress (Koh and Jennings 2007; Koh et al. 2003) also contributed to poor post-flight phase kinematic variables and deviated vault performances in this sample. Furthermore, the current study revealed that the gymnasts' average AV for both 5.2 and 5.6 DV vault performance in this competition was similar at 7.91 ms^{-1} (range = 7.75–8.38), which was slightly lower than the 8.1 ms^{-1} value recorded during the Stuttgart World Championship (Maria et al. 2016). Thus, further development of the AV in this DV might not guarantee better vault performance. In contrast, slower approach velocities may put gymnasts at risk if horizontal velocity was insufficient but higher DVs were performed (Takei et al. 2000).

During the 1st flight phase, the gymnasts were required to displace their bodies from the springboard to the table, minimize their loss of horizontal moment conversion, and optimize their entrance angles for the 2nd flight phase (Koh and Jennings 2007). In the latter flight phase, the gymnasts were further scrutinized on whether they maintained the same direction as during the handspring, performed in a counter direction manner (Tsukahara), or performed rotations towards the table (Bradshaw et al. 2009; Koh and Jennings 2007). In a previous study utilizing elite gymnasts (Bradshaw et al. 2009), the table contact time was longer for the Tsukahara vault (0.22 ms^{-1}) which required the gymnast to contact the table with their hands in a consecutive manner compared to the simultaneous hand contact during a handspring (0.14 ms^{-1}) vault. This study recorded longer table contact durations (0.27 ms^{-1}) regardless of direction of rotation, possibly due to different DVs performed by the gymnasts. It may be necessary to consider the variations in body entrance angles or angular moment strategies to keep body entrance angles low and improve angular momentum for gaining more flight height and flight duration during the 2nd flight phase (Koh and Jennings 2007). In addition, the variability of hand positions, reaction force during table support, and distance between table and body, may be technical optimization factors that also need to be emphasized (Schwiezer 2003). Finally, the ability to convert horizontal moment to vertical velocity and angular momentum on the table are essential for improving vault performance (Hiley et al. 2015).

Previous studies have demonstrated that a successful 2nd flight phase depended on the technical elements produced in previous phases (Dainis 1981; Gervais 1994; Hiley et al. 2015; Koh and Jennings 2007). The quicker the table contact duration, the larger the potential for generating impulse to gain better height and flight duration before landing. The current data revealed that vaulting height did not discriminate according to DV values lower than 5.6 even though increased AV had been observed. On the other hand, AV was enhanced when DVs were between 4.0 and 5.2, with vaulting height and flight duration optimized. This kinematic characteristic explained the complexity of vault characteristics at different DVs, especially for elite gymnasts. Elite gymnasts tend to intensify upper- rather than lower-body strength to optimize performance during the 2nd flight phase when higher DVS (~5.6) are set, and alter table clearing techniques especially for DVs >5.2. However, when lower DVs were involved (4.0–4.8), the data suggests that gymnasts may need to emphasize good technique to achieve longer flight time.

As stated earlier, the current model consistently over-predicted judges' scores. The first possible reason could be related to the inclusion criteria. Although judges completed their evaluation after each gymnast landed on the mat and only successful landings were analyzed, landing kinematic related variables were not included in this study. However, any extra steps taken or oscillation movements caused additional score deductions from the E-judges that were included in the analysis. The second possible reason for over-predicted scores is related to the video recording speed. Both total duration (3 s) and recording speed (50 fps) may not provide sufficient information. These two aspects may have compromised modeling predictive accuracy.

A final point that could have influenced modeling predictive accuracy is related to the organization of vault technique training that associates DV with different vault phases. Gymnasts performing vaults with different levels of DV were required to work on different vaulting phases. For example, as a gymnast trains from low DV (4.0) work toward higher DV (4.8), he was required to improve AV and post-flight duration to be able to have better quality vault performance at 4.8 DV, and this is followed by the development of AV at a DV of 5.2. For the last progression to a DV of 5.6, he has to improve further on post-flight duration and MH. To be able to sustain the required kinematic standards with progressing DV, gymnasts have to acquire high levels of fitness and technical accuracy. Therefore, training objectives need to be sequenced correctly by coaches to monitor training, reduce the risk of injury and improve performance in elite artistic gymnastic vault performance.

CONCLUSION

Selected kinematic physical performance variables and known DV observed through 2D video analysis may potentially be sufficient to form a judges' scores prediction model without detailed technical input. The DVs analyzed in this study are limited to a range between 4.0 and 5.6 for groups I and II vault events. The different DV vault characteristics and the PLSR equation may assist coaches improve vault coaching, training monitoring, injury prevention, and offer a better scientific approach toward training.

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Conflicts of interest
There are no conflicts of interest.

REFERENCES

Atiković, A. (2012). New regression models to evaluate the relationship between biomechanics of gymnastic vault and initial vault difficulty values. *Journal of Human Kinetics*, *35*, 119.

Atiković, A., & Smajlović, N. (2011). Relation between vault difficulty values and biomechanical parameters in men's artistic gymnastics. *Science of Gymnastics Journal*, *3(3)*, 91-105.

Bradshaw, E., & Sparrow, W. A. (2001). The approach, vaulting performance, and judge's score in women's artistic gymnastics. In *XIX International Symposium of Biomechanics in Sports* (pp. 311-314). University of San Francisco, Exercise & Sport Science Department.

Bardshaw, E., Hume, P., Calton, M., & Aisbett, B. (2009). Reliability of a gymnastics vaulting feedback system. In Proceedings of the 27th *International Conference on Biomechanics in Sports* (2009) (pp.1-4). Retrieved from https://ojs.ub.uni-konstanz.de/cpa/article/view/3240. [Last accessed on 2021 Dec 10].

Dainis, A. N. (1981). A model for gymnastics vaulting. *Medicine and Science in Sports and Exercise*, *13(1)*, 34-43.

Dillman, C. J., Cheetham, P. J., & Smith, S. L. (1985). A kinematic analysis of men's Olympic long horse vaulting. *Journal of Applied Biomechanics*, *1(2)*, 96-110.

Federation Internationale de Gymnastique. (2016). Code of points for men's artistic gymnastics (2017th – 2020th ed.). Retrieved from http://www.fig-gymnastics.com/publicdir/rules/files/mag/CoP_MAG_2017-2020_ICI-e.pdf. [Last accessed on 2021 Dec 10].

Fernandes, S. M., Carrara, P., Serrão, J. C., Amadio, A. C., & Mochizuki, L. (2016). Kinematic variables of table vault on artistic gymnastics. *Revista Brasileira de Educação Física e Esporte*, *30*, 97-107.

Gervais, P. (1994). A prediction of an optimal performance of the handspring 1 12 front salto longhorse vault. *Journal of Biomechanics*, *27(1)*, 67-75.

Heinen, T., Vinken, P. M., & Velentzas, K. (2012). Judging performance in gymnastics: A matter of motor or visual experience? *Science of Gymnastics Journal*, *4(1)*, 63.

Hiley, M. J., Jackson, M. I., & Yeadon, M. R. (2015). Optimal technique for maximal forward rotating vaults in men's gymnastics. *Human Movement*

Science, *42*, 117-131.

King, M. A., & Yeadon, M. R. (2005). Factors influencing performance in the Hecht vault and implications for modelling. *Journal of Biomechanics*, *38(1)*, 145-151.

Koh, M., & Jennings, L. (2007). Strategies in preflight for an optimal Yurchenko layout vault. *Journal of Biomechanics*, *40(6)*, 1256-1261.

Koh, M., Jennings, L., Elliott, B., & Lloyd, D. (2003). A predicted optimal performance of the Yurchenko layout vault in women's artistic gymnastics. *Journal of Applied Biomechanics*, *19(3)*, 187-204.

Schurr, S. A., Marshall, N. A., Resch, J. E., & Saliba, S. A. (2017). Two-dimensional video analysis is comparable to 3D motion capture in lower extremity movement assessment. *International Journal of Sports Physical Therapy, 12(2)*, 163-172.

Schwiezer, L. (2003). *Vaults with the new table*. Lausanne: International Gymnastics Federation.

Takei, Y. (2007). The Roche vault performed by elite gymnasts: Somersaulting technique, deterministic model, and judges' scores. *Journal of Applied Biomechanics*, *23(1)*, 1-11.

Takei, Y., Blucker, E. P., Nohara, H., & Yamashita, N. (2000). The Hecht vault performed at the 1995 World Gymnastics Championships: Deterministic model and judges' scores. *Journal of Sports Sciences*, *18(11)*, 849-863.

Veličković, S., Petkovic, D., & Petkovic, E. (2011). A case study about differences in characteristics of the run-up approach on the vault between top-class and middle-class gymnasts. *Science of Gymnastics Journal*, *3(1)*, 25.

Veljković, A., Veličković, S., Sands, W. A., Đurović, D., & Trajković, N. (2016). Explosive power in gymnasts: Is there any scientific basis for gender differences? *Facta Universitatis, Series: Physical Education and Sport*, *14(1)*, 121-126.