KINEMATIC CHARACTERISTICS OF THE APPROACH RUN ON HANDSPRING VAULT BY HIGH LEVEL MALE GYMNASTS

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Abstract

The approach run is a fundamental precondition for successful vault performance, as it enables the gymnast to develop maximum controlled horizontal velocity. The purpose of this study was to investigate the length, frequency, and velocity of steps during the run-up phase (approach run) in the execution of the handspring vault on the vaulting table. Nine high-level male artistic gymnasts, who performed the handspring vault under training conditions, volunteered to participate in the study. Five video cameras—four stationary and one scanning—were used to record the run-up phase, the hurdle step, and the take-off from the springboard. The gymnasts performed six trials of the handspring vault with a three-minute rest between each trial. Results showed that the final step was shorter than the penultimate step, and the penultimate step was longer than the preceding step. Additionally, the gymnasts demonstrated a gradual increase in their run-up velocity, a key requirement for a successful jump, up to the penultimate step. The average step frequency among gymnasts ranged from 3.20 to 4.88 steps per second, while the average step velocity across the six attempts was between 4.03 and 7.37 m/sec. Finally, a gradual increase in the gymnast's velocity was observed up until the last step, with the final step being shorter than the penultimate step and the penultimate step being longer than the one before it.

Keywords: *Kinematic characteristics, step length, approach run, hurdle step, handspring vault.*

INTRODUCTION

Vaulting in artistic gymnastics (AG), is the only event that consists of a single exercise, and due to the complexity of the movements involved is the most researched and best understood apparatus (Prassas et al., 2006). Vaulting is one of the events of AG that characterized by very short duration lasting up to five to six seconds (Čuk & Karacsony, 2004) and consisted by seven phases; (i) run-up, (ii) hurdle step, (iii) take-off form board, (iv) 1st flight phase, (v) push-off, (vi) 2nd flight phase, and (vii) landing (Takei, 2007). The approach run is one of the basic preconditions for successful performance on the vault as it enables the gymnast to developed the maximum possible controlled horizontal velocity which facilitates proper execution of the next phases (Veličković et al., 2011). Running velocity, is one of the most crucial elements for a good vault, as listed by previous authors (Atiković & Smajlović, 2011; Cuk & Karacsony, 2004). Previous findings by Čuk et al. (2007) who investigated the relationship between the difficulty values (DV) of vault and runway velocity in top level male artistic gymnasts revealed that the correlation between each gymnast's runway velocity and DV of the vault was much lower than the correlation between average velocity of the jump and its DV. Furthermore, the study by Atiković (2012) who investigated the relation between vault difficulty value and biomechanical parameters in men's AG, revealed that the best model only predicted the second flying phase with 95% of the variation explained. Furthermore, the approach run is not performed just to develop the gymnasts the maximum possible velocity but involves complicated motor control as gymnasts must balance the velocity requirements with an accurate take-off (Bradshaw, 2004). Thus, the goal of the gymnasts to achieve the maximum controlled take-off angle and take-off velocity during the last stride, hurdle step, relies on maximizing step velocity (SV) during the approach run phase. Increasing approach velocity has resulted in higher velocity at springboard take-off, an increase in temporal parameters in 1st and 2nd flight phases, and a decrease in springboard and vault contact times which permit greater number of body rotations during second flight phase (Farana et al., 2013). During take-off from the springboard and vaulting table, the horizontal kinetic energy that was gathered during the run-up, is converted into angular and vertical kinetic energy to facilitate an optimal second flight phase (Prassas et al, 2006). The development of the necessary propulsion on the springboard in order to gain enough height and distance for hand-placement on the vaulting table is heavily dependent on the velocity achieved at the last step of the approach and the resultant take-off velocity and angle prior to landing on the springboard (i.e. the hurdle step). Further, increasing post-flight time provides gymnasts with the ability to complete more complex acrobatic movements, increasing the degree of difficulty and the potential for a higher score (Bradshaw, Hume, Calton & Aisbett, 2010).

The technique of performing the approach run in vaulting, particularly during the final two steps and the hurdle, differs significantly from running in simpler conditions where a hurdle step is not required after the last stride (Meeuwsen and Magill, 1987). Considering that the hurdle step must be executed from a precise distance, which is largely dependent on the velocity achieved during the last stride, the primary objective for gymnasts is to maximize step velocity (SV). This is accomplished by increasing both step frequency (SF) and step length (SL), the two components that constitute SV (Hunter et al., 2004), although these components are inherently different.

However, SF and SL during sprint running exhibit a negative interaction due to the conflicting demands associated with increasing each (Hunter et al., 2004; Salo et al., 2011). The importance of approach velocity is underscored by Tashiro et al. (2008), who highlight its significant contribution to the successful execution of the vault. Numerous studies have also emphasized the positive correlation between run-up velocity and gymnastic scores (Sands & McNeal, 1995; Takei, 1988; Takei et al., 1996). According to Sands (2000), the run-up phase is considered one of the predictors of a successful vault, with maximum running velocity and the number of steps being crucial elements in this prediction.

The initial increase in velocity, up to sub-maximum levels of around 6 m/s, is primarily due to an increase in SL (Thorstensson & Robertson, 1987). Following this, further increases in velocity are largely attributed to an increase in SF (Kuitunen et al., 2002; Mero & Comi, 1985; Weyand et al., 2000).

When performing the approach run, gymnasts progressively increase their velocity as they near the springboard, aiming to achieve maximum possible speed during the take-off phase. This increase in velocity enables experienced gymnasts to execute better rotations around the body axes, thanks to greater speed and push, allowing them to perform vaults efficiently even at very high speeds (Penitente et al., 2007). As Bradshaw (2004) noted, the run-up phase during vaulting can be divided into two distinct phases: (a) an accelerative phase, where the gymnast builds velocity, and (b) a visually controlled (targeting) phase, where, once near top velocity, gymnasts use their vision to regulate their step pattern, ensuring they 'hit' the springboard in the optimal position for take-off. According to the existing literature, this study is the first to examine the entire run-up phase on the vaulting table with high-level gymnasts performing the handspring vault.

METHODS

The sample consisted of nine high level male artistic gymnasts (mean age 23.33 ± 5.22 years; body mass: 62.89 ± 6.47 kg; height: 169.22 ± 06.51 cm) that were voluntarily participated in this study. They were members of national team with average training experience 19.00 ± 5.45 years and participating in international competitions. After being informed of the purpose of the study, it was clarified that they have the right to leave at any time during the experimental process if they so wished. Approval for the investigation was obtained from the School of Physical Education and Sport Science's, of the National and Kapodistrian University's ethics committee (1350/03-03-2022). Written informed consent was obtained from the participants. The study was conducted in accordance with the Declaration of Helsinki for human experimentation.

The experimental task involved the run-up phase (approach run) for executing a handspring on the vaulting table, with each gymnast using their full individual approach run. A personalized warm-up, similar to what they typically perform before a competition, preceded each set of handspring vaults. The approach run distance was measured from the leading edge of the vaulting table, and the springboard was positioned according to the gymnasts' self-selected springboard-to-vaulting table distance. Gymnasts were instructed to perform each vault with maximum effort. A six-minute passive rest period was observed between each trial.

Prior to testing, a familiarization session was conducted where all gymnasts performed three handspring vaults, with 3-minute recovery periods between each vault. This session allowed for the accurate determination of (a) the length of their approach run, (b) the springboard-to-vaulting table distance (BTD), and (c) the distance between the last support phase of the approach run (take-off to hurdle step) and the springboard. Two days after the familiarization procedure, the gymnasts returned to the gymnasium to perform six handspring vaults.

According to the guidelines of the International Gymnastics Federation (F.I.G., 2022), the vaulting event consists of an approach runway, a springboard, and a vaulting table set at a height of 1.35 m. The 25-m long and 1-m wide runway is marked with custom black-and-white markers placed at 1 m intervals along its length, parallel to the boundaries' long axis. White tape strips were also placed at the four edges of the springboard for added precision.

The approach phase towards the vault table was recorded using one panning and four stationary high-speed video cameras (Casio Computer Co. Ltd, Exilim-Pro-EX-F1, Shibuya, Japan) at a sampling rate of 300 fps (resolution: 512 × 384 pixels). The position of each camera, along with the overall process of recording and analyzing the kinematic characteristics of the approach run, followed procedures outlined in a previous study (Dallas & Theodorou, 2020).

Twenty-two anatomical points (including the tip of the toe, 5th metatarsal, heel, ankle, knee, hip, shoulder, elbow, wrist, and 5th metacarpal on both sides of the body, the 7th cervical vertebra, and the top of the head) were marked with spherical markers of 0.02 m in diameter. These markers were attached to the skin using black double-sided adhesive tape to create a white-on-black contrast. The collected videos were digitized using kinematic analysis software (Ariel Dynamics Inc., APAS v13.3.0.3, Trabuco Canyon, CA, USA), and the coordinates of the body’s center of mass (CoM) were calculated for every frame based on the anatomical data provided by Plagenhoef (1985).

A second-order low-pass Butterworth filter with a cut-off frequency of 6 Hz was applied for smoothing the data. The accuracy of the 2D reconstruction was determined by the root mean square error (RMSE), calculated after randomly re-digitizing 10% of the captured frames. An error of 0.45 cm and 0.63 cm was found for the X (horizontal) and Y (vertical) axes, respectively.

Toe–table distances (TTDs) for each foot placement during the gymnasts' approach run were measured using a 5-point model. This model included the toe-off point during the support phase (contact) of the gymnast’s foot on the ground and the four markers surrounding the foot at ground contact (Hay & Koh, 1988). The support phase refers to every instance of the gymnast’s foot contacting the ground while running on the runway, hurdling, or stepping on the springboard. The horizontal distance between the toe and the line formed by the two closest digitized markers (toe–marker distance) was obtained. TTD was then calculated by adding the toe–marker distance to the marker–table distance.

The validity of this procedure for calculating the TTD was assessed by recording test panning and stationary videos from each respective camera, with a gymnast placing his foot on the runway at known distances (0.10 m, 1 m, 2 m, 3 m, and every 2 m thereafter up to 25 m from the front edge of the vaulting table) (Berg & Mark, 2005; Bradshaw, 2004). The TTD of the ‘calibration feet’ was then calculated using the aforementioned method. The comparison between the actual TTD and the TTD derived from video analysis revealed a mean absolute error of 0.01 m in the measured distances.

The accuracy of the kinematic analysis was further determined through intra-researcher reliability. For this purpose, 10% of the recorded frames were re-digitized, and the same data analysis was conducted. The intraclass correlation coefficient (ICC) was found to be 0.998 (95% confidence interval: 0.997–0.999).

A step was defined as the distance between two consecutive foot touchdowns (support phases), and its length was calculated by subtracting the consecutive TTDs. TTDs and step lengths were calculated for all support phases and steps, respectively, of each gymnast’s approach run. The distance from the toe to the leading edge of the springboard at the moment of landing on the springboard was identified as the toe–board distance (TBD).

Based on the XY coordinates extracted from the digitized anatomical points, the following kinematic (dependent) variables (DV) were calculated for the approach run: (a) step length [cm], (b) step frequency [steps/sec], (c) horizontal velocity [m/sec], and (d) length of the hurdle step [m]. The duration (contact time) of the support phase during the hurdle step (TClast) and on the springboard (TCsb) was defined as the time elapsed (in seconds) from the initial contact to the final contact of the foot with the ground or springboard, respectively. Descriptive statistics were employed to calculate the aforementioned DVs during the performance of the approach run.

All statistical analyses were conducted using SPSS software (SPSS v. 28, IBM Corp., NY). In the initial stage of data processing, kinematic characteristics (length, frequency, and speed) were recorded for all six attempts of each athlete. Descriptive statistics were then employed to compute the means and standard deviations of the dependent variables across each athlete's six attempts. Subsequently, an analysis of variance with repeated measures was performed to assess differences between individual running steps.

RESULTS

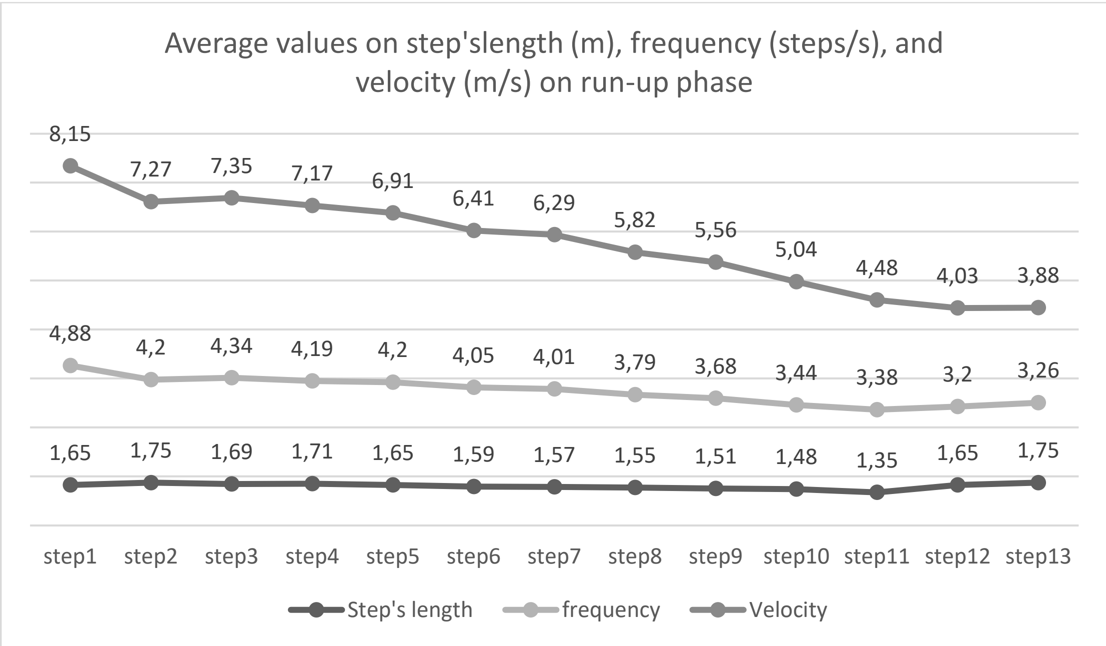
Kinematic analysis showed that the mean step length across the six attempts was 156.31 ± 8.78 cm. Detailed values for each gymnast are presented in Table 1.

Furthermore, the average step frequency across 6 attempts was 3.85 ± 0.31 steps per second. Detailed values for each gymnast are presented in Table 2.

Kinematic analysis showed that the average step velocity of the gymnasts during the entire approach run was 6.03 ± 1.36 m/sec. Detailed values for each gymnast are presented in Table 3.

However, the run-up phase of the gymnasts is characterized by a continuous increase in horizontal velocity and step frequency, while step length generally increases. Notably, the penultimate stride is on average 10 cm shorter than the final stride (see Graph 1).

The repeated measures analysis revealed a statistically significant difference in running steps between individual strides ($F = 16.520$, $p < .001$). Significant differences were noted in the 2nd, 3rd, 4th, 5th, 7th, and 8th strides.



Graph 1. Characteristics of the run up phase

Table 1. *Data on the average step length for each gymnast across 6 attempts on handspring vault.*

Step	G1	G2	G3	G4	G5	G6	G7	G8	G9	x ± sd
HS	294	310	280	276	311	294	314	312	316	300.78±15.24
LS	175	182	167	150	155	163	174	161	160	165.22±10.26
S2	165	178	184	156	175	194	192	171	160	175.00±13.42
S3	169	179	167	156	174	171	181	166	161	169.33±8.04
S4	163	186	171	158	181	174	187	163	158	170.89±11.03
S5	158	168	173	161	169	163	168	163	160	164.78±4.94
S6	147	170	170	152	176	175	145	149	149	159.22±13.11
S7	144	161	165	163	166	155	159	144	155	156.89±8.26
S8	140	159	161	169	168	160	145	143	154	155.89±10.00
S9	138	148	146	160	169	170	140	140	149	151.11±12.32
S10	138	153	145	168	162	157	137	136	134	147.78±12.60
S11	123	137	148	141	145	128	125	136		135.37±9.27
S12	119	109	137	138	115	125	130			124.71±11.02
S13	107		144		113	112				119.00±16.87
X	145.07	160.83	159.84	156.00	159.07	157.46	156.91	152.00	154.00	159.22±11.56

G: Gymnast; HS: Hurdle step; LS: Last step; S: Step; x: mean value; sd: standard deviation

Table 2. *Data on the average step frequency (s $^{-1}$) (step/sec) for each gymnast across 6 attempts on handspring vault.*

Step	G1	G2	G3	G4	G5	G6	G7	G8	G9	x ± sd
LS	5.00	4.82	4.10	5.46	5.00	5.14	4.76	4.80	4.89	4.88 ± 0.36
S2	4.27	4.11	4.22	4.60	3.93	4.14	3.92	4.13	4.52	4.20 ± 0.23
S3	4.32	4.15	4.04	4.72	4.12	4.59	4.24	4.18	4.73	4.34 ± 0.26
S4	4.47	3.91	4.04	4.47	3.74	4.26	4.08	4.13	4.61	4.19 ± 0.28
S5	4.38	3.95	3.79	4.54	3.89	4.45	4.35	4.01	4.47	4.20 ± 0.29
S6	4.45	3.78	3.78	4.24	3.54	4.10	4.10	3.94	4.53	4.05 ± 0.32
S7	4.26	3.73	3.62	4.15	3.59	4.23	4.36	3.94	4.27	4.01 ± 0.30
S8	4.22	3.44	3.58	3.83	3.09	3.65	4.13	3.86	4.36	3.79 ± 0.40
S9	4.00	3.35	3.31	3.81	3.03	3.74	4.13	3.67	4.11	3.68 ± 0.38
S10	3.94	2.96	3.10	3.41	2.76	3.39	3.85	3.52	4.05	3.44 ± 0.45
S11	3.81		2.99	3.57	2.69	3.30	3.57	3.31	3.84	3.38 ± 0.39
S12	3.68		2.73	3.23		2.99	3.03	3.10	3.65	3.20 ± 0.35
S13	3.44			3.18				2.87	3.56	3.26 ± 0.30
X	4.17 (0.40)	3.82 (0.51)	3.60 (0.48)	4.09 (0.66)	3.58 (0.67)	3.99 (0.61)	4.04 (0.43)	3.80 (0.51)	4.27 (0.42)	3.89 (0.49)

G: Gymnast; LS: Last step; S: Step, x: mean value; sd: standard deviation

Table 3. *Data on the average step velocity (m/sec) for each gymnast across 6 attempts on handspring vault.*

Step	G1	G2	G3	G4	G5	G6	G7	G8	G9	x ± sd
LS	8.78	8.79	7.55	8.21	7.77	8.40	8.32	7.75	7.79`	8.15 ± 0.46
S2	7.05	7.35	7.05	7.17	6.91	8.07	7.53	7.09	7.25	7.27 ± 0.35
S3	7.33	7.44	6.90	7.38	7.20	7.86	7.67	6.90	7.55	7.35 ± 0.32
S4	7.29	7.17	7.04	7.09	6.78	7.44	7.67	6.75	7.30	7.17 ± 0.29
S5	6.95	6.65	6.43	7.33	6.60	7.27	7.35	6.53	7.16	6.91 ± 0.37
S6	6.57	6.44	6.25	6.46	6.25	7.19	5.94	5.89	6.78	6.41 ± 0.40
S7	6.16	6.04	5.85	6.78	5.96	6.58	6.96	5.69	6.64	6.29 ± 0.45
S8	5.92	5.47	5.25	6.51	5.19	5.84	6.00	5.54	6.74	5.82 ± 0.53
S9	5.54	4.97	4.79	6.11	5.14	6.37	5.82	5.16	6.14	5.56 ± 0.57
S10	5.46	4.56	4.24	5.75	4.50	5.32	5.30	4.80	5.43	5.04 ± 0.52
S11	4.70		3.31	5.30	3.81	4.79	4.60	4.18	5.21	4.48 ± 0.68
S12	4.40		3.11	4.42		4.13	3.50	3.90	4.78	4.03 ± 0.57
S13	3.70			4.60				3.28	3.96	3.88 ± 0.55

G: Gymnast; LS: Last step; S: Step, x: mean value; sd: standard deviation

DISCUSSION

The contribution of this research is particularly important since it recorded the entire run-up phase of the gymnasts, unlike most other studies that focus on only the last two to four steps. Variations in the length of the final strides are attributed to the visual adjustments athletes make to precisely approach the vault. The run-up phase for the gymnasts ranged from 21.15m to 24.26m (average: 23.16 ± 0.85m) and comprised 10-13 strides. The average run-up length was 23.16m, with an average of 12.11 steps, a step length (SL) of 1.67m, a step frequency (SF) of 3.93 steps/sec, and a step velocity (SV) of 6.18 m/sec. The average length of the hurdle step was 3.01m, consistent with estimates for Olympic male gymnasts (Uzunov, 2007). Our findings regarding the run-up distance are comparable to those of Heinen et al. (2013), who reported an average approach-run distance of 19.56 ± 0.29m to the leading edge of the vaulting table.

The results revealed a progressive increase in velocity from the first to the last step, which is a key requirement of the run-up phase. However, a slight decrease of -1.08% was observed in the penultimate step (7.35 vs. 7.27 m/sec). This increase in velocity is primarily due to the rise in step length (SL) (Thorstensson & Roberthson, 1987) and step frequency (SF) (Kuitunen et al., 2002). The mean velocity of 8.15 m/sec at the last step is consistent with findings from Van der Eb et al. (2012), who reported similar values (8.00 ± 0.6 m/sec), and Milčić et al. (2019), who noted a velocity of 8.06 m/sec for high-level gymnasts performing the handspring vault. This value also falls within the range of 7.50 to 9.95 m/sec reported in other studies (Brehmer & Naundorf, 2011; Fujihara, 2016). It is noteworthy that our gymnasts employed similar tactics in the final steps before the hurdle step, reinforcing previous findings (Heinen et al., 2013; Veličković et al., 2011) which reported an increase in velocity during these last steps. Specifically, Veličković et al. (2011) observed that top-level and middle-class gymnasts exhibited the highest velocity values on the final step when performing complex vaults, such as the Handspring forward and salto forward straight with 5/2 turns, or the Roche with a ½ turn. This progressive increase in run-up velocity, peaking in the last stride or the final two strides, has been documented in other studies (Velickovic, Petkovic, & Petkovic, 2011; Sands & Cheetham, 1986), with gymnasts maintaining their velocity in the last 5 meters (Arkaev & Suchilin, 2004). Any fluctuations in speed may be attributed to the necessary visual adjustments athletes make to align their approach to the springboard (Bradshaw, 2004). This is consistent with previous studies indicating that gymnasts aim to reach the springboard at the highest possible velocity (Bradshaw, 2004). Additionally, Velickovic et al. (2011) found that top-level gymnasts demonstrated a gradual increase in velocity, peaking at 9.95 m/sec in the final step of the approach run, which is higher than the 8.57 m/sec reported for high-level gymnasts and the 8.15 m/sec observed in our study. The 8.15 m/sec recorded in our study aligns with findings by Tan et al. (2023), who reported a mean velocity of 7.87 ± 0.48 m/sec during the final 5 meters of the run-up for handspring vault performance.

However, our results contrast with those of Veličković et al. (2011), who observed a decrease in velocity in the middle of the run-up among elite gymnasts, while our findings show a continuous increase in average run-up velocity. It is important to note that achieving maximum velocity just before take-off from the springboard facilitates the subsequent execution of the first flight phase (Fernandes et al., 2016). Furthermore, the development of effective propulsion for a successful first flight phase significantly relies on the velocity attained during the last step of the hurdle step (Dallas & Theodorou, 2020).

However, it is confirmed that gymnasts do not adopt the same tactics as track and field athletes regarding the length of the final three steps. A shorter length of the last step could negatively impact both the approach angle to the springboard and the angle of the first flight phase. Instead, gymnasts aim to increase the length of the last step to minimize the loss of horizontal speed in the subsequent phase. During the run-up, gymnasts meticulously adjust their approach to the springboard, leading to a reduction in length in the last two strides as they visually fine-tune their final steps. This finding aligns with previous studies on high-level male (Dallas & Theodorou, 2020) and female gymnasts (Heinen, 2011; 2013), as well as the Yurchenko vault (Bradshaw, 2004), which emphasize the need for precise distance and timing adjustments during the last strides and the subsequent hop-to-foot phase (Meeuwsen & Magill, 1987).

Finally, some limitations of this study should be highlighted.

First, the handspring vault is a relatively simple maneuver for high-level gymnasts, and despite the provided instructions, participants may not have exerted maximal effort to develop their running velocity. Second, the infrequent practice of the handspring vault before the study could have impacted their performance effort. Third, the study did not examine other phases of the vault or assess technical performance, which limits the comprehensiveness of the analysis.

Moreover, the results may not be broadly applicable. The participants were high-level male artistic gymnasts performing under training conditions. Given the small sample size, the findings should be generalized with caution, considering that high-level athletes might share similar run-up execution patterns. Future research should explore kinematic characteristics in high-level female gymnasts and in younger gymnasts performing vaults with varying difficulty levels.

CONCLUSIONS

The results of the present study demonstrated a progressive increase in the gymnasts' velocity throughout the entire run-up, culminating in the last stride before the hurdle step. Additionally, the technique observed in the final three steps of the run-up was characterized by variations in step length: the last step was shorter than the penultimate step, while the penultimate step was longer than the one preceding it.

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