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Run-up speed and jumping ground reaction force of male elite gymnasts on vault in China

Zhenke Tan [a,b,1], Xiaozhi Yao [a,1], Yuanyan Ma [c,1], Ye Bi [a,1], Yijia Gao [a,1], Yuanji Zhao [a,1], Nie Yingjun [a,*]

[a] *College of the Physical Education,Wuhan Sports University, Wuhan, 430079, China*
[b] *College of the Physical Education, Jishou University, Jishou, 416000, China*
[c] *College of the Sports, Huazhong Normal University, Wuhan, 430079, China*

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ABSTRACT

Background: A high run-up speed and a big jumping ground reaction force are crucial to perform difficult movements and improving the quality of movement performance in the competition vault. However, the relationship between performance in the competition vault and run-up speeds, as well as jumping ground reaction force, still needs to be discovered in detail.
Objective: We aimed to investigate the interrelations between different run-up speeds and jumping ground reaction force, and to explore the different requirements of performing different vault styles as well as difficult movements on run-up speed and jumping ground reaction force.
Methods: The data, including vaulting run-up speed and jumping ground reaction force of 30 Chinese male elite gymnasts of performance testing, were analyzed. Descriptive statistics and Binary logistic regression analysis were used for statistical analysis.
Results: There was no significant difference in the pedaling run-up speed between the Front handspring types and Cartwheel types ($p > 0.05$). The comparison between interval run-up speeds revealed that the last 5 m run-up speeds were faster during the 25 m run-up distance, and 30 m sprint speed was strongly associated with the 25 m vaulting run-up speed of Handspring and Cartwheel ($r = 0.81$, $p < 0.01$). There are significant differences in the jumping ground reaction force of different types and difficult movements ($p < 0.01$). When the D-score is greater than 4.6, the jumping ground reaction force will increase significantly. Jumping ground reaction force was strongly correlated with 25 m run-up speed ($r = 0.715$, $p < 0.01$), last 5 m run-up speed ($r = 0.718$, $p < 0.01$), and 30 m sprint speed ($r = 0.704$, $p < 0.01$) respectively, but not significantly associated with last 10-5 m run-up speed as well as before the last 10 m run-up speed ($p > 0.05$).
Conclusions: The special requirement for run-up speed and jumping ground reaction force may vary as the difficult vault. Moreover, the optimization of interval run-up speeds and improvement of the 25 m run-up speed may contribute to the bigger jumping ground reaction force and increase the potential to perform more difficult Handspring/Cartwheel vaults. The topic may merit an interventional study to optimize run-up rhythm and improve lower limb strength for achieving higher run-up speeds and bigger jumping ground reaction force within the limited run-up distance to perform more difficult vaults for male elite gymnasts in China.

* Corresponding author. College of the Physical Education,Wuhan Sports University, Wuhan, 430079, China.
E-mail addresses: 1789078529@qq.com (Z. Tan), 849021124@qq.com (X. Yao), 442707557@qq.com (Y. Ma), 469873995@qq.com (Y. Bi), 1130354527@qq.com (Y. Gao), 178090274@qq.com (Y. Zhao), 29907939@qq.com (N. Yingjun).
[1] Zhenke Tan, Xiaozhi Yao, Yuanyan Ma, Ye Bi, Yijia Gao, and Yuanji Zhao, contributed equally to this work and share first authorship.

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1. Introduction

Vaulting has developed rapidly, with multiple difficult vaulting maneuvers performed in international competitions in the past decade [1]. In competitive gymnastics vaulting, the final score is obtained by adding up the difficulty score (D-score), being judged by the difficulty of the selected movements, and the execution score (E-score), being judged by the completion quality of the selected movements [2]. An overwhelming body of evidence has demonstrated that a higher run-up speed and a greater jumping ground reaction force are crucial to perform difficult vaults and improving the quality of movement completion for achieving high final scores in competitions [3–5]. For example, the faster run-up speed and the greater power pedaling will benefit for athletes to generate better angular momentum and vertical velocity, as well as to achieve faster vertical axis rotation and better landing distance accordingly, which is conducive to perform difficult vaults in the second flight phase and achieve high E-sore [6]. Related research also reported that for every 7 % decrease in the horizontal and vertical speed, the athlete's landing distance would be reduced by 13 % and 25 % respectively [7], which has a serious impact on the E-score of the difficult vaults. In addition, the insufficiency of run-up speeds and jumping ground reaction force may increase the risk of injury when gymnasts perform more difficult movements (D-score) [8]. However, to this day, it is unclear what interval speeds during run-up are important to attain a high run-up speed and jumping ground reaction force, and what are the specific requirements of performing different difficult vaults on run-up speed and jumping ground reaction force. So to design specific vault training programs to help athletes reap the great benefits of run-up speed and jumping ground reaction force on better developing difficult vaults, a better understanding of the interrelationship between the levels of run-up speed as well as jumping ground reaction force and the different styles of the vault as well as different difficult vaults, is vitally important.

The overall competitive ability of Chinese gymnastics ranks among the top in the world and has provided a favorable experience for the training and competition of gymnastics. However, in recent years, the development of difficult vaults appeared to stagnate in China, and Chinese gymnasts' competitiveness in vaults is relatively lower in international competitions [9]. In this context, effectively developing difficult vaults has become a necessity to improve the competitiveness of Chinese gymnastics [10]. Related research reported that some main factors, such as weak leg strength, poor explosive power, and insufficient speed, seriously affected athletes to develop difficult vaults [11]. Significantly, the run-up speed and jumping ground reaction force are the core elements that affect athletes' performance quality of difficult vaults in competitions [12].

Therefore, this study tested the level of run-up speed and jumping ground reaction force of Chinese male elite gymnasts on vault, and aimed to investigate the interrelations between different run-up speeds and jumping ground reaction force, and to explore the different requirements of performing different vault styles as well as difficult movements on run-up speed and jumping ground reaction force. Tests and analyses such as the present study are essential for providing important references and evidence for coaches to optimize specific and tailoring training processes of run-up speed and jumping ground reaction force to better improve Chinese male elite athletes' performance of difficult vaults in competitions.

2. Methods

2.1. Subjects

The data of 30 male elite gymnasts who were all certified as Master Sportsman (the highest athlete's technical certification in China) were included in the analysis (age: 17.71 $\pm$ 1.64 years; average training duration: 13.7 years; height: 166.69 $\pm$ 5.51 cm; weight: 56.21 $\pm$ 4.78 kg). Gymnasts were not recruited specifically, but the performance testing procedures were an annual recurring part of the usual preparation of national gymnasts in six provinces (Hunan, Hubei, Zhejiang, Yunnan, Guizhou, and Guangxi). Full ethical approval was obtained from Wuhan Sports University, and all participants were informed about the testing procedures before the different tests, as well as given written informed consent to publish these case details.

2.2. Procedures

For the purpose of performance testing, participants were required to attend the tests in the standard gymnasium where the Chinese national team officially participates in training and competitions, including vaulting interval speeds within 25 m run-up distance and jumping ground reaction force from September 1, 2021, to January 10, 2022, in six provinces of Hunan, Hubei, Zhejiang, Yunnan, Guizhou, and Guangxi in China. According to the international standards for vault competition, the height of the men's vault is 1.35 m. The interval speeds include a run-up speed of 25 m, the speed before the last 10 m, the speed of the last 10-5 m, and the speed of the last 5 m on vault (Fig. 1). In addition, the 30 m sprint speed was tested due to this speed being a crucial talent selection index for evaluating the displacement velocity of gymnasts in China. During the test, the room temperature of the test venue was maintained at 25° Celsius to 27° Celsius, and the wind speed was less than 1 m per second, in order to minimize the impact of environmental factors on the athletes' vaulting performance. The run-up speed above was measured by the TCi - System 2018 infrared velocimeter, and all intervals run-up speed was calculated. Jumping ground reaction force was measured by a testing platform (a 9286B biomechanical portable multi-component force plate pressure test bench). The influence of the springboard on the data during the test can be eliminated by inputting the weight of the springboard into the force measurement program. The testing platform remains activated from the start of the run until the athlete completes the movement , is leveled with the floor and fixed under the springboard to ensure it will not interfere with the athlete's vaulting movements. The testing platform measures the downward force exerted by the athlete's body during contact with the springboard. The testing platform directly measures the jumping ground reaction force and automatically

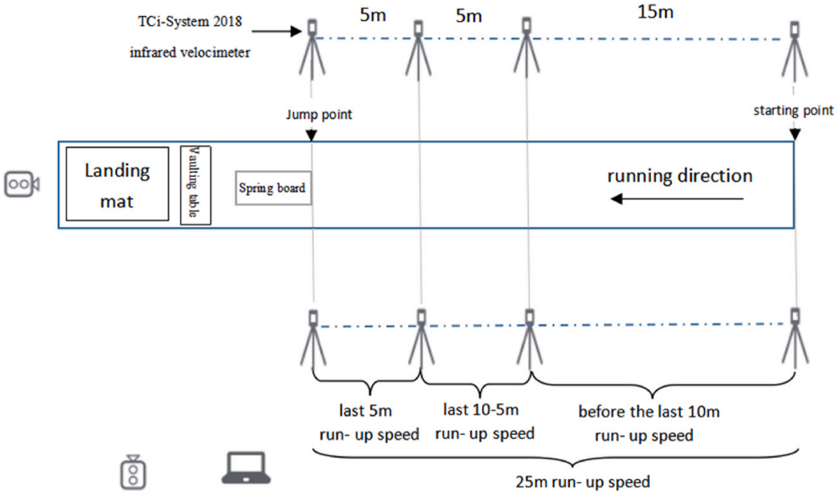

Fig. 1. Testing measurement of vaulting run-up speed and jumping ground reaction force.

Table 1
Vault movements being tested.

Vault movements		D - Score
Front handspring type	Front handspring group front flip (F1)	2.4
	Front handspring straight body front flip turn 180° (F2)	4.0
	Front handspring straight body front flip turn 540° (F3)	4.8
	Two-week front handspring front flip (F4)	5.2
	Front handspring straight body front flip turn 900° (F5)	5.6
Cartwheel type	Chukahala (C1)	2.2
	Straight body Chukahala turn 180° (C2)	3.6
	Straight body Chukahala turn body turn 360° (C3)	4.0
	Straight body Casamachu turn 540° (C4)	5.2
	Straight body Casamachu turn 720° (C5)	5.6
	Straight body Casamachu turn 900° (C6)	6.0

generates data and graphs. The units used in the test are Newtons (N). The testing procedures include an early preparatory phase in order to provide training recommendations for athletes and coaches.

Within two days, at the beginning of the week and after an individual warm-up, the athletes performed two competition vaults under training conditions (soft landing mat allowed). Infrared velocimeters have been positioned 10 m away from the springboard and 5 m away from both sides of the springboard. The pressure test bench has been fixed under the pedal (Fig. 1). This study focused on testing the run-up speed and jumping ground reaction force of the types of Front handspring and Cartwheel movements (Table 1) due to Chinese male gymnasts mainly choosing these two types of movements in training and competitions currently. The 30 m sprint speed has been tested on the track by the TCi-System 2018 infrared velocimeter.

2.3. Statistical analysis

SPSS software 26.0 is employed to analyze all obtained data. Descriptive characteristics of the gymnasts were presented as mean and standard deviation (M ± SD). To express the correlations among variables, Spearman correlation coefficients (r) were used. Binary logistic regression analysis was used to reveal the differences between the two vault types as well as difficulty movements in terms of run-up speed and jumping ground reaction force. A statistical significance level was at $p < 0.05$. Diagnostic tests, such as examining residual plots and conducting tests for multicollinearity, were performed to validate these assumptions. The results indicated that all assumptions were met, allowing us to proceed with the regression analyses.

3. Findings

3.1. Vaulting run-up speed

Overall, the run-up speed was gradually increasing in a limited run-up distance (25 m), and the interval speeds might vary in different vaulting run-up stages (Table 2). The interval run-up speed of the last 5 m was faster than other interval speeds.

A two-independent sample nonparametric test revealed that there was no significant difference in the vaulting run-up speed between the Front handspring type and Cartwheel type on the vault ($p > 0.05$). The interval run-up speeds were interrelated with difficult

Table 2
Vaulting run-up speed and sprint speed (m/s).

Interval speed of Vaulting run-up	Min	Max	M±SD
25 m run-up speed	5.50	7.43	6.36 ± 0.43
before the last 10 m run-up speed	4.46	8.45	5.88 ± 0.96
the last 10-5 m run-up speed	5.81	8.62	6.70 ± 0.94
the last 5 m run-up speed	6.85	8.62	7.87 ± 0.48
30 m sprint speed	6.58	8.15	7.76 ± 0.39

M = mean; SD = standard deviation.

Table 3
Interval run-up speed of different movements in the Cartwheel type (m/s).

Interval speed of Vaulting run-up	C1 (M ± SD)	C2 (M ± SD)	C3 (M ± SD)	C4 (M ± SD)	C5 (M ± SD)	C6 (M ± SD)	F	P
25 m run-up speed	6.37 ± 0.49	6.35 ± 0.28	6.43 ± 0.43	6.01 ± 0.56	6.06 ± 0.63	6.19 ± 0.60	1.604	0.212
before the last 10 m run-up speed	6.73 ± 1.42	5.89 ± 0.56	5.82 ± 0.76	5.13 ± 0.44	5.02 ± 0.23	5.55 ± 0.60	1.956	0.037
the last 10-5 m run-up speed	5.64 ± 1.24	6.56 ± 0.80	7.01 ± 0.77	7.04 ± 0.55	7.69 ± 0.58	6.52 ± 1.18	0.757	0.592
the last 5 m run-up speed	7.20 ± 0.58	7.76 ± 0.51	8.06 ± 0.43	8.20 ± 0.34	8.47 ± 0.16	8.14 ± 0.47	1.770	0.015

M = mean; SD = standard deviation.

Table 4
Interval run-up speed of different movements in the Front handspring type (m/s).

Interval speed of Vaulting run-up	F1 (M ± SD)	F2 (M ± SD)	F3 (M ± SD)	F4 (M ± SD)	F5 (M ± SD)	F	P
25 m run-up speed	5.96 ± 0.28	6.30 ± 0.27	6.36 ± 0.16	6.47 ± 0.63	6.09 ± 0.34	2.297	0.104
before the last 10 m run-up speed	5.05 ± 0.4	5.95 ± 0.92	5.41 ± 0.43	5.97 ± 1.06	5.22 ± 0.56	3.316	0.037
the last 10-5 m run-up speed	7.15 ± 0.29	6.86 ± 1.48	7.94 ± 0.46	6.73 ± 0.19	6.94 ± 0.48	1.154	0.024
the last 5 m run-up speed	8.20 ± 0.19	7.78 ± 0.34	8.2 ± 0.47	8.03 ± 0.40	8.50 ± 0.26	4.333	0.015

M = mean; SD = standard deviation.

movements (D-score), and the run-up speed increased with the increase of D-score in the same type generally (Table 3 and Table 4, $P < 0.05$).

In order to provide individual training references and evidence for coaches and athletes, all interval speeds of each participant have been further analyzed, and we found that a few athletes' speed of the last 5 m was slightly lower than the last 10-5 m, and several athletes' speed of the last 10-5 m was lower than the speed before the last 10 m in the Cartwheel type (Fig. 2).

3.2. Jumping ground reaction force

Jumping ground reaction force showed significant difference between Front handspring and Cartwheel types ($p < 0.05$). The jumping ground reaction force may vary with the different types of movements, and the jumping ground reaction force of Cartwheel type movements was lower than that of the Front handspring type (Table 5). In addition, the jumping ground reaction force of excellent gymnastics reached 5301.76 N, which was about ten times the average of the athlete.

As shown in Table 6, there are significant differences in jumping ground reaction force of movements of different difficulty ($P < 0.01$). And the higher the D-sore, the greater the jumping ground reaction force. For difficult movements with D-sore above 4.8, the

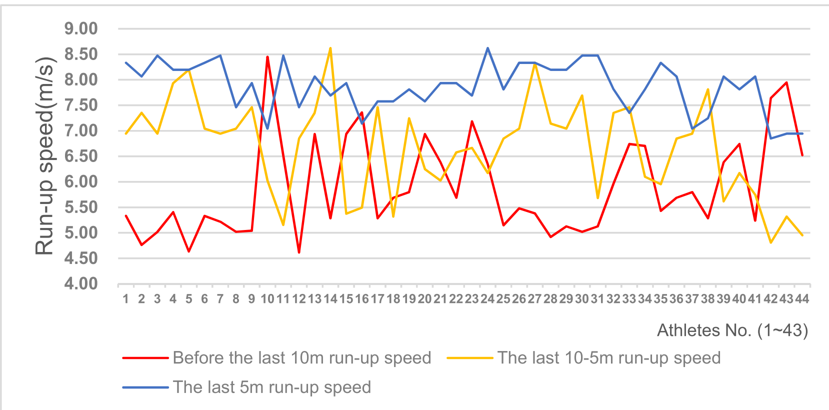

Fig. 2. Linear graph of run-up speed (m/s) .

Table 5
Jumping ground reaction force of Front handspring/Cartwheel types (N).

Movements Type	Jumping ground reaction force (M ± SD)
Total	5301.76 ± 1096.52
Front handspring type	5472.33 ± 910.82
Cartwheel type	5114.95 ± 1265.86
F	1.717
P	0.028

M = mean; SD = standard deviation.

jumping ground reaction forces were generally above 5000 N, and the jumping ground reaction force for the movements with a D-sore of 5.6 and above might be reach above 6000 N.

3.3. Interrelations between vaulting run-up speed and jumping ground reaction force

Our study found jumping ground reaction force was strongly correlated with 25 m run-up speed($r = 0.715$, $p < 0.01$), the last 5 m run-up speed ($r = 0.718$, $p < 0.01$), and 30 m sprint speed ($r = 0.704$, $p < 0.01$) respectively, but not significantly associated with last 10-5 m run-up speed as well as before the last 10 m run-up speed (Table 7, $p > 0.05$).

Jumping ground reaction force was taken as the dependent variable, and 25 m run-up speed (a) , before the last 10 m run-up speed (b), the last 10-5 m run-up speed (c), the last 5 m run-up speed (d) and 30 m sprint speed (e) were taken as the regression independent variables.The probability of companionship was 0.000 (Table 8), which was considered to be able to describe the companionship relationship with the multiple linear regression model, and the corresponding regression coefficients table was continued (Table 9). After eliminating the indicators with P-value greater than 0.05 in the table of regression coefficients, and derive the regression equation Y of the jumping ground reaction force and run-up speed as:

$Y = -7513.523 + 4735.785*a-2582.575*b-826.76*c-68.446*d+524.192*e.$

Table 6
Jumping ground reaction force of different movements (N).

Movements	Jumping ground reaction force (M ± SD)
C1	3198.1 ± 276.47
F1	5211.34 ± 609.45
C2	4925.79 ± 725.22
C3	4567.94 ± 846.08
F2	5295.23 ± 163.25
F3	5270.34 ± 102.48
F4	5720.58 ± 229.45
C4	5519.33 ± 467.54
F5	6336.22 ± 1322.24
C5	6139.31 ± 716.96
C6	6983.05 ± 706.81
P	0.001

M = mean; SD = standard deviation.

Table 7
Correlation between interval run-up speed and jumping ground reaction force.

Speed		25 m run-up speed	Before the last 10 m run-up speed	The last 10-5 m run-up speed	The last 5 m run-up speed	30 m sprint speed
Jumping ground reaction force	r	0.715	−0.145	0.245	0.718	0.704
	p	0.001	0.56	0.87	0.001	0.001

Table 8
Linear regression model analysis of variance table.

	Quadratic Sum	Free Degree	Mean Square	F	P
Recurrence	23300000.00	5	4660140.945	6.235	.000
Residual Error	28400000.00	38	747382.508		
Total	51700000.00	43			

Table 9
Linear regression model analysis of variance.

	Non-standardized coefficients		standard coefficient	T	P
	Regression Coefficient	Standard Error	β		
constant	−7513.523	4341.434		−1.731	0.002
25 m run-up speed	4735.785	1668.5	1.907	2.838	0.047
before the last 10 m run-up speed	−2582.575	1024.193	−2.223	−2.522	0.000
the last 10-5 m run-up speed	−826.76	376.241	−0.709	−2.197	0.003
the last 5 m run-up speed	−68.446	456.072	−0.03	−0.15	0.033
30 m sprint speed	524.192	467.71	0.188	1.121	0.016

4. Discussions

4.1. Interval speed of vaulting run-up

This study showed that the run-up speed of elite male gymnasts was a slow acceleration in the early stage and then started to explode in the last 10-5 m, reaching the maximum speed in the last 5 m. The maximum speed in the limited vaulting run-up distances (25 m) appeared in the last 5 m generally, which may be beneficial to steadily improve the step frequency and stride length in the final stage of the run-up to improve the run-up rate, as well as to do the follow-up action in vaulting. Related studies showed that the speed of vaulting run-up of Olympic gymnasts was 7.93 m/s [13], even reaching 9.95 ± 0.74 m/s in the last step and 8.58 ± 0.18 m/s in the penultimate step, and the run-up speed of the world's best athletes could reach 8.6 m/s in the vaulting [14]. Thus, it can be seen that the run-up speed of Chinese male elite gymnasts in vaulting may need to be further improved.

This study showed a part of the athletes experienced a deceleration in intervals speed with the increase in run-up distance. This may be due to insufficient lower limb strength or total body maximum strength [15] and may be related to other factors, such as neural control, technical mastery and running posture.

In addition, run-up speed is different from 30 m sprint running speed and may be coordinated with the individual's special technical ability so that the professional technical level and the running speed can reach a dynamic balance and form a better and exclusive running rhythm [16]. If the speed of the vaulting run-up reaches the fastest level in advance, it will easily cause a disordered run-up rhythm at the later stage and a sharp drop in horizontal speed when the board is on, which may affect the quality of the vaulting. Therefore, athletes should strengthen the rhythm of running training in daily training and form a relatively fixed incremental type of running speed rhythm. At the same time, strengthening the core strength quality is necessary for improving the stability of running rhythm in vaulting run-up.

Related research has shown that different types of vaulting movements require different horizontal speeds of vaulting run-up [1], e.g., the last 5 m running speed of the Front handspring may be higher than that of the Cartwheel category, due to without any rotation around the longitudinal axis of the body during the pedaling and bracing phases [17]. However, we have yet to find this difference. This inconsistency can be further analyzed in terms of the different spatial requirements of the different types of movements when pedaling onto the board.

The speed of the vaulting run-up increased gradually and reached the highest speed in the last 5 m, and the higher the difficulty of the movement, the faster the speed of the last 5 m. Related studies also showed that the running speed increased with the increase of the D-score, and the difficulty score of 4.6 may be the watershed of the athletes' running speed. The run-up speed may be much faster for movements with a score above 4.6 than that with a score below 4.6 [18]. This may be due to the fact that the greater the difficulty, the higher the required horizontal speed. In order to ensure the D-score and E-score of the movement [19], gymnast may actively increase their own running speed when approaching the vault pedal [20].

4.2. Jumping ground reaction force of vaulting run-up

Related studies have shown that the higher the difficulty of vaulting movements, the higher the requirements for pedal power and vertical speed. Furthermore, the greater the jumping ground reaction force, the greater the upward reaction force for gymnasts, which may be more favorable to producing higher pedaling height and faster vertical speed [21,22]. Combined with the results of this study, a possibility was found that the higher the difficulty of an athlete completing a movement, the greater the required jumping ground reaction force, in order to provide sufficient motivation for the athlete.

A significant difference shows between the jumping ground reaction force of the types of Front handspring and Cartwheel movements ($p < 0.05$). Cartwheel vaults are consisted of run-up and performing round-off which ends with a take-off on the springboard. Related studies reported that the gymnasts must be fully prepared for the next rotating action when pedaling, which may result in gymnasts not being able to pedal as fully as when doing the Cartwheel action [23], thus reducing the jumping ground reaction force. But related research have found no significant difference between the jumping ground reaction force of them [24]. And more research is necessary to explain such inconsistent findings.

In addition, the standard deviation of the jumping ground reaction force was too relatively large, which indicated that the jumping ground reaction force varies among male elite gymnasts in China. This may be due to personal pedaling habits, height, and weight. Related research also indicated that some coaches might be too limited in using technical movements to develop gymnasts' strength, and the measures and content of training also were too single to comprehensively develop gymnasts' lower limb explosive strength [25]. Therefore, the gymnasts' core strength, especially lower limb strength, should be developed with multiple measures in the daily training, which could be beneficial to the development of more difficult and innovative vault movements.

4.3. Correlation between interval speed of vaulting run-up and jumping ground reaction force

This research found a significant, but not linear, correlation between jumping ground reaction force and run-up speed. Some research also reported that for every 0.2 m/s increase in run-up speed, there is a 2 % increase in the explosive power of the lower limb muscles [26]. However, when the gymnasts' run-up speed reaches a certain range, their jumping ground reaction force will no longer increase; after exceeding the threshold, the gymnasts' jumping ground reaction force will instead show a decreasing trend, and it will easily lead to inaccurate pedal position affecting the quality of the movement negatively.

A highly significant correlation has been found between the athletes' jumping ground reaction force and the last 5 m run-up speed. Related research showed that the vaulting power was related to the horizontal speed and the height of the body's center of gravity before jumping. The run-up speed of the last 5 m may determine gymnasts' horizontal speed when jumping. In addition, the shorter the gymnasts' pedaling time, the smaller the horizontal speed loss rate, the higher the vertical speed utilization, and the better the pedaling effect[1,15].

4.4. Limitations

Firstly, there are multiple factors affecting the run-up speed and jumping ground reaction force of male elite gymnasts in vaulting, and it is necessary to further analyze the characteristics of the run-up and pedaling from various aspects, such as personal characteristics, technical characteristics, step frequency, stride length, body weight, body angle, etc. Secondly, our study analyzed Front handspring and Cartwheel movements due to Chinese male gymnasts mainly choosing these two types of movements in training and competitions currently. With the diversified development of vaulting horse movements, the scope of the investigation and the sample of subjects can be improved in the future. Finally, run-up speed and jumping ground reaction force mainly lead to the high quality of the actions, so it is necessary to analyze run-up speed and Jumping ground reaction force more precisely by combining the performed quality of the movements.

5. Conclusion

The run-up speeds and jumping ground reaction force is closely related to the vault D-score. The interval run-up speeds are different at different run-up stages on the vault. The jumping ground reaction force was strongly correlated with the 25 m run-up speed and the last 5 m run-up speed. The run-up speed and running rhythm of Chinese male elite gymnasts in the limited run-up distances (25 m) should be emphasized in future training. The optimization of interval run-up speeds by improving lower limb strength may contribute to bigger Jumping ground reaction force and increase the potential to perform more difficult Handspring/Cartwheel vaults for male elite gymnasts in China.

Data availability statement

Data included in article/supp. material/referenced in article. Data will be made available on request.

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CRediT authorship contribution statement

Zhenke Tan: Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Xiaozhi Yao:** Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Yuanyan Ma:** Investigation, Methodology, Project administration, Resources. **Ye Bi:** Investigation, Methodology, Project administration, Resources. **Yijia Gao:** Investigation, Methodology, Project administration, Resources. **Yuanji Zhao:** Conceptualization, Resources, Supervision. **Nie Yingjun:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Full ethical approval was obtained from Wuhan Sports University (WHSU-07038854), and all participants were informed about the testing procedures before the different tests, as well as given written informed consent to publish these case details. We would like to acknowledge the support of Wuhan Sports University. We also would like to express our sincere thanks to the editor and reviewers for their helpful comments.

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