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Research article

Does swing leg braking matter in long jump take-off? A 3-D kinematic analysis based on elite athletes

Zhiyong Jin [a], Gongju Liu [b], Houwei Zhu [c], Zhe Zheng [c], Xu Pan [b], Huiju Pan [c,*]

[a] *Harbin Sport University, Haerbin, China*
[b] *Scientific Research Department, Zhejiang College of Sports, Hangzhou, China*
[c] *College of Physical Education and Health Science, Zhejiang Normal University, China*

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ABSTRACT

The objective of this study was to explore the braking technical characteristics of the swing leg of elite male athletes in long jump take-off and its dependencies on the extension velocity of the support leg and the balance. Two cameras were used to capture 8 elite male long jump athletes (25.88 ± 3.00 years) under competitive conditions at a National Indoor Athletic Championships Final, a 3-D kinematic analysis method was conducted to analyze the take-off technique of the athletes. The results showed that the rapid braking of the swing leg increased the extension velocity of the support leg. Compared to the swing leg that started braking at the moment of maximum knee flexion of the support leg (SPKnee maximum flexion moment), athletes' performance was greater when swing leg started braking at the moment of maximum ankle flexion of the support leg (SPAnkle maximum flexion moment). Furthermore, the swing leg exhibited an inward movement during its forward swing, and the inward angle was significantly correlated with the balance maintenance ($r = - 0.50, P = 0.004$). In conclusion, a relatively delayed rapid braking and moderate inward movement of the swing leg during the take-off phase are conducive to achieving a better take-off effect in long jump.

1. Introduction

The long jump mainly consist of four phases: run-up, take-off, flight and landing. In the free fall after take-off, athletes cannot vary their kinetic energy through movement before landing [1]. Therefore, in addition to the fast run-up, the key to achieving excellent results primarily depends on the proper technical movements during the take-off phase, which can utilize the maximum kinetic energy gained during the run-up [2]. Proper techniques can also maximize the physiological functions of athletes and can improve athletic performance by maximizing the biomechanical effects [3].

In the take-off phase, to maintain balance and increase the take-off impulse, athletes should extend their support leg rapidly while actively swinging their arms and swing leg [4,5]. The accelerated hip flexion of the swing leg causes its angular acceleration in the early phase, which can increase the ground reaction force (GRF), and the hip braking of the swing leg causes its angular deceleration in the late phase, which can decrease the GRF [6,7]. Furthermore, the active swing of the swing leg can not only increases the touch-down angle, reduces the loss of horizontal speed, but also promotes the rapid forward movement of the center of gravity (COG) of the body to reduce the support time required to complete the take-off quickly [8,9]. In addition, the deviation of the COG of the body from the

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[*] Corresponding author.
E-mail address: panhuiju1964@outlook.com (H. Pan).

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support point in the horizontal plane is bound to increase its arm of force, resulting in a corresponding increase in torque and making it more difficult to maintain balance [10]. A change in the position of certain limb segments in the human body is bound to cause a change in the position of the COG of the body.Thus, the rapid sway and direction change of the swing leg is an essential factor affecting the take-off effect.

It has been proven in many studies that the rapid swing of the limb segments can increase the GRF in the process of various jumps, and the swing segments in the take-off phase of the long jump contribute up to 64 % of the GRF, of which the swing leg contributes approximately 37 % [11–14]. The limb segments do not continuously accelerate but decelerate and brake normally after the early acceleration during the take-off phase. Current theories suggest that the rapid braking of the limb segments serves two main roles: (1) changing the acceleration direction of the limb segments to reduce the GRF, thereby lightning the load on the support leg to complete take-off rapidly [15]. (2) The sudden braking of the limb segments can produce a drag mechanism that increases the extension velocity of the support leg [16,17]. Thus, it seems that although the braking of the limb segments has been proven to accelerate the extension velocity of the support leg at the end of take-off, previous studies [12–14,16,17] have focused more on the effect of the upper limb

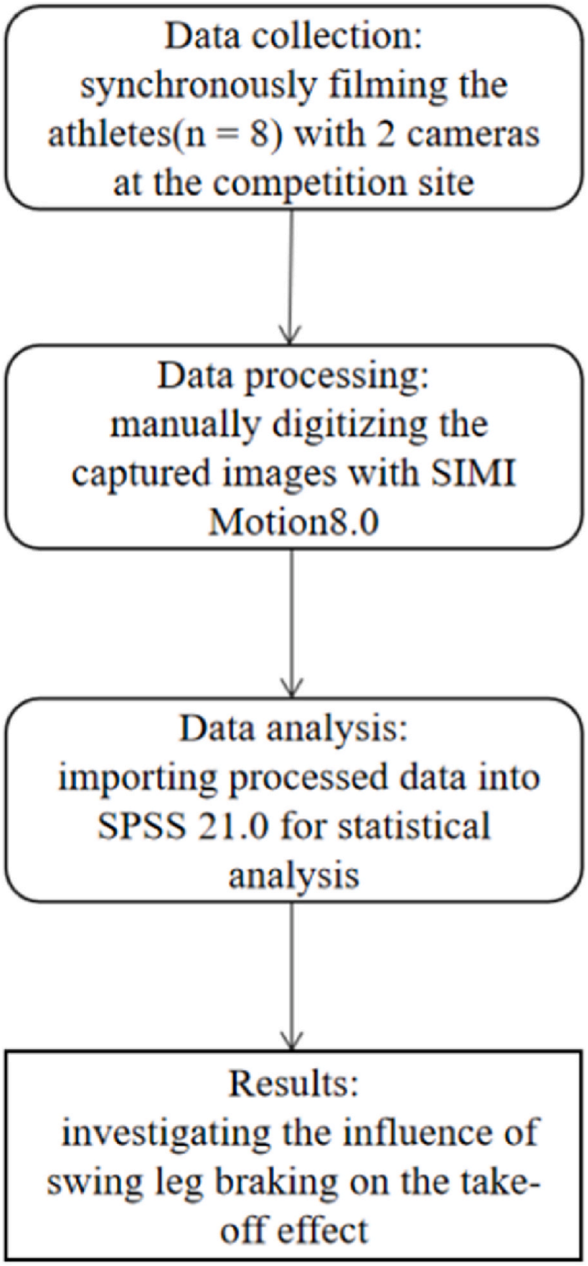

Fig. 1. Protocol flow chart.

rather than the lower limbs. Previous studies [5–7,11] have only expounded on its influence on the GRF from a kinetic perspective. However, the technical characteristics of swing leg braking and its influence on the take-off effect remain unclear.

The world records for jump events have not increased significantly and have gradually leveled off recently [18,19]. The improvement in athletic ability could be attributed to a variety of mechanisms, and in terms of the training practice, under the training background of athletes constantly approaching the human physiological limits, the physiological factors have decreasing influence on athletic performance. Further performance improvements depend primarily on improvements or innovations in sports techniques [20,21]. Such as Sado et al. reported that the technique of pelvic rotation in the frontal plane could effectively reduce the loss of horizontal velocity during the take-off phase, while increasing the vertical velocity at the instant of take off [22]. Although previous studies [5–7,11] have illustrated the effect of swing leg braking on the GRF from a dynamic perspective, the influence of the swing leg braking technique on the take-off effect in the long jump is still not fully understood.

Thus, the main purpose of this study was to investigate the technical characteristics of swing leg braking during the take-off phase in elite male long jump athletes, with a focus on the deceleration of the swing leg, braking timing, and swing direction. Secondly, examined the influence of the swing leg braking technique on the critical parameters of the take-off, mainly including the results and extending velocity of the support leg. We hypothesized that in long jump take-off, variations in the swing leg technique would have an impact on the take-off effect.

2. Methods

2.1. Participants

To restore the authenticity of the technical performance of elite athletes as much as possible, the data were captured during the men's long jump of the 2019 National Indoor Athletic Championships Final. The take-off technique of all valid trial jumps (total: 31 times, 3–5 times per athlete) from 8 athletes (age: 25.88 ± 3.00 years; personal best (PB): 7.94 ± 0.19 m; best in this competition (BC): 7.59 ± 0.25 m) was selected to analyze the relationship among variables. All participants had finished in the top three places in national competitions before, and reached the National First-Class of Athlete Grade. Video data were collected from the public competition, and this method did not have any effect on the athletes' performance. This study was authorized by the Ethics Committee of Zhejiang Normal University and informed consent was obtained from all subjects involved in the study.

2.2. Procedures

Fig. 1 illustrates the comprehensive research workflow. Initially, two cameras (SONY HDR-FX1000E, Tokyo, Japan) were used to synchronously film the athletes at the competition site at a frame rate of 50 Hz. The cameras were respectively placed on the second floor of the competition venue at a height of approximately 4.8 m, approximately 17 and 21 m away from the board respectively. The angle between the main optical axes of the two cameras was approximately 100°.The filming range was from three steps before the board to the end of the pit, a PEAK (3 m × 3 m × 3 m) radial calibration frame (composed of 24 points) was used to calibrate the movement space near the board, and all athletes did not exceed this range during take-off phase. The calibration frame was filmed prior to the competition, following which the subsequent take-off movements of athletes were filmed with the same camera positions and other relevant parameters. Motion space calibration was performed before and after the game to prevent errors caused by camera position movement (Fig. 2).

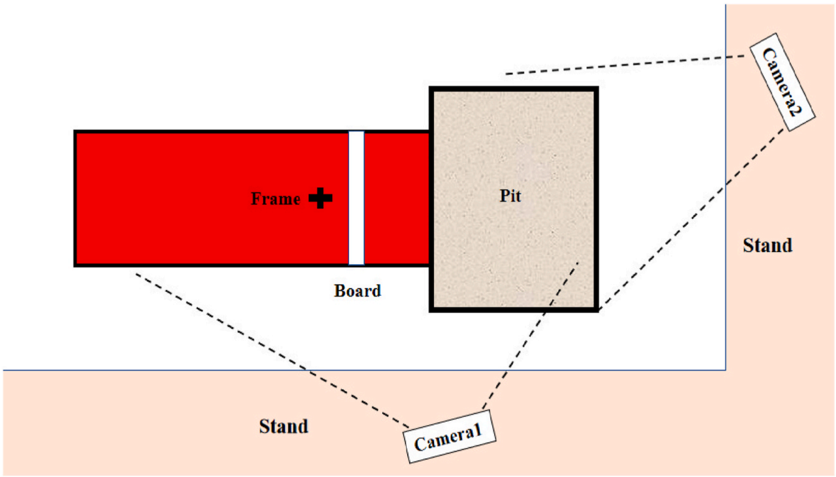

Fig. 2. Plan of the competition site.

2.3. Data processing

The video files were imported into SIMI Motion 8.0 (SIMI Reality Motion Systems, Germany), and the images were captured from 5 frames before the touch-down to the board to 5 frames after take-off. The images were manually digitized frame by frame by an experienced anatomist. The event synchronization technique (synchronization of two key instants: the moment of touch down and the moment of take-off) was applied to synchronize the images of two cameras through SIMI Motion Twin. The head, bilateral hand, elbow, shoulder, hip, knee, ankle, foot tip and heel, a total of 17 joint points were selected for analysis. The inertia parameters of the human body and the center of gravity (COG) of the segments were calculated according to the Hanavan human mechanics model [23] (composed of 15 rigid bodies, including the head, upper and lower torsos, as well as bilateral arms, forearms, hands, thighs, calves and feet). During the video analysis process, certain joint points might occlude occasionally in one side of the camera, it is common and unavoidable in the use of manual digitization methods. In such cases, the occluded joint points were estimated by the experienced operator based on the position of the joints in the last and next frames, as well as the images from the other camera. To measure the reliability of the digitization process, four trial jumps were randomly selected for repeated digitization. The intraclass correlation coefficient (ICC) values (0.96) for hip flexion velocity of swing leg showed minimal total errors [24]. The Direct Linear Transformation (DLT) algorithm was used to establish the three-dimensional coordinates, the positive direction of the X-axis represented the run-up direction of athletes, while the positive direction of the Y-axis was on the left side, and the positive direction of the Z-axis was perpendicular to the ground (Fig. 3). Raw data were smoothed by low-pass digital filter, the cut-off frequency was set to 6 Hz after residual analysis [25].

After data processing, the maximum hip flexion velocity of the swing leg (SWHip peak flexion velocity), deceleration of swing leg (SWDeceleration), the moment of swing leg starts braking, and the hip extension velocity of support leg (SPHip extension velocity), knee extension velocity of the support leg (SPKnee extension velocity), and ankle extension velocity of the support leg (SPAnkle extension velocity) were mainly calculated. Meanwhile, the trajectory of the knee joint of the swing leg and the COG of body were plotted in the horizontal plane to examine the swinging direction of the swing leg. The change of the angle between the swing leg and the horizontal plane in unit time was defined as the hip angular velocity of the swing leg. The time corresponding to the SWHip peak flexion velocity was defined as the instant when the swing leg started braking, from this instant to take-off, it was the braking phase of the swing leg. The value of deceleration of swing leg was calculated as $(\omega_{\text{take-off}} - \omega_{\max})/T_{\text{brake}}$ ($\omega_{\text{take-off}}$, hip flexion velocity of the swing leg at the instant of take-off; $\omega_{\max}$, maximum hip flexion velocity of the swing leg; T_{brake}, braking time of swing leg), results are shown as positive values. The time corresponding to the minimum angle of the hip, knee, and ankle joints of the support leg to the instant of take-off was defined as the extension phase of each joint. The extension velocity of each joint was calculated using the following:

$$\left(\theta_{take-off} - \theta_{min}\right)/T_{extension}$$

$\theta_{\text{take-off}}$, joint angle at the moment of take-off; $\theta_{\min}$, minimum joint angle; $T_{\text{extension}}$, joint extension time.

The coordinates of the COG of body and the knee joint of the swing leg in the X and Y-axes were recorded during the take-off phase, and the projection of two points on the X–Y horizontal plane was performed to observe the movement trajectory and direction of the swing leg. In addition, to further quantify the influence of the change in swing leg direction on the COG of body, the foot tip of the support leg was marked to record its coordinates in the X–Y horizontal plane, and linear regression was used to calculate the function of the trajectory of the COG of body (y_1) and the knee joint of the swing leg (y_2):

$$y_1 = k_1x + b_1, y_2 = k_2x + b_2$$

The tangent value of the angle between the two functions was calculated as follows:

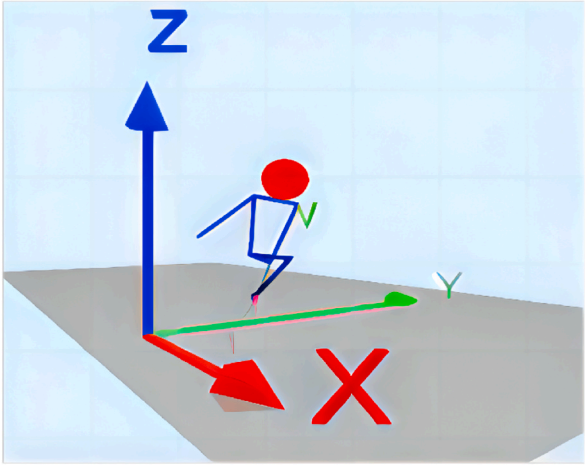

Fig. 3. Space coordinate of 3D kinematic analysis.

$$\tan\theta = \frac{k_1 - k_2}{1 + k_1 \times k_2}$$

Then tanθ was converted into an angle to represent the direction of the swing leg. The distance from the foot tip of the support leg to the COG of body was used to represent the lateral deviation of the COG of body, calculated as follows:

$$\mathrm{d} = \left| \frac{\mathrm{k_1 x - y_1 + b_1}}{\sqrt{\mathrm{k_1}^2 + 1}} \right|$$

The correlation between the two variables was compared. In addition, to examine the influence of the braking timing of the swing leg on the take-off effect, the samples ($n = 31$) were divided into the SPKnee maximum flexion moment (moment of maximum knee flexion of the support leg) group ($n = 14$) and the SPAnkle maximum flexion moment (moment of the maximum ankle flexion of the support leg) group ($n = 17$) based on the braking timing characteristics as all samples started swing leg braking at SPKnee maximum flexion moment or SPAnkle maximum flexion moment. Fig. 4 shows the specific phases of the take-off.

2.4. Statistical analysis

Descriptive statistics (mean ± standard deviation [SD]) were calculated for each variable. Statistical Package for the Social Sciences (SPSS), version 21.0 (IBM, Armonk, NY) was used for statistical analysis. Shapiro–Wilk tests were used to evaluate the normality of the parameter distributions. The data were normally distributed and linearly correlated. Thus, two-tailed Pearson's correlation coefficients were used to analyze the relationships between the swing leg metrics and the support leg or COG of body metrics. The magnitude of effects was defined as follows: $r = 0–0.1$ (trivial), 0.1–0.3 (small), 0.31–0.5 (moderate), 0.51–0.7 (large), 0.71–0.9 (extremely large) and 0.91–1.0 (almost perfect) [26]. An independent sample *t*-test was used to determine the effects of swing leg braking timing on the take-off effect by comparing the differences of kinematic variables between different braking timings (SPKnee maximum flexion moment and SPAnkle maximum flexion moment). Significance was set at $P < 0.05$. A post-hoc power analysis (G*Power v. 3.1.9.7) was conducted to evaluate the statistical power. Table 1 presents the abbreviations of the primary variables along with their definitions and calculation methods.

Touch-down

SPKnee maximum flexion

SPAnkle maximum flexion

Take-off

Fig. 4. Specific phases of the take-off.

Table 1
Definition of relevant variables.

Abbreviations (unit)	Definition
SWHip peak flexion velocity (rad.s)	Maximum hip flexion velocity of the swing leg (Relate to the loss of horizontal speed, rapid forward movement of center of gravity (COG) of body)
SWDeceleration (rad/s^2)	Deceleration of the swing leg (Average hip deceleration of swing leg from the moment of maximum hip flexion velocity of swing leg to the moment of take-off. Relate to the ground reaction force (GRF), quick take-off) Calculation: (ωtake-off - ωmax)/Tbrake (ωtake-off, hip flexion velocity of swing leg at the moment of take-off; ωmax, maximum hip flexion velocity of swing leg; Tbrake, braking time of swing leg)
SPHip extension velocity (rad/s)	Hip extension velocity of the support leg (Average hip extension velocity from the moment of minimum angle to the moment of take-off. Relate to the take-off impulse, quick take-off) Calculation: (θtake-off - θmin)/Textension (θtake-off, hip angle at the moment of take-off; θmin, minimum hip angle; Textension, hip extension time)
SPKnee extension velocity (rad.s)	Knee extension velocity of the support leg (Average knee extension velocity from the moment of minimum angle to the moment of take-off. Relate to the take-off impulse, quick take-off) Calculation: (θtake-off - θmin)/Textension (θtake-off, knee angle at the moment of take-off; θmin, minimum knee angle; Textension, knee extension time)
SPAnkle extension velocity (rad/s)	Ankle extension velocity of the support leg (Average ankle extension velocity from the moment of minimum angle to the moment of take-off. Relate to the take-off impulse, quick take-off) Calculation: (θtake-off - θmin)/Textension (θtake-off, ankle angle at the moment of take-off; θmin, minimum ankle angle; Textension, ankle extension time)
SPHip maximum flexion moment	Moment of maximum hip flexion of the support leg
SPKnee maximum flexion moment	Moment of maximum knee flexion of the support leg
SPAnkle maximum flexion moment	Moment of maximum ankle flexion of support leg
SW-Horizontal plane angle (°)	Angle between swing leg and horizontal plane (Relate to the hip flexion velocity of swing leg, the height of COG of body, below the horizontal plane is represented by negative values)
SW-COGTrajectory angle (°)	Angle between the trajectory of center of gravity of body and the trajectory of the swing leg on the X–Y horizontal plane (Swing direction of the swing leg)
SP-COGTrajectory distance (m)	Distance between the support point and the trajectory of center of gravity of body (Relate to the balance maintaining)

3. Results

3.1. Braking velocity of the swing leg and jump effect

The post-hoc power analysis showed that the statistical power >0.85, with the effect size >1.12 (alpha level set at 0.05). Table 2 shows the main study variables. It is noteworthy that the extension velocity of the three joints in the support leg increased sequentially from proximal to distal (SPHip extension velocity: 0.62 ± 0.07 rad/s, SPKnee extension velocity: 7.62 ± 0.91 rad/s, and SPAnkle extension velocity: 10.16 ± 1.45 rad/s). Table 3 presents the correlations among the main study variables. SWDeceleration exhibited significant correlations with the SPKnee extension velocity ($r = 0.65$, $P < 0.001$), SPAnkle extension velocity ($r = 0.70$, $P < 0.001$), and Results ($r = 0.45$, $P = 0.011$). The rapid braking of swing leg was conducive to increasing the extension velocity of the support leg and jumping distance. SWDeceleration was also correlated with the SWHip peak flexion velocity ($r = 0.44$, $P = 0.013$). The rapid swing of the swing leg in the early stage prompted its quick braking in the late stage.

Table 2
Main study variables ($n = 31$).

Variables	Mean ± SD
Results (m)	7.38 ± 0.28
SWHip peak flexion velocity (rad/s)	12.34 ± 1.01
SWDeceleration (rad/s^2)	117.90 ± 16.69
SPHip extension velocity (rad/s)	0.62 ± 0.07
SPKnee extension velocity (rad/s)	7.62 ± 0.91
SPAnkle extension velocity (rad/s)	10.16 ± 1.45
SW-Horizontal plane angle (°)	0.37 ± 3.78

SWHip peak flexion velocity, maximum hip flexion velocity of the swing leg; SWDeceleration, deceleration of the swing leg; SPHip extension velocity, hip extension velocity of the support leg; SPKnee extension velocity, knee extension velocity of the support leg; SPAnkle extension velocity, ankle extension velocity of the support leg; SW-Horizontal plane angle, angle between the swing leg and the horizontal plane.

Table 3
Correlation coefficient matrix of main variables.

Variables	SWDeceleration	SWHip peak flexion velocity	SW-Horizontal plane angle	SPHip extension velocity	SPKnee extension velocity	SPAnkle extension velocity	Results
SWDeceleration	1						
SWHip peak flexion velocity	0.44**	1					
SW-Horizontal plane angle	0.35	0.57**	1				
SPHip extension velocity	0.34	0.49**	0.43*	1			
SPKnee extension velocity	0.65**	0.62**	0.57**	0.38*	1		
SPAnkle extension velocity	0.70**	0.47**	0.37*	0.59**	0.77**	1	
Results	0.45*	0.74**	0.44*	0.60**	0.58**	0.71**	1

*, $P < 0.05$; **, $P < 0.01$.

3.2. Braking timing of the swing leg and jump effect

All samples started the swing leg braking at the moment of maximum knee flexion of the support leg (SPKnee maximum flexion moment) or the moment of the maximum ankle flexion of support leg (SPAnkle maximum flexion moment) (Fig. 5). As shown in Table 4 that the Results in the SPAnkle maximum flexion moment group (Group SPAnkle) were significantly better than those in the SPKnee maximum flexion moment group (Group SPKnee) (7.48 ± 0.28 m, 7.26 ± 0.25 m, $P = 0.029$). Moreover, some lower limb variables also exhibited statistically significant differences between the two groups, with the SWHip peak flexion velocity (12.67 ± 1.04 rad/s, 11.93 ± 0.85 rad/s, $P = 0.042$), SPAnkle extension velocity (10.66 ± 1.58 rad/s, 9.54 ± 1.03 rad/s, $P = 0.030$), and SW-Horizontal plane angle (1.84 ± 3.80°, −1.42 ± 2.98°, $P = 0.014$) in Group SPAnkle were higher than those in Group SPKnee. During the take-off phase, a relatively later initiation of the swing leg braking was associated with a larger swing amplitude of the swing leg and faster extension velocities of the support leg. Figs. 6–9 depict the specific conditions of the variables that exhibited significant differences under different swing leg braking timing. Relative to the initiation of braking at the SPKnee maximum flexion moment, the majority of the athletes exhibited increased SWHip peak flexion velocity, SPAnkle extension velocity, SW-Horizontal plane angle and Results when the swing leg initiated braking at the SPAnkle maximum flexion moment.

A typical trial jump. SPKnee maximum flexion moment, Moment of maximum knee flexion of support leg; SPAnkle maximum flexion moment, Moment of maximum ankle flexion of support leg.

3.3. Swing direction of swing leg and jump effect

Fig. 10 depicts the trajectories of the swing leg knee joint and the COG of body in the X–Y plane for each athlete during their BC take-off phase. For the majority of the participants, the swing leg exhibited an inward and forward swinging motion, thereby progressively approaching the body's COM.

The positive direction of the X-axis represents the run-up direction of athletes, the positive direction of the Y-axis represents its left side.

Table 5 further presents quantitative information regarding the swing direction of the swing leg and its correlation with the take-off effect (balance maintaining and extension velocity of the support leg). The angle between the trajectory of the COG of body and the trajectory of the swing leg on the X–Y horizontal plane (SW-COGTrajectory angle) was 9.85 ± 3.26°, demonstrating a moderate correlation with the SP-COGTrajectory distance. ($r = -0.50$, $P = 0.004$). However, no significant correlation was observed between

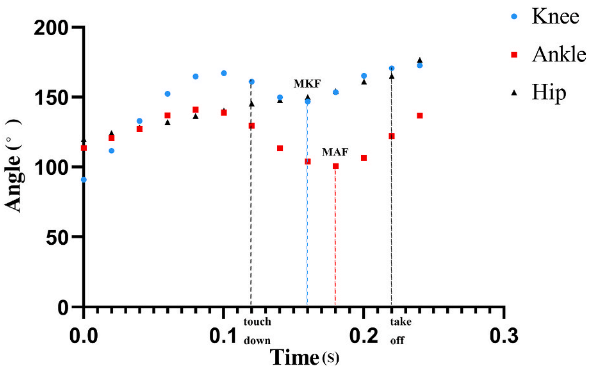

Fig. 5. Angle degree change of support leg joints.

Table 4
Variables in different braking timing of swing leg.

Variables	SPKnee maximum flexion moment (n = 14)	SPAnkle maximum flexion moment (n = 17)	Total (n = 31)
	Mean ± SD	Mean ± SD	Mean ± SD
SPHip extension velocity(rad/s)	0.61 ± 0.07	0.63 ± 0.08	0.62 ± 0.07
SPKnee extension velocity(rad/s)	7.36 ± 1.03	7.84 ± 0.76	7.62 ± 0.91
SPAnkle extension velocity(rad/s)*	9.54 ± 1.03	10.66 ± 1.58	10.16 ± 1.45
SWHip peak flexion velocity(rad/s)*	11.93 ± 0.85	12.67 ± 1.04	12.34 ± 1.01
SWDeceleration(rad/s^2)	115.76 ± 19.51	119.66 ± 14.35	117.90 ± 16.69
SW-Horizontal plane angle(°)*	−1.42 ± 2.98	1.84 ± 3.80	0.37 ± 3.78
Results(m)*	7.26 ± 0.25	7.48 ± 0.28	7.38 ± 0.28

*, significant difference between the two groups, $P < 0.05$. SPKnee maximum flexion moment, Moment of maximum knee flexion of the support leg; SPAnkle maximum flexion moment, Moment of maximum ankle flexion of the support leg.

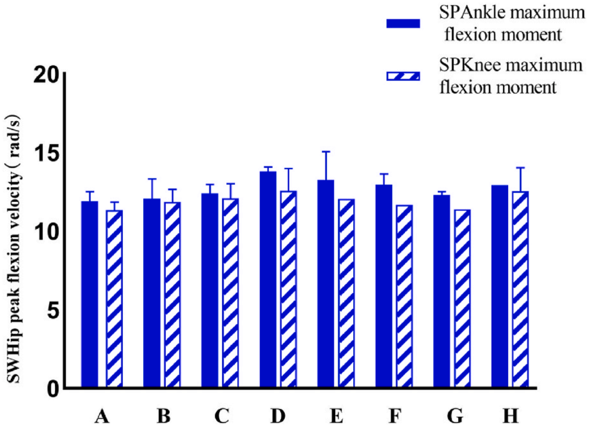

Fig. 6. The SWHip peak flexion velocity of each athlete at different swing leg braking timing (Mean ± SD)
A-H, athletes A-H.

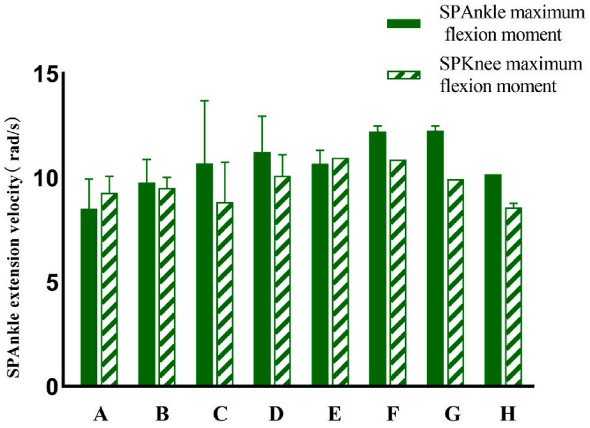

Fig. 7. The SPAnkle extension velocity of each athlete at different swing leg braking timing (Mean ± SD).

the SW-COGTrajectory angle and the extension velocity of the support leg. Nevertheless, despite the lack of a significant correlation between the SW-COGTrajectory angle and extension velocity of the support leg, Figs. 11–13 demonstrated that the high value of the support leg extension velocities predominantly occurred within the range of the SW-COGTrajectory angles from 7.24° to 11.18°. Moreover, a similar phenomenon was also observed between the SP-COGTrajectory and extension velocity of the support leg, and the high value of the support leg extension velocity was primarily focused on the range of 0.08–0.12 m of the SP-COGTrajectory distance (Figs. 14–16).

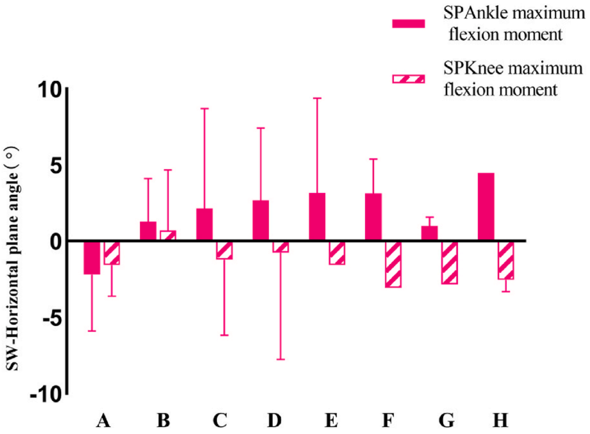

Fig. 8. The SW-Horizontal plane angle of each athlete at different swing leg braking timing (Mean ± SD).

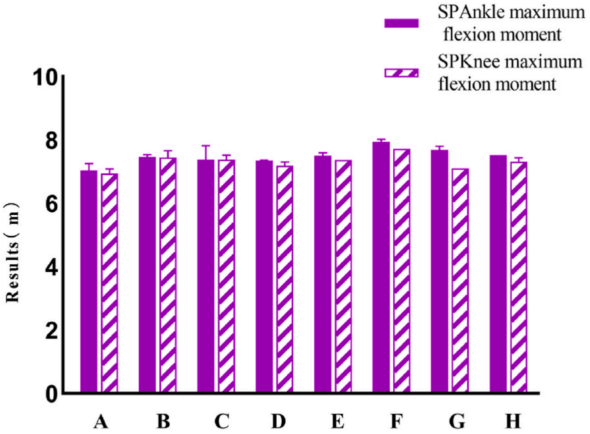

Fig. 9. The Results of each athlete at different swing leg braking timing (Mean ± SD).

4. Discussion

The purpose of this study is to explore the technical characteristics of swing leg braking in elite male athletes and its influence on the take-off effect in long jump take-off. The deceleration, braking timing, and swing direction of the swing leg were analyzed to demonstrate the influence of the braking technique on the take-off effect. In terms of deceleration, we found that the fast swing leg braking accelerated the extension velocity of the support leg, and the SWDeceleration was affected by the SWHip peak flexion velocity to a certain extent. As to the braking timing, the SPAnkle maximum flexion moment group showed faster SPAnkle extension velocity and more swing leg lifting at the end of take-off than the SPKnee maximum flexion moment group. In addition, the swing leg swang forward as well as inward approaching the sagittal plane of body, an "arc swing" technique was used to maintain balance and strengthen the extension velocity of support leg.

4.1. *Braking velocity of swing leg*

A variation in the hip angular velocity of the swing leg is an essential factor affecting the take-off effect [27]. Luhtanen et al. reported that elite athletes exhibit a faster swing leg deceleration and greater elevation of the COG of body during take-off compared with normal athletes [11]. Consistent with previous research, the present study revealed significant correlations between the BVS and both SPKnee extension velocity ($r = 0.65$, $P < 0.001$), and SPAnkle extension velocity ($r = 0.70$, $P < 0.001$). The change in the acceleration direction of the swing leg reduced the GRF, thereby lightning the load on the support leg and subsequently accelerating its extension velocity [2,11]. Moreover, the full extension of the joints in the support leg also raised the COG of body while giving full play to Lombard's Paradox to optimize the take-off effect [28–30]. However, the enhancing effect of swing leg braking on the extension velocity of the support leg was only observed in the knee and ankle joints, and there was no significant correlation between the SPHip extension velocity and the SWDeceleration. This phenomenon might be related to the muscle-function patterns involved in the extension of the support leg. During the take-off process, the support leg extends in a proximal-to-distal sequence, with proximal

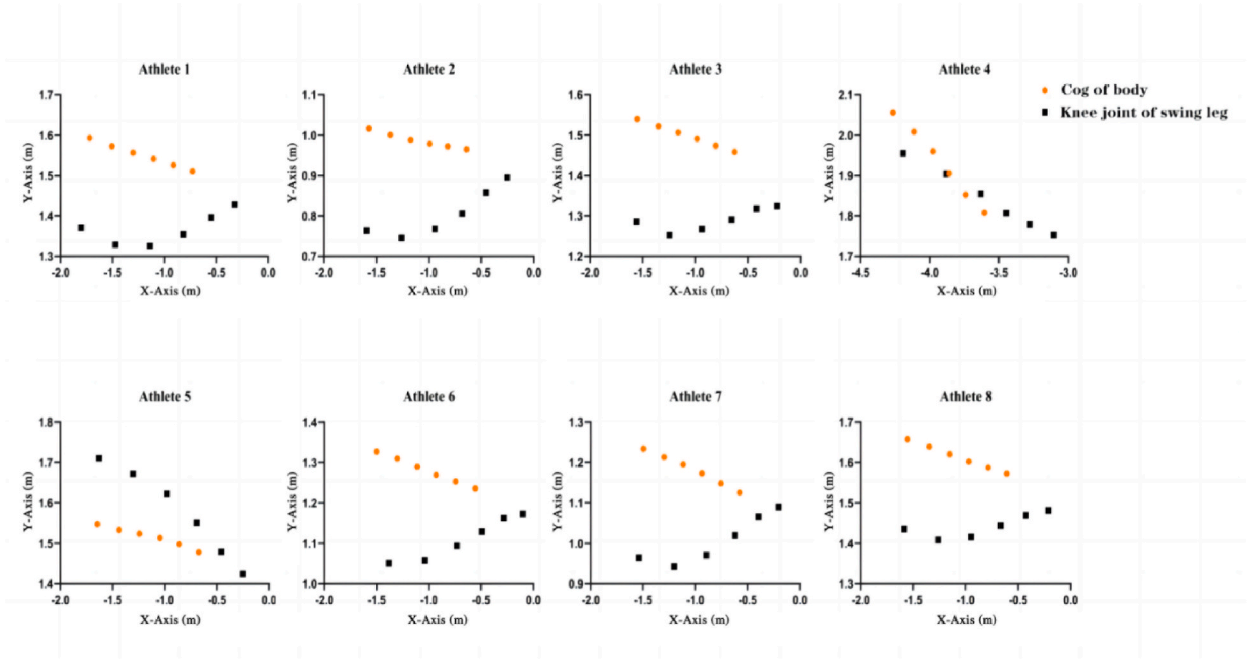

Fig. 10. Moving trajectories of knee joint of swing leg and COG of body in BC.

Table 5
Relationships between swing direction of swing leg and extension velocity of support leg and balance maintaining.

Variables (Mean ± SD)	Variables (Mean ± SD)	Correlation Coefficient(r)
SW-COGTrajectory angle (9.85 ± 3.26°)	SP-COGTrajectory distance (0.12 ± 0.02 cm)	−0.50**
	SPHip extension velocity (0.62 ± 0.07 rad/s)	−0.22
	SPKnee extension velocity (7.62 ± 0.91 rad/s)	−0.06
	SPAnkle extension velocity (10.16 ± 0.45 rad/s)	−0.12

SW-COGTrajectory angle, angle between the trajectory of COG of body and the trajectory of the swing leg on the X–Y horizontal plane; SP-COGTrajectory distance, distance between the support point and the trajectory of COG of body.

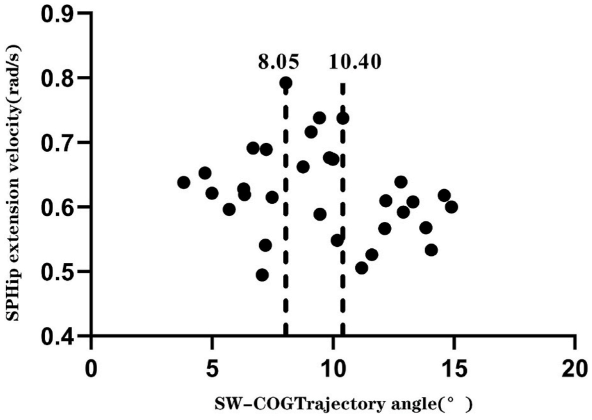

Fig. 11. SW-COGTrajectory angle—SPHip extension velocity.

muscles initially overcoming resistance to generate a certain acceleration, followed by the contraction of the distal muscles to facilitate a rapid and efficient take-off [31]. Furthermore, the variation in the joint angles of the support leg during the take-off phase also provided insights into the above phenomenon. As depicted in Fig. 5, during the buffering stage of the initial take-off phase (wherein the joint angles of the support leg continue to decrease), there was no discernible decrease in the hip joint angle of the support leg. In accordance with the findings reported by Gerrit et al., during the early stage of take-off, the hip extensors played a crucial role in

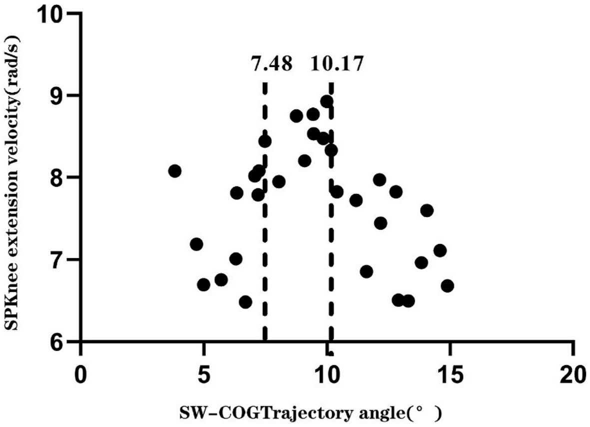

Fig. 12. SW-COGTrajectory angle—SPKnee extension velocity.

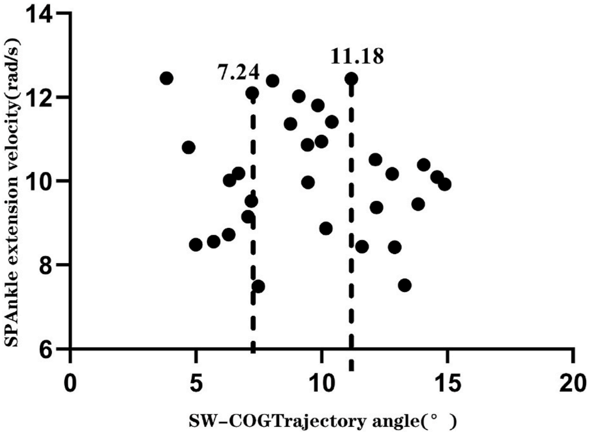

Fig. 13. SW-COGTrajectory angle—SPAnkle extension velocity.

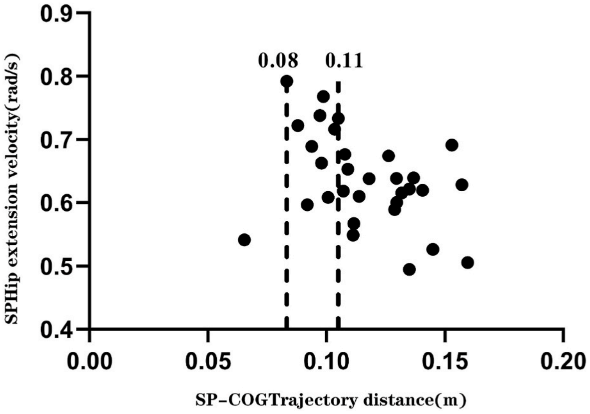

Fig. 14. SP-COGTrajectory distance—SPHip extension velocity.

resisting the ground impact at touch-down and the hip joint angle continued to increase to generate an initial acceleration [32]. This mechanism contributed to ensuring that the COG of body does not fluctuate extensively in the vertical direction. During the later stage of take-off, the myoelectric activity of the hip extensors such as the gluteus was significantly decreased and mechanical propulsion work was primarily accomplished by the knee and ankle joints of the support leg [33]. Because the swing leg braking was initiated in the later stage of take-off, its effect on the hip joint was less than that on the knee and ankle joints. The rapid swing leg braking is

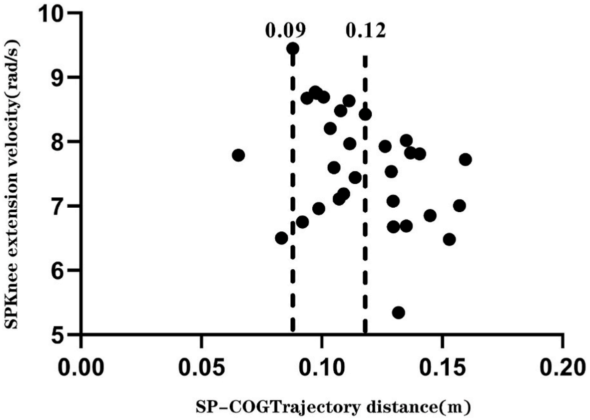

Fig. 15. SP-COGTrajectory distance—SPKnee extension velocity.

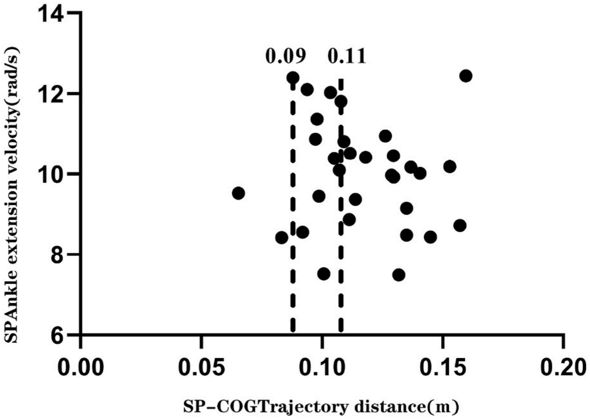

Fig. 16. SP-COGTrajectory distance—SPAnkle extension velocity.

beneficial for a quick take off at the end.

Moreover, a significant correlation between the SWHip peak flexion velocity and SWDeceleration ($r = 0.44$, $P = 0.013$) was also observed, indicating that an initial rapid swinging motion of the swing leg was conducive to subsequent swift braking. On the basis of the contraction patterns exhibited by the hip extensors during the swing process of the swing leg, the rapid deceleration following the acceleration of the swing leg can be considered as a stretch-shortening cycle (SSC) contraction in the hip extensors of the swing leg [34]. Previous studies have demonstrated that the residual force enhancement (RFE) was one of the principal factors influencing the SSC effect, and an increase in the stretch amplitude of the agonist muscles during the SSC period can enhance the RFE, thereby strengthening the SSC effect [35,36]. Therefore, the rapid swing of the swing leg during the early stage increased its swing amplitude and led to a further stretching of the hip extensors, consequently resulting in an increase in SWDeceleration through enhanced RFE. Thus, in addition to the support leg, the SSC effect of the hip extensors of the swing leg should also be emphasized in training. Plyometrics training (PT) and eccentric training (ET) have been proven to improve the muscle-tendon unit (MTU) function and change the muscle activation strategies, thereby effectively enhancing the SSC ability [37,38]. Accordingly, unilateral or bilateral flywheel training and drop jump (DJ) protocols can be incorporated into the strength and conditioning training programs [39,40]. In addition, such potential improvement may serve to mitigate inter-limb asymmetries, thereby fostering an enhancement in run-up speed while concurrently reducing the risk of lower limb injury [41].

In addition, from a dynamic perspective, the rapid swing of the swing leg can inevitably increase the moment of momentum about the backward rotation of body. However, the rapid swing of the swing leg during the early stage also facilitated its quick braking during the late stage, thereby promoting a reduction in the moment of momentum and maintaining the trunk in an appropriate upright or forward position, which is beneficial for better preparation of subsequent aerial movement [42]. Therefore, the rapid swing of the swing leg in the early stage and its fast braking in the late stage should be considered as a interdependent procedures that can affect the take-off effect, and it is necessary to analyze both together to comprehensively analyze the performance.

4.2. Braking timing of the swing leg

Although previous studies have elucidated the kinetic mechanisms underlying the effects of swing leg braking on GRF, the impact of the braking timing on take-off performance remains unclear, which is critical for a comprehensive understanding of how swing leg braking influences the take-off effect in long jumps [11–14]. In light of this, we compared the take-off performance under different swing leg braking timings. The results showed that the jumping distance achieved by the SPAnkle group (7.48 ± 0.28 m) was greater than that of the SPKnee group (7.26 ± 0.25 m), resulting in a statistically significant difference (P = 0.029). From the perspective of specific lower limb kinematic parameters (Table 4), the braking timing of swing leg can can exert an influence on the extension velocities of the lower limbs. Nonetheless, this influence appeared to be exclusive to the ankle joint and did not extend to either the hip or knee joints, as Table 4 shows that the SPAnkle extension velocity in Group SPAnkle was higher than that in Group SPKnee (10.66 ± 1.58 rad/s, 9.54 ± 1.03 rad/s, P = 0.030), but there was no significant difference in the SPHip extension velocity and SPKnee extension velocity between the two groups. A previous study has demonstrated that the majority of the vertical impulses during the take-off phase is accumulated primarily during the buffering phase (impact phase), which can be increased by the rapid swing motion of the swing leg [4]. As depicted in Fig. 5, at the moment of SPKnee peak flexion, SPAnkle was still undergoing its buffering phase and the continued rapid swing of the swing leg provided additional impulse accumulation for SPAnkle. Moreover, the extended swing duration of the swing leg also resulted in an increased SWHip peak flexion velocity (11.93 ± 0.85 rad/s, 12.67 ± 1.04 rad/s), thereby increasing the impulse accumulation at SPAnkle, which ultimately led to a faster extension velocity at the ankle joint of the support leg. In addition, the variation in swing leg braking timing that induced changes in both the active swing duration and peak swing velocity, also resulted in a corresponding impact on the swing amplitude. In the present study, the SW-Horizontal plane angle was greater in the Group SPAnkle (1.84 ± 3.80°) than in the Group SPKnee (−1.42 ± 2.98°), and a positive correlation (r = 0.44, P = 0.012) was observed between the SW-Horizontal plane angle and Results. This finding was consistent with the study of Covadonga et al., where a significant association between the SW-Horizontal plane angle and jump height was reported in elite high jump athletes [43]. Despite the fact that these two studies originated from different events, the fundamental principles and mechanisms by which an elevated swing leg at the take-off instant contributed to improved performance are essentially similar. The study conducted by Sado et al. demonstrated that an increased pelvic elevation caused by the swing leg high lifting, was conducive to enhancing performance in multiple forms of unilateral jump tasks [22,44]. They suggested that such phenomenon was related to the uniquely wide and short configuration of the human pelvis, representing an adaptive and efficient exploitation of the human morphologies. Meanwhile, the COG of body was also vertically higher as it was affected by the high-lifted swing leg to optimize the take-off effect [45]. Therefore, an appropriate extension of the acceleration time of the swing leg is beneficial to athletes to complete the quick take-off. Accordingly, in the take-off technique training section, emphasis should also be placed on the active swing of the swing leg during the take-off phase, as well as its quick braking immediately prior to take off.

4.3. Swing direction of the swing leg

Given the lack of previous studies on the swing direction of the swing leg, we tracked the motion of the knee joint in the swing leg, and investigated its influence on the take-off performance. During the take-off phase, athletes exhibited a forward and inward "arc-shaped" movement pattern in the swing leg (Fig. 10). A negative correlation was found between the SW-COGTrajectory angle and SP-COGTrajectory distance (r = - 0.50, P = 0.004), suggesting that an appropriate inward swing of the swing leg contributes to better balance maintenance in long jump take-off. Furthermore, despite the lack of significant correlation between the SW-COGTrajectory angle and the extension velocity of the support leg, the high values at the SPHip (Fig. 11), SPKnee (Fig. 12), and SPAnkle extension velocity (Fig. 13) were predominantly concentrated within the SW-COGTrajectory angle range of 7–11°, indicating that a moderate inward swing motion of the swing leg was was conducive to promoting the faster extension of the support leg during the take-off phase. Moreover, a similar phenomenon was also observed between the SP-COGTrajectory distance and the extension velocity of the support leg. As shown in Figs. 14–16, the high values at the SPHip, SPKnee, and SPAnkle extension velocities were predominantly concentrated within the SP-COGTrajectory distance range of 0.08–0.12 m, suggesting that a moderate deviation of the COG of body from the support point also contributed to enhancing the extension velocity of the support leg. The above findings were consistent with the study by Perttunen et al., which demonstrated that an increase in plantar pressure in the fifth metatarsal region of the support leg during the take-off phase was associated with enhanced jumping distance in the triple-jump [46]. In the present study, the distal end of the second phalangeal bone was calibrated as the support point. Previous studies [47,48] have shown that the average foot width in adult Asian males is approximately 0.10 ± 0.05 m, and no correlation exists between foot width and height in males. Thus, the SP-COGTrajectory distance range of 0.08–0.12 m roughly corresponds to the lateral plantar region, which was highly associated with triple jump performance according to a study by Perttunen et al. Considering the evidence in the present study that a moderate inward swing of the swing leg facilitated the rapid extension of the support leg, it is proposed that an appropriate inward swing of the swing leg induced a lateral deviation of the COG of body on the horizontal plane, thereby altering plantar pressure distribution and subsequently enhancing the extension velocity of the support leg. Nevertheless, the relevant mechanism remains to be further proved through future research incorporating kinetic and EMG data. In the take-off technique training section, it is recommended to emphasize a moderate inward swing of the swing leg. However, excessive anterolateral plantar pressure may increase the wear between the femur and tibia, and frequent practice of relevant take-off techniques might elevate the risk of patellofemoral pain syndrome [49].

The current study discussed the effects of the changes in the braking angular velocity, braking timing and swing direction of the swing leg on the take-off effect of elite male athletes in long jump take-off. The present study has its limitations. One of the main limitations is related to the data processing. Although the ICC values proved the reliability of the manual digitization process, due to the data in the present study were collected within an actual competitive environment, affixing marker points directly onto the athletes was unfeasible in order to avoid any potential disruptions to their performance, and this represents a primary limitation shared among similar studies. Furthermore, constrained by the filming conditions inherent to the competition venue, the filming was conducted from a relatively distant position. In addition, this study only included a relatively small sample size that included only elite athletes, the differences between athletes at different levels could not be compared, and some biomechanical parameters such as electromyography and kinetics were not evaluated. Future research may be conducted at a closer filming distance, or advanced experiments could be carried out under laboratory settings, thereby enhancing the accuracy of the data while facilitating a more detailed analysis of the jumping biomechanics.

5. Conclusions

The analysis leads to the following conclusions: The relatively delayed initiation of swing leg braking, combined with a moderate inward swing strategy was conducive to a better take-off effect in long jump take-off. Thus, in the take-off technique training, it is recommended to emphasize the appropriate extension of the active swing duration of the swing leg, moderate inward swing action, and immediate fast braking prior to take off. Moreover, given that the acceleration and deceleration of the swing leg during the take-off phase are interdependent procedures, the SSC function of the hip extensors in the swing leg should also be strengthened. Specific training interventions such as unilateral or bilateral DJ and flywheel training may also contribute to improved athletic performance, while potentially reducing the risk of lower limb injuries.

Our study may provide a reference for other jump-related activities and events, such as the triple jump and high jump. However, further investigation into specific events is required in the future.

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This research received no external funding.

Ethics statement

This study was performed in accordance with the ethical standards detailed in the Declaration of Helsinki, and authorized by the Ethics Committee of Zhejiang Normal University (Ethic Code: ZSRT2018064). Prior to the experiment, all participants have provided written informed consent.

Informed consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data will be available from the corresponding author on request.

Declaration of interest’s Statement

The authors report there are no competing interests to declare.

CRediT authorship contribution statement

Zhiyong Jin: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Gongju Liu:** Writing – original draft, Data curation. **Houwei Zhu:** Resources, Investigation. **Zhe Zheng:** Investigation, Data curation. **Xu Pan:** Software, Investigation. **Huiju Pan:** Writing – review & editing, Supervision, Resources, Funding acquisition.

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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