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Challenge in the men's high jump: A brief report on biomechanical analysis of the techniques for top three men high jumpers in the IAAF World Championships in Athletics, Osaka 2007

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Abstract

This brief report described interim results of kinematic analysis of the jumping techniques for top three men high jumpers at Osaka WC. Finalists in the men's high jump at Osaka WC were videotaped to obtain three-dimensional coordinates of twenty-three body landmarks in video images of the best jump for each jumper with a three-dimensional DLT method. Thomas's run-up CG velocity was high in the last stride(7.73 m/s) and at the takeoff foot touchdown(7.87 m/s) and his inward lean of the body, 8.2 deg was the greatest of the three jumpers. Thomas's technique was characterized by a strong forward lean of the trunk and deeply flexed support knee in the preparation phase, accelerative transition to the takeoff phase, fully used takeoff knee and hip, and the large inward lean of the body. The silver medalist, Rybakov from Russia who also cleared 2m35 exhibited us an orthodox and beautiful high jump technique with a double arm swing from large backward lean of the body at the takeoff foot touchdown. Although the bronze medalist, Ioannou decreased his horizontal CG velocity during the last stride, his technique was characterized by relaxed last few strides, running up transition to the takeoff phase and the quick takeoff.

1. Introduction

The high jump, as we know it today, became popular in the 19th century. The high jump was adopted as an event of the athletics of the modern Olympic Games in 1986. The most primitive style of the high jump is a scissors style in which a straight run-up is used. Starting with the scissors style, the technical evolution of the high jump has been taken place, for instance, the western roll, the straddle and the Fosbury-flop which is the most fashionable at present, and the record of the high jump has been improved.

The Fosbury-flop became famous all over the world, by Dick Fosbury's victory in the Mexico Olympic Games in 1968, who invented a back lay-out clearance technique from a curved run-up. Most of high jumpers use the Fosbury-flop at present, and the current world records for men and women were established with this style (men: 2m45, women: 2m09).

Although the high jump technique can be divided into four phases: run-up, preparation, takeoff, and clearance, the takeoff is the most important phase. Basic principles of the takeoff are common in various styles mentioned above, which have been formulated by the study on the takeoff motion of the straddle style whose run-up is straight. However, there is still less information on the takeoff motion of the Fosbury-flop than that of the straddle style, because the takeoff of the Fosbury-flop is a three-dimensional nature and more complicated than that of the straddle style because of its curved run-up.

The detailed three-dimensional analyses of the high jump at the IAAF World Championships in Athletics were conducted at the Championships held in Tokyo 1991, Athens 1997, and Helsinki 2005. The men's high jump at the 11th IAAF World Championships in Athletics, Osaka 2007, henceforth Osaka WC, was a very

Table 1 Results of men's high jump, Osaka 2007

Rank	Name	NAT	Result(m)	2.16	2.21	2.26	2.30	2.33	2.35	2.37
1	Donald THOMAS	BAH	2.35	-	×○	×○	○	××○	○	×××
2	Yaroslav RYBAKOV	RUS	2.35	-	○	○	○	○	×○	×××
3	Kyriakos IOANNOU	CYP	2.35	○	○	○	×○	×○	×○	×××
4	Stefan HOLM	SWE	2.33	-	○	○	○	○	×××	
5	Tomas JANKU	CZE	2.30	○	○	○	○	×××		
5	Victor MOYA	CUB	2.30	○	○	○	○	×××		
7	EikeONNEN	GER	2.26	○	-	○	×-	××		
8	Jaroslav BABA	CZE	2.26	○	○	×○	×××			

high level competition in which three jumpers cleared the height of 2m35, as shown in Table 1, the final result of this event. In addition to the high performance, an interesting topic of athletic fans and medias was that a less experienced young high jumper Thomas from Bahama won this competition with a little strange-looking style in which he ran-up and jumped up like a running shot of basketball and dabbled his legs before clearing the bar in the airborne phase. On the contrary, Rybakov from Russia who also cleared 2m35 exhibited us an orthodox and beautiful high jump technique with a double arm swing from large backward lean of the body at the takeoff foot touchdown.

This brief report described interim results of kinematic analysis of the jumping techniques for top three men high jumpers at Osaka WC.

2. Methods

2.1 Subjects and data collection

Fifteen finalists in the men's high jump at Osaka WC were videotaped with two high-speed video cameras(HSV-500, NAC Co.) operating at 250 Hz for left-footed jumpers and two normal digital video cameras(VX-1000, Sony) operating at 60 Hz for right-footed jumpers. These cameras were fixed on the top row corridor of the Nagai stadium so that they covered the videotaping area from the 3rd last stride to the bar. These cameras were synchronized by using an event method in which we used instants of the touchdown of the takeoff and the last stride as synchronization events.

Two videotaping areas were set for the left-footed and right-footed jumpers, respectively. The videotaping area was 6 m long in the direction parallel to the bar as a x axis, 6 m long in the perpendicular direction to the bar as a y axis, and 3 m high as a z axis. The areas were calibrated by standing a calibration pole vertically every two meters in each area before the start of the final.

2.2 Data reduction

Twenty-three body landmarks in video images of the best jump for each jumper were digitized from at least five frames before the touchdown(TD) of the support foot of the second last stride to ten frames after the toe-off of the takeoff foot. Three-dimensional coordinates of the segment endpoints were reconstructed with a DLT method from the digitized coordinates, smoothed with a Butterworth digital filter of optimum cutoff frequencies (5.0 to 7.5Hz) chosen by a residual method. The mean errors of the three-dimensional coordinates of the calibration points were 0.01m in the x axis, 0.02m in the y axis, and 0.01m in the z axis, respectively.

The whole body center of gravity(CG) estimated after Ae's body segment parameters (1996) for athletes and its derivative was calculated to obtain CG heights relating to the performance and CG velocity during the final stage of the run-up and the takeoff phase. Three CG heights as performance descriptors(Hay, 1993) were as follows:

H1: the height of the jumper's CG at the instant of takeoff

H2: the height that the jumper raises the CG during the flight

H3: the difference between the maximum height reached by the CG and the height of the crossbar

In this report, H2 was calculated from the vertical CG velocity of jumpers at the instant of takeoff, and H3 was the difference between the sum of H1 and H2 and the official record.

Although several joint and segment angles were calculated, only angle explained in this report was the knee joint angle which was defined as an angle between the thigh and shank. As parameters to evaluate the condition of the takeoff we calculated the inward and backward lean angles of the body and the trunk lean angle. Figure 1 showed the definition of inward lean and backward lean angles of the body. In the X'-Z' plane, the angle between the vertical line and a line connecting CG and the ankle joint of the takeoff leg (CG-ankle line) was defined as an inward lean angle of the whole

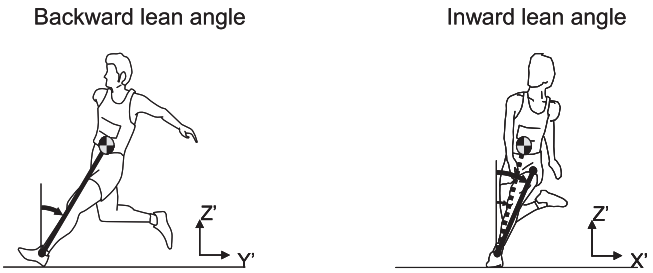

Figure 1 Definitions of the inward and backward lean angles

body. In the Y'-Z' plane, the angle between the vertical line and the CG-ankle line was obtained as a backward lean angle of the whole body. The trunk lean angle was the angle between the vertical line and a line connecting the midpoint of both shoulders and the midpoint of both hips.

3. Results and discussion

3.1 Motions of the top three jumpers in the final phase of the run-up and takeoff phase

Figures 2 to 4 show sequence stick pictures of the best jump for the top three jumpers before TD of the 2nd last stride to the instant of takeoff. The left limb and the trunk were depicted in solid lines and the right limb shown in broken lines. The stick pictures on the upper row is the lateral view of a jumper, which was transformed as if an observer was watching the jumper from the position perpendicular to the direction of the horizontal CG velocity of the jumper, and those on the lower row is the backward view of the jumper.

Thomas (Bahama) in Figure 2

Being very different from two other jumpers, Ryvakov and Ioannou, Thomas strongly inclines his body, especially the trunk forward in the 2nd stride, probably also in the 3rd stride, which looks like a basketball running shot or a high jump from a short run-up used in a practice. And the deeply flexed knee joint seen in the pictures(3,11 and 12) is also one of his features. Defying the guess of the audience and media in the Nagai stadium that his jumping motion was new and completely different from other jumpers in all the phases from the beginning of run-up to the landing, he raises his trunk and body during the last stride to prepare for his strong takeoff. At the instant of takeoff foot TD, his backward lean of the body and the takeoff leg is large although the trunk backward lean looks a little smaller than other jumpers. His double-arm swing, almost vertical body at the takeoff, and highly raised thigh of the swing leg reveal his excellent techniques. Although dabbling legs before the crossbar clearance is his most characteristic, we all know that the height CG is raised is determined by the takeoff motion. From the backward view, we can observe his large inward lean of the leg during the 2nd and last strides(1 to 10), which is still maintained at the takeoff foot TD(14 and 15).

Rybakov (Russia) in Figure 3

Rybakov who cleared 2m35 exhibites us an orthodox

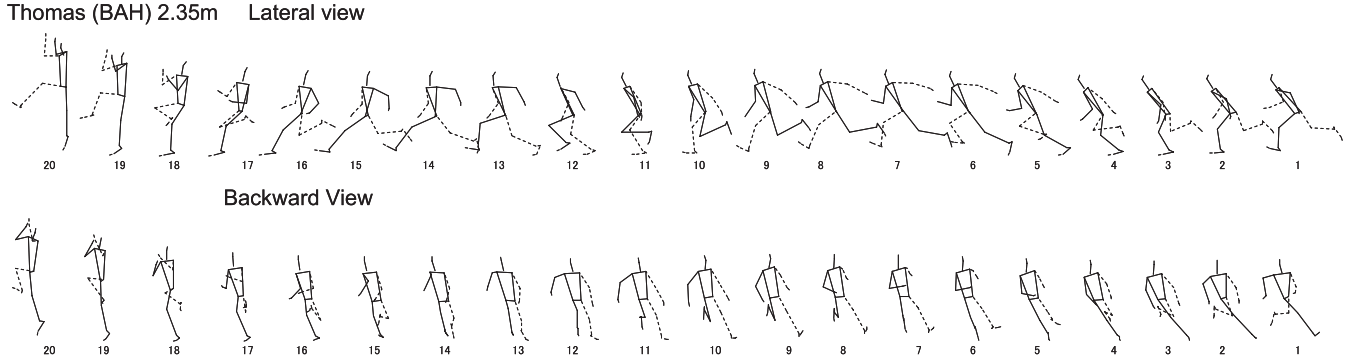

Figure 2 Sequence stick pictures of Thomas 2m35

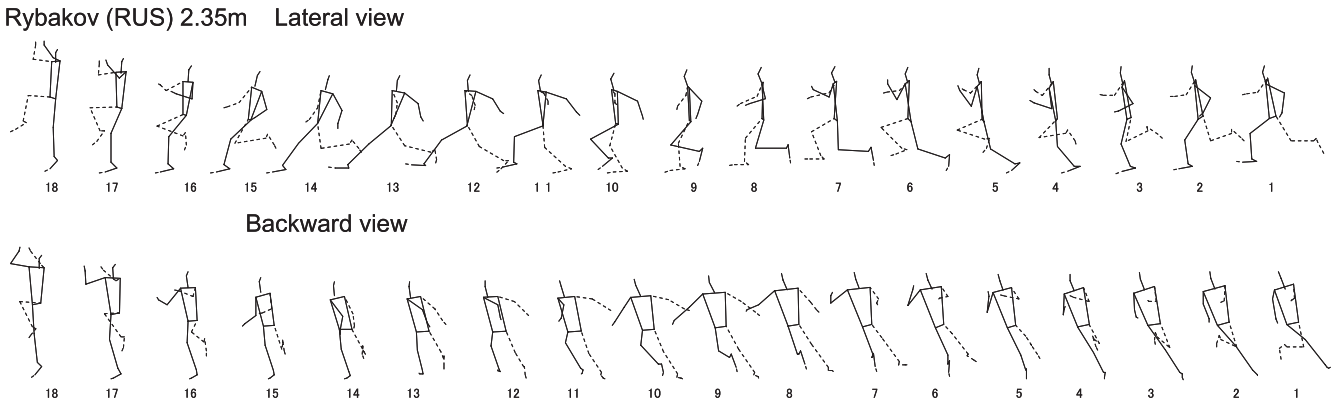

Figure 3 Sequence stick pictures of Rybakov(2m35)

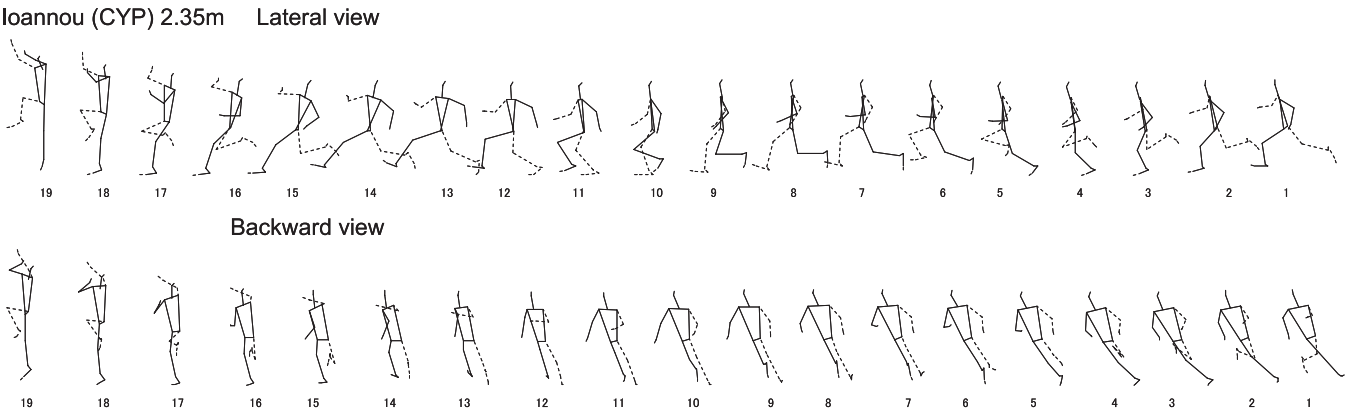

Figure 4 Sequence stick pictures of Ioannou(2m35)

and beautiful high jump technique with a double arm swing from a large backward lean of the body at the takeoff foot TD, which we can frequently see in textbooks of athletics. From the lateral view, he inclines his body forward appropriately in the 2nd last stride. He raises his trunk, lowers his CG and prepares his arms for the double-arm swing in the 2nd and last strides although his knee is less flexed than Thomas. In the takeoff phase, he inclines his takeoff leg and trunk backward and swings his arms and swing leg in a wide range of motion. From the backward view, his inward lean of the body during the 2nd last stride is as large as Thomas, but he changes the direction of his progression acutely during the support phase(8 to 10). At the takeoff foot TD(14), his inward lean was kept.

Ioannou (Cyprus) in Figure 4

Ioannou who also cleared 2m35 with a so-called a semi-double arm swing demonstrates a good form similar to Rybakov although a little larger upward movement of his body is observed in the 2nd stride(6 to 8). In the last stride, he floats his body, as seen in the 2nd stride, which may have caused a little delayed TD of the takeoff foot, slapping the foot down to the ground. From the backward view, his inward lean of the body in the 2nd last stride is very large but it becomes smaller at the instant of takeoff foot TD.

3.2 Performance descriptors and CG velocity

Table 2 shows the heights of the CG as performance descriptors and takeoff time. Table 3 shows CG velocity in the last stride and takeoff phases. Thomas's performance was characterized by his prominent H2(1.10m) but less efficient clearance height, H3(-0.14m). Rybakov showed the highest H1 by making use of his tall body height. The time of the takeoff phase ranged within the normal, compared with that of the in Tokyo WC.

Surprisingly Thomas's run-up velocity was high in the last stride(7.73 m/s) and at the takeoff foot TD(7.87 m/s), which was a little slower than that of the high jumpers in Tokyo WC(8.15±0.33 m/s and 7.52±0.25 m/s, Iiboshi et al, 1994) and a little faster than that of Helsinki WC(7.78±0.34 m/s at the takeoff foot TD). In addition, it is likely that he accelerated his CG velocity in the last stride while most of high jumpers tended to decrease the

Table 2 Performance descriptors of the top three high jumpers

Name (Nationality)	Height (m)	Weight (kg)	Analyzed record (m)	Max. CG height (m)	H1 (m)	H2 (m)	H3 (m)	Takeoff time (s)
Thomas (BAH)	1.90	75	2.35	2.49	1.40	1.10	-0.14	0.180
Rybakov (RUS)	1.98	82	2.35	2.46	1.45	1.01	-0.11	0.192
Ioannou (CYP)	1.93	60	2.35	2.38	1.40	0.98	-0.03	0.148

Table 3 The CG velocity and projection angle for the top three high jumpers

Name (Nationality)	CG velocity (m/s)						Projection angle (deg)
	Horizontal			Vertical			
	Last stride	Takeoff		Last stride	Takeoff		
	on	on	off	on	on	off	
Thomas (BAH)	7.73	7.87	3.82	-0.47	-0.11	4.64	50.9
Rybakov (RUS)	7.41	7.57	3.66	-1.01	-0.10	4.45	50.6
Ioannou (CYP)	7.75	7.61	3.80	-0.62	0.09	4.38	49.0

Table 4 Body lean angle at the TD for the top three high jumpers

Name (nationality)	Body lean at takeoff foot TD(deg)		
	Backward	Inward	Trunk
Thomas (BAH)	43.5	8.2	13.3
Rybakov (RUS)	43.0	2.9	14.3
Ioannou (CYP)	40.0	3.5	13.4

Table 5 Knee joint angle in the last stride and takeoff phase for the top three high jumpers

Name (nationality)	Knee joint angle (deg)				
	Last stride		Takeoff		
	on	off	on	Max flextion	off
Thomas (BAH)	150	141	161	133	172
Rybakov (RUS)	154	151	170	139	174
Ioannou (CYP)	144	136	151	145	177

CG velocity in the last stride to prepare for the takeoff. The similar tendency as Thomas was observed in the case of Rybakov whose CG velocity was also increased from 7.41 m/s at the last stride to 7.57 m/s at the TD. However, Ioannou decreased his CG velocity but his CG velocity(7.61 m/s) at the TD was still faster than the jumpers at Tokyo WC(7.52±0.25 m/s.).

The downward vertical velocity at the TD for Thomas and Rybakov was smaller than that of the high jumpers of Tokyo WC(- 0.12±0.53 m/s) and Helsink WC(-0.33±0.16m/s), and that of Ioannou was positive, although some jumpers very often transitted to the takeoff with positive vertical CG velocity.

The projection angle of the CG was similar to that of Helsinki WC(51.1±2.3 deg) and larger than Tokyo WC(47.8±3.5 deg).

3.3 Body lean angle and knee joint angle

Table 4 shows backward and inward leans of the body and overall lean angle of the trunk and Table 5 indicates knee joint angle in the lst stride and the takeoff phase. Figure 5 demonstrates a knee joint angle vs. CG vertical velocity diagram for the three high jumpers during the takeoff phase.

The backward lean of the body ranged from 40.0 deg of Ioannou and 43.5 deg of Thomas which were larger than that of Tokyo WC(37.7±3.4 deg), although there was no difference in the trunk lean angle among three jumpers. The inward lean of the body at the instant of takeoff TD for Thomas, 8.2 deg was the largest of the three jumpers and much larger than that of Tokyo WC(3.2±3.1 deg). The large inward lean of the body at the instant of takeoff TD is one of the features of Thomas.

As seen in Figures 2 to 4 and Table 3, the three high jumpers flexed the knee joint during the last stride although the patterns were different. After the TD of the last stride, Thomas and Ioannou flexed the support knee joint more and maintained the knee flexion or less extended it toward the toe-off, although Rybakov did not flex his support knee so much during the support phase, adopting the technique of inclining the support leg forward to lower the CG. However, observation of Figures 2 to 4 revealed that they all inclined the shank forward deeply with regardless of the degree of the knee

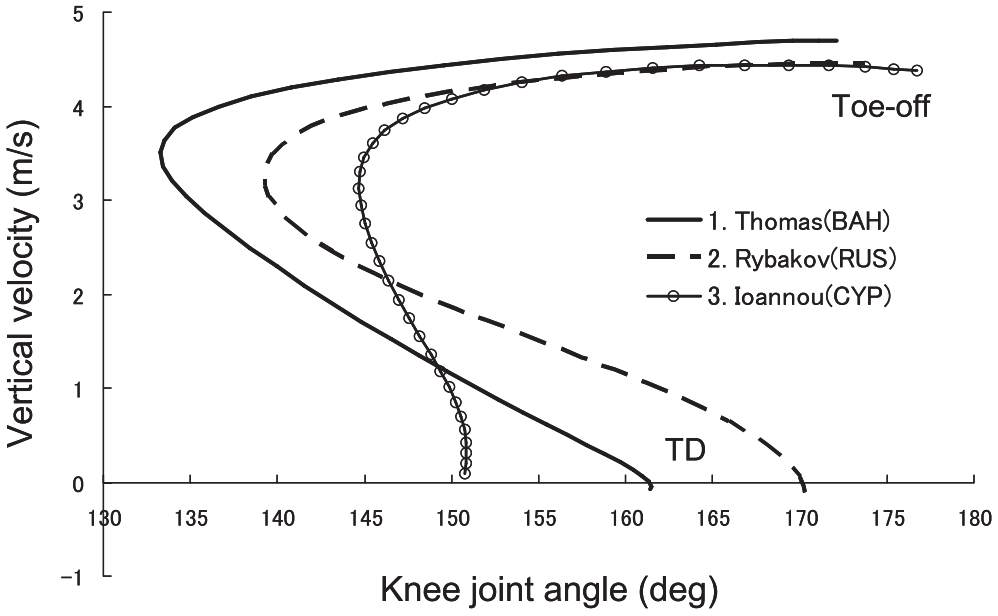

Figure 5 Knee joint angle vs. vertical CG velocity diagram for the top three high jumpers

flexion during the support phase of the last stride. In sprint running, it is said that the fast forward lean of the support shank in the first half of the support phase is a critical factor to decrease the negative braking force. The technique of inclining the shank forward may be a reason why the three jumpers could make the decrease in the horizontal CG velocity smaller during the final phase of run-up.

As shown in Figure 5, Rybakov most extended his knee and Ioannou most flexed his knee at the instant of takeoff foot TD. Thomas flexed his knee deeply to 133 deg during takeoff phase, which was ranked as one of the maximum knee flexion, as reported that the minimum knee joint angle was 127.9 deg in Helsinki WC and 132.9 deg in Tokyo WC. Although the knee was flexing during the first half of the takeoff phase, the vertical CG velocity was increasing from the instant of takeoff TD. This is often called as a high jump paradox that the vertical CG velocity increases due to the rotation of the body around the takeoff foot in spite that the takeoff knee flexes. The ratio of the vertical CG velocity at the instant of the maximum knee flexion was reported as 78.7±6.1% in Tokyo WC, and those of the three jumpers were 77% for Thomas, 76% for Rybakov, and 75% for Ioannou, which means there was no remarkable difference. The results indicated that Thomas effectively used the rotation of the body as well as the strong knee extension to obtain the vertical CG velocity during the takeoff phase.

3.4 Remarks on the takeoff techniques

Thomas's feature was the great inward lean, 8.2 deg. Okuyama et al. (2003) suggested that the use of the hip abductors of the inward inclined takeoff leg in the high jump was an important factor to enhance the vertical velocity during the takeoff. Since great ground reaction forces, especially the vertical component tends to adduct the takeoff hip joint, a high jumper has to resist the adduction moment of the ground reaction forces by exerting great hip abduction torque. On the contrary, a strong abduction torque of the takeoff leg generated by the hip abductors can exert great force on the ground, which helps to raise a high jumper vertically. In other words, the inward lean of the body in the initial stage of the takeoff phase may have helped to develop great force of the abductors and the ground reaction forces and contribute to raising the body upward.

For Ioannou, his vertical CG velocity at the TD was positive. During the takeoff phase, a high jumper has to generate impulse to absorb the forward and downward velocity of the CG and to acquire the upward CG velocity to raise his body in the air. The positive or small negative vertical CG velocity at the TD implies that the impulse to absorb downward CG velocity was not necessary or smaller than the case of large negative vertical CG velocity. Thomas's technique was characterized by a strong forward lean of the trunk and deeply flexed support knee during the preparation phase, accelerative transition to the takeoff phase, fully used takeoff knee and hip, and the large inward lean of the body. Although

Ioannou decreased his horizontal CG velocity during the last stride, his technique was characterized by the relaxed last few strides, running up transition to the takeoff phase and the quick takeoff.

With a creative idea of athlete and coach, a new technique often emerges from a combination of existing techniques which excellent athletes employ in the real world. In this context, a combination of the techniques of Thomas and Ioannou may be a challenging trial in the world of the high jump.

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