3D Biomechanical Analysis of Women's High Jump Technique

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ABSTRACT

The purpose of the present study was to investigate the three-dimensional kinematics of contemporary high jump technique during competition and to compare the results with findings from previous elite-level events. The participants in the women's high jump event of the European Athletics Premium Meeting "Thessaloniki 2009" served as subjects. The jumps were recorded using three stationary digital video cameras, operating at a sampling frequency of 50fields/sec. The kinematic parameters of the last two strides, the take-off and the bar clearance were extracted for analysis through software. The results indicated that the kinematic parameters of the approach (i.e. horizontal velocity, stride length, stride angle, height of body centre of mass) were similar to those reported in the past. However, a poor transformation of horizontal approach velocity to vertical take-off velocity was observed as a greater deceleration of the swinging limbs could be seen at the instant of take-off. Considerable backward lean at take-off, large take-off angle and inefficient bar clearance were also noted. The authors recommend that the athletes studied consider giving a greater emphasis to the key technique elements of the take-off phase and of the bar clearance.

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Introduction

Currently, most top high jumpers use one of the versions of the Fosbury Flop technique[1]. The technique, which comprises the approach, the preparation for the take-off, the take-off, the flight phase and bar clearance and the landing[2], is differentiated from the other jumping styles mainly by the so called "J" approach and back lay-out position used to cross the bar.

The single most important factor and essential contributor to the height cleared, is the height of the flight of the body's centre of mass (BCM), which is a result of the vertical impulse produced during the take-off phase[3,4].

Key biomechanical factors that describe the take-off are the knee angle of the take-off leg, the angle of the lead leg thigh, the angle of the trunk position and the angles of forward/backward and inward lean[4,5].

The support and flight times, the stride lengths and frequencies, the path of the BCM, the angle of the run-up and the horizontal, vertical and resulting BCM velocities are the parameters that are usually used to analyse the approach[4,6,7,8].

Research data for female high jumpers exist from the Olympic Games[7,9], IAAF World Championships in Athletics[10,11,12], IAAF World Junior Championships[7] and IAAF World Indoor Championships[9]. Furthermore, data are also available from longitudinal observations of elite female high jumpers[4,13,14,15,16]. In the present study, international level female high jumpers were analysed in order to observe the three-dimensional kinematics of contemporary high jump technique during competition and to compare the results with findings from previous elite-level events.

Methods

Subjects & Data Collection

The participants in the women's high jump of the European Athletics Premium Meeting "Thessaloniki 2009" in Thessaloniki, Greece, on 10 June 2009 served as the subjects.

All jumps were recorded using three stationary JVC digital video-cameras (GR-DVL9600EG; GR-D720E; GR-D815; Victor Co., Japan), operating at a sampling frequency of 50fields/sec. The video-cameras were fixed on tripods and were positioned on the stands (Figure 1). The synchronisation of the captured videos from the three video-cameras was accomplished with the use of the audio signals recorded, using the audio synchronisation method provided by the analysis software.

The area used by the jumpers for the approach and the take-off was calibrated by placing 2.5m´0.02m poles at predefined spots on the field, in order to produce three-dimensional coordinates with the use of a 3D-DLT technique[17]. The Y-axis was parallel to the long side of the crossbar; the X-axis was perpendicular to the Y-axis; the Z-axis was perpendicular and vertical to the X- and Y-axes. The accuracy of the 3D reconstruction was determined by Root Mean Square error. Errors of 2.5cm, 1.8cm and 1.5cm were found for the X-, Y- and Z-axes, respectively.

Data Analysis

All trials above 1.84m were recorded and each jumper's highest valid jump was selected for further analysis. Eighteen anatomical points on the body (tip of the toe, ankle, knee, hip, shoulder, elbow, wrist and fingers on both sides of the body, the neck and the top of the head) and selected parts of the crossbar and the uprights were manually digitised in each field (Figure 1, page 33). The coordinates of the BCM were calculated for every field using the segment parameters derived with the method proposed from PLAGENHOEF[18]. A 6Hz cut-off frequency, based on residual analysis[19], was selected for smoothing.

The coordinates of the digitised points were used for the calculation of the biomechanical parameters presented in this study. Spatial parameters (i.e. stride length, stride angle, BCM height) and the body configuration (i.e. joint angles and inclination of body segments) were calculated using the extracted coordinates of the digitised points at selected time-instants of the jumpers' attempts.

Video synchronisation, digitisation, smoothing and analyses were conducted using the A.P.A.S.-XP software (Ariel Dynamics Inc., Trabuco Canyon, CA). Descriptive statistics (average ± standard deviation) were utilised for the presentation of the results.

Results

Seven jumpers cleared 1.84m, with the mean official result being 1.90m (Table 1). Vlasic won the competition with a jump of 2.01m, the 16th best result in 2009[20]. Four of the studied jumpers (Vlasic, Radzivil, Stergiou, Forrester) used the double-arm technique while the other three (Spencer, Dusanova, Klyugina) used running-arm technique.

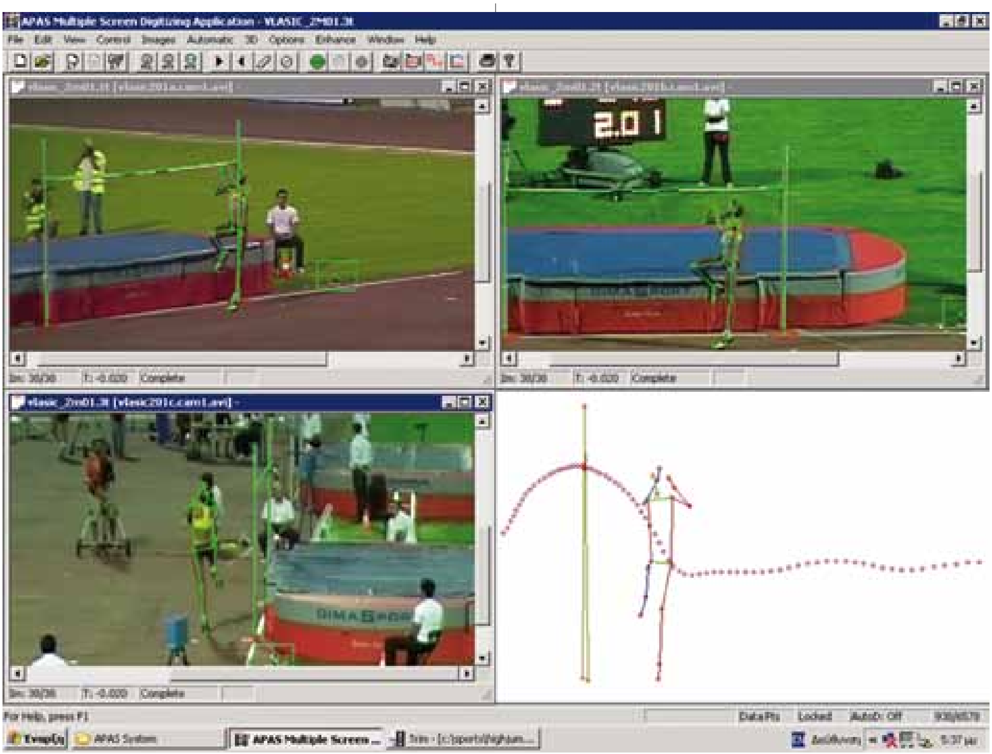

Figure 1: The filming views, the digitizing process and the 3D reconstruction of Vlasic's successful attempt at 2.01m using the APAS-XP software (Ariel Dynamics Inc., Trabuco Canyon, CA)

Table 1: The height of the body centre of mass at the instants of touchdown and take-off (H0 and H1, respectively), the height of the flight (H2) and the height of bar clearance (H3), along with the maximum height achieved (H_{MAX}) (The values are also presented as percentage (%) of the official result (H_{OFF})[5])

ATHLETE	NAT	RANK	H_{OFF} (m)	H0 (m)	H1 (m)	H2 (m)	H3 (m)	H_{MAX} (m)	H0%	H1%	H2%	H3%
VLASIC	CRO	1	2.01	0.99	1.41	0.65	0.05	2.06	49.3	70.1	32.3	-2.4
SPENCER	LCA	2	1.93	0.89	1.33	0.70	0.10	2.03	46.1	68.9	36.3	-5.2
RADZIVIL	UZB	3	1.91	0.91	1.31	0.63	0.03	1.94	47.6	68.6	33.0	-1.6
DUSANOVA	UZB	4	1.88	0.89	1.30	0.64	0.06	1.94	47.3	69.1	34.0	-3.1
KLYUGINA	RUS	4	1.88	0.91	1.38	0.62	0.12	2.00	48.4	73.4	33.0	-6.4
STERGIOU	GRE	6	1.88	0.89	1.29	0.62	0.03	1.91	47.3	68.6	33.0	-1.6
FORRESTER	CAN	7	1.84	1.08	1.48	0.51	0.15	1.99	58.7	80.4	27.7	-8.1
Mean (n=7)			*1.90*	*0.94*	*1.36*	*0.62*	*0.08*	*1.98*	*49.3*	*71.3*	*32.8*	*-4.1*
SD			*0.05*	*0.07*	*0.07*	*0.06*	*0.05*	*0.05*	*4.3*	*4.4*	*2.6*	*2.6*

The results indicate that almost one third of the height of the jump was the actual flight. Radzivil and Stergiou better exploited their maximum flight height, since the bar was only 0.03m beneath the maximum point of their BCM flight paths. Spencer, Klyugina and Forrester had the potential for a height closer to 2.00m with ideal technique, since each was able to lift her BCM more than 0.10m over the bar height at their best valid jump.

Stergiou and Klyugina took off nearer to the end of the bar (less than 0.40m), while Vlasic and Forrester took off closer to the centre of the bar (more than 1.1m from the end of the bar). With the exception of Radzivil and Klyugina, the jumpers took-off about 0.9m away from the bar (Table 2).

Dusanova and Klyugina cleared the bar in the descending part of their BCM flight path, while Radzivil reached the highest point of her flight curve 0.21m behind the bar (Figure 2).

The jumpers' body configuration at the instant of take-off is presented in Figure 2. With regard to the fulfilment of the key elements of high jumping technique[1,2,21,22] the following deviations were observed:

- the inadequate backward lean of the body at touchdown,
- the inadequate knee extension of the take-off leg at take-off,
- the lead knee angle (not "locked" in a proper position at take-off),
- the inability to set the body parallel to vertical at takeoff,
- the improper swing of the arms during the clearance of the bar.

Vlasic and Stergiou executed the last stride with a minimum knee angle of about 130°, while the other jumpers had a more flexed knee angle (about 120°). The average touchdown angle of the support leg was 34° ± 3, with the jumpers who cleared less than 1.90m having a larger inclination (Table 3). Stergiou had the lowest touchdown knee angle (151°), the lowest minimum knee angle (128°) and the second largest range of motion of the knee joint during the concentric phase of the take-off (36°). In contrast, Vlasic had the largest touchdown knee angle (151°), the largest minimum knee angle (146°) and the second lowest range of motion of the knee joint during the concentric phase of the take-off (25°). Vlasic and Dusanova almost extended their knee of the support leg at the instant of take-off. On the contrary, Radzivil took-off with a more flexed knee (158°), since she executed the jump with the lowest range of motion of the knee joint during the concentric phase of the take-off (22°).

Differences concerning the relationship of the magnitude of knee flexion of the take-off leg and the development of vertical BCM velocity in the take-off phase among jumpers were detected. Figure 3a compares the development of vertical BCM velocity between Vlasic and Stergiou, who had the largest and smallest touchdown and minimum knee angle, respectively. Figure 3b shows the development of vertical BCM velocity between two jumpers (Spencer, Forrester) with almost equal knee flexion, but different vertical take-off velocity of the BCM. Figure 3c represents the alterations of the development of vertical velocity of the BCM during the take-off phase among the jumpers who cleared 1.88m (Dusanova, Klyugina, Stergiou). Finally, Ridzivil and Klyugina achieved different jumping heights, although the development of the vertical BCM velocity compared to the knee joint angle of the take-off leg during the take-off phase seemed to be identical (Figure 3d).

Vlasic's performance was characterised by the largest horizontal and vertical take-off velocities of the BCM recorded in the present study (Table 4). Spencer was the only jumper who had a positive vertical velocity of the BCM at the touchdown. The horizontal velocity of the BCM was reduced in a range of 2.5-3.3m/sec (Spencer and Radzivil, respectively), while the change of the vertical velocity of the BCM varied from 3.4m/sec (Forrester) to 4.5m/sec (Vlasic). The mean take-off angle was 51.6° (±5.2). These factors led to the achievement of heights of flight ranging from 0.51m (Forrester) to 0.70m (Spencer).

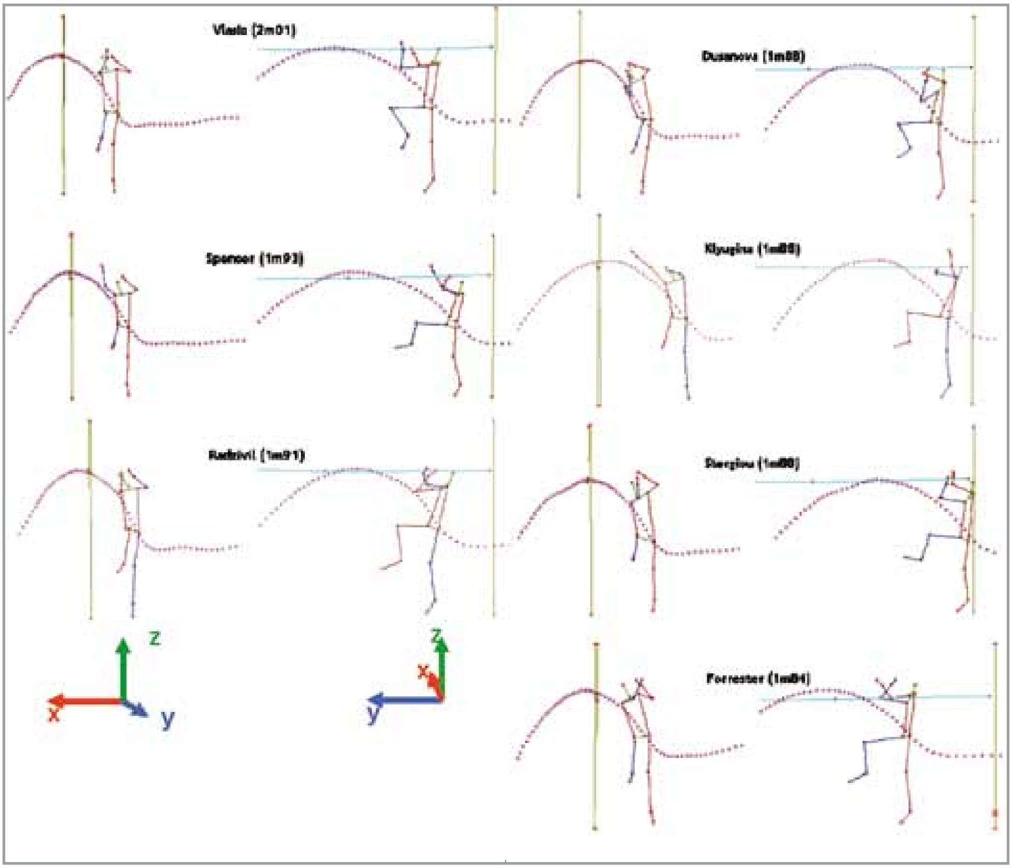

Figure 2: Stick figures of the examined jumpers at the instant of take-off (The path of the body centre of mass is also displayed)

Table 2: Toe-to-post (TP; Y-axis) and toe-to-bar (TB; X-axis) distances at the instant of the touchdown for the take-off (BB_{TO} and BB_{Hmax} represent BCM-to-bar distance in the X-axis at the instant of take-off and at the instant of maximum BCM height during the flight, respectively.)*

ATHLETE	H_{OFF} (m)	TP (m)	TB (m)	BB_{TO} (m)	BB_{Hmax} (m)
VLASIC	2.01	1.12	0.80	0.70	0.04
SPENCER	1.93	0.69	0.90	0.82	-0.02
RADZIVIL	1.91	0.63	0.56	0.54	0.21
DUSANOVA	1.88	0.57	0.88	0.83	-0.11
KLYUGINA	1.88	0.39	1.29	1.00	-0.10
STERGIOU	1.88	0.20	0.93	0.77	0.06
FORRESTER	1.84	1.33	0.77	0.61	0.15
Mean (n=7)	***1.90***	***0.70***	***0.88***	***0.75***	***0.03***
SD	***0.05***	***0.40***	***0.22***	***0.15***	***0.12***

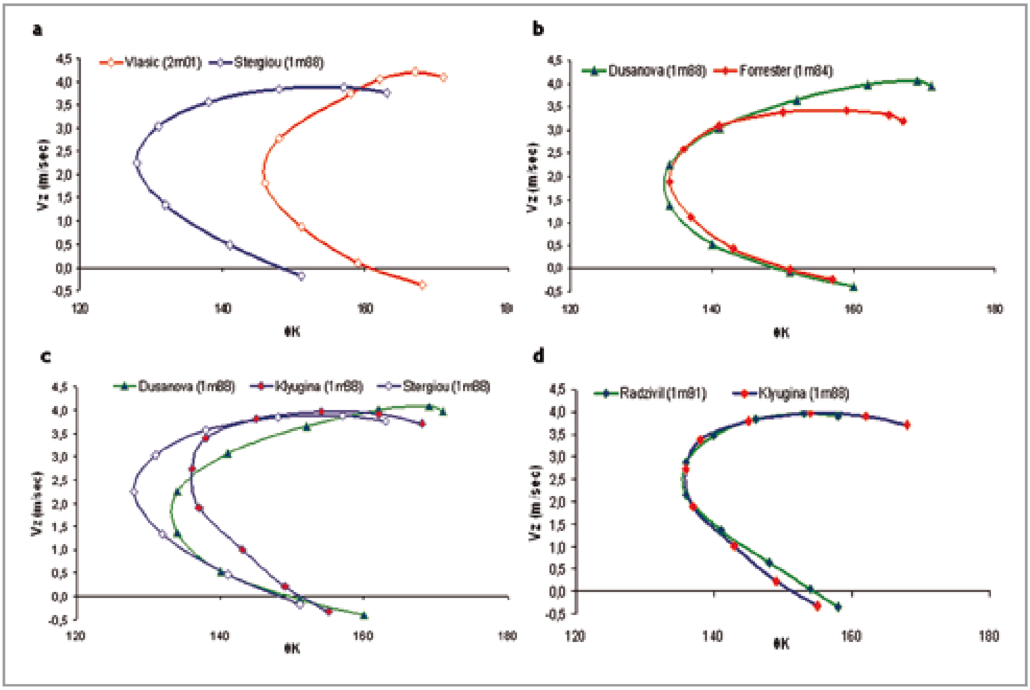

Figure 3: The relationship between the knee angle of the take-off leg (qK) and the vertical velocity of the body centre of mass (Vz)

Table 3: The take-off leg's touchdown angle (jTD) and the knee angles (q_K) at the instant of the touchdown (TD), the minimum knee angle (AM) and take-off (TO). q_KROM represents the range of motion of the knee joint during the concentric phase of the take-off (q_K1LS represents the minimum knee angle during the support phase of the last stride.)

ATHLETE	H_{OFF} (m)	θ_K1LS (º)	φTD (º)	θ_KTD (º)	θ_KAM (º)	θ_KTO (º)	θ_KROM (º)
VLASIC	2.01	130	32	168	146	171	25
SPENCER	1.93	115	31	155	131	162	31
RADZIVIL	1.91	118	31	158	136	158	22
DUSANOVA	1.88	123	34	160	134	171	37
KLYUGINA	1.88	-	37	155	136	168	32
STERGIOU	1.88	131	37	151	128	164	36
FORRESTER	1.84	123	37	157	134	167	33
Mean (n=7)	*1.90*	*123*	*34*	*158*	*135*	*166*	*31*
SD	*0.05*	*6*	*3*	*5*	*6*	*5*	*6*

Table 4: The horizontal (V_H) and the vertical (V_Z) velocity values at the instant of touchdown (TD) and toe-off (TO) for the jump, their change during the take-off phase (DV_H, DV_Z) and the projection angle of the BCM (AngPr)

ATHLETE	H_{OFF} (m)	V_HTD (m/sec)	V_HTO (m/sec)	ΔV_H (m/sec)	V_ZTD (m/sec)	V_ZTO (m/sec)	ΔV_Z (m/sec)	AngPr (°)
VLASIC	2.01	7.13	4.38	-2.75	-0.37	4.09	4.46	47.5
SPENCER	1.93	6.86	4.38	-2.48	0.16	3.92	3.76	46.4
RADZIVIL	1.91	6.11	2.80	-3.31	-0.35	3.90	4.25	59.1
DUSANOVA	1.88	6.32	3.40	-2.92	-0.39	3.96	4.35	55.1
KLYUGINA	1.88	6.73	4.04	-2.69	-0.33	3.71	4.04	55.5
STERGIOU	1.88	6.85	3.77	-3.08	-0.18	3.76	3.94	51.8
FORRESTER	1.84	6.83	4.01	-2.82	-0.22	3.14	3.36	45.5
Mean (n=7)	***1.90***	***6.69***	***3.83***	***-2.86***	***-0.24***	***3.78***	***4.02***	***51.6***
SD	*0.05*	*0.35*	*0.57*	*0.27*	*0.19*	*0.31*	*0.38*	*5.2*

With regard to the swinging limbs' contribution to the take-off action, four jumpers had greater arm than lead leg maximum vertical velocity (Table 5). Results revealed a considerable contribution to Vlasic's vertical take-off velocity of the BCM from the movement of her lead leg in the vertical axis. On the contrary, the vertical velocity of Stergiou's arms was the highest among the jumpers examined. Furthermore, the greatest deceleration regarding vertical velocity of the lead leg was observed for Klyugina (-3.2m/sec), while Forrester had greater deceleration concerning the vertical velocity of the arms (-2.3m/sec). Stergiou seemed to exploit the vertical velocity of the swinging segments, since the deceleration of both her lead leg and arms were about 1.0m/sec. It is worth noting that Forrester's low vertical take-off velocity of the BCM of was accompanied by low values for the lead leg and arm vertical take-off velocities (3.1m/sec and 3.8m/sec, respectively).

Table 5: The maximum (MAX) and toe-off (TO) vertical velocities (V_Z) of the lead leg (L) and the arms (A; mean of left and right arm) during the take-off ($DV_Z L$ and $D_Z VA$ represent the deceleration[11] of the lead leg and the arms upon the completion of the lake-off, respectively. The maximum angular velocity of the lead leg's hip (wH) and knee (wK) joints during the take-off are also presented.)

ATHLETE	H_{OFF} (m)	$V_Z L_{MAX}$ (m/sec)	$V_Z L_{TO}$ (m/sec)	$\Delta V_Z L$ (m/sec)	$V_Z A_{MAX}$ (m/sec)	$V_Z A_{TO}$ (m/sec)	$\Delta_Z VA$ (m/sec)	ωH (rad/sec)	ωK (rad/sec)
VLASIC	2.01	7.51	5.83	-1.7	6.65	5.71	-0.9	6.1	10.1
SPENCER	1.93	7.04	4.76	-2.3	6.62	6.06	-0.6	9.5	13.7
RADZIVIL	1.91	6.63	4.18	-2.5	6.82	6.18	-0.6	3.6	10.8
DUSANOVA	1.88	6.35	4.27	-2.1	6.44	5.28	-1.2	7.5	7.7
KLYUGINA	1.88	7.66	4.50	-3.2	5.67	4.55	-1.1	8.7	10.5
STERGIOU	1.88	5.57	4.60	-1.0	7.94	7.08	-0.9	7.0	16.5
FORRESTER	1.84	5.78	3.06	-2.7	6.11	3.83	-2.3	3.9	10.9
Mean (n=7)	***1.90***	***6.65***	***4.46***	***-2.2***	***6.61***	***5.53***	***-1.1***	***6.6***	***11.5***
SD	*0.05*	*0.8*	*0.8*	*0.7*	*0.7*	*1.1*	*0.6*	*2.3*	*2.9*

With the exception of Dusanova, the maximum angular velocity of the lead leg's knee joint was greater than that of the hip joint. Stergiou extended her knee faster (16.5 rad/sec), while Spencer flexed her hip faster (9.5 rad/sec) than the other examined jumpers (Table 5). The slowest hip flexion was observed for Radzivil and Forrester (3.6 rad/sec and 3.9 rad/sec, respectively) while the slowest knee extension was observed in Dusanova (7.7 rad/sec).

Although the average stride length was almost equal for the last two strides of the approach (2.08m ± 0.35m and 2.05m ± 0.12m for the penultimate and the last stride, respectively), three of the analysed jumpers reduced the length of their last stride compared to the penultimate (Table 6). For those who decreased the length of the last stride, the change was of a magnitude of 0.33m. The average increment of the length of the last stride for the other three jumpers was 0.28m.

The development of the approach velocity was connected to the trend observed for the stride length. Vlasic and Stergiou decreased their stride length with a near to zero reduction of their horizontal velocity between the last two strides of their approach. Furthermore, both exhibited the smoothest development of BCM horizontal velocity during the last strides of the approach (Figure 4). In contrast, four of the examined jumpers increased their horizontal velocity during the last stride. The stride angle was constantly decreasing as the jumpers reached the bar (69° ± 6, 45° ± 5 for the penultimate and last stride, respectively). Although the fact that the BCM path during the last strides of the approach was internally of the foot placements for all of the jumpers, Spencer, Stergiou and Forrester took off with their BCM projection aside of their take-off point (Figure 5). Moreover, Ratzivil took off with her BCM projection behind of her take-off point, mainly because of the large backward lean of her body at take-off.

The average lowering of the BCM from the instant of the toe-off of the penultimate stride till the touchdown for the take-off was 0.10m (Table 7). Spencer was the only jumper who lowered the BCM height during the support phase of the penultimate stride. In conctrast, Ratzivil did not lower her BCM height during the support phase of the last stride (Figure 6). The larger vertical BCM displacement during the take-off phase was observed for Klyugina (0.47m).

Discussion

The mean official height cleared by the jumpers examined in the present study was 1.90m ± 0.05, almost 0.10m lower than the jumps analysed in biomechanical studies for female high jumping during the IAAF World Championships

Table 6: The stride angles (qS), the length (S) and the horizontal (V_H) velocity values at the instant of toe-off for the penultimate (2LS) and last stride (1LS)

ATHLETE	H_{OFF} (m)	S2LS (m)	S1LS (m)	ΔS (m)	θS_{2LS} (°)	θS_{1LS} (°)	V_H2LS (m/sec)	V_H1LS (m/sec)	ΔV_H (m/sec)
VLASIC	2.01	2.37	2.23	-0.14	72	51	7.40	7.38	-0.02
SPENCER	1.93	1.88	2.17	0.29	60	49	7.37	7.53	0.16
RADZIVIL	1.91	1.81	1.97	0.16	71	42	6.26	6.89	0.63
DUSANOVA	1.88	1.63	1.97	0.34	64	38	6.09	6.72	0.63
KLYUGINA	1.88	-	-	-	-	-	-	-	-
STERGIOU	1.88	2.47	1.97	-0.50	69	44	7.37	7.33	-0.04
FORRESTER	1.84	2.34	1.99	-0.35	75	48	6.81	7.02	0.21
Mean (n=6)	*1.90*	*2.08*	*2.05*	*-0.03*	*69*	*45*	*6.88*	*7.15*	*0.26*
SD	*0.05*	*0.35*	*0.12*	*0.35*	*6*	*5*	*0.59*	*0.32*	*0.30*

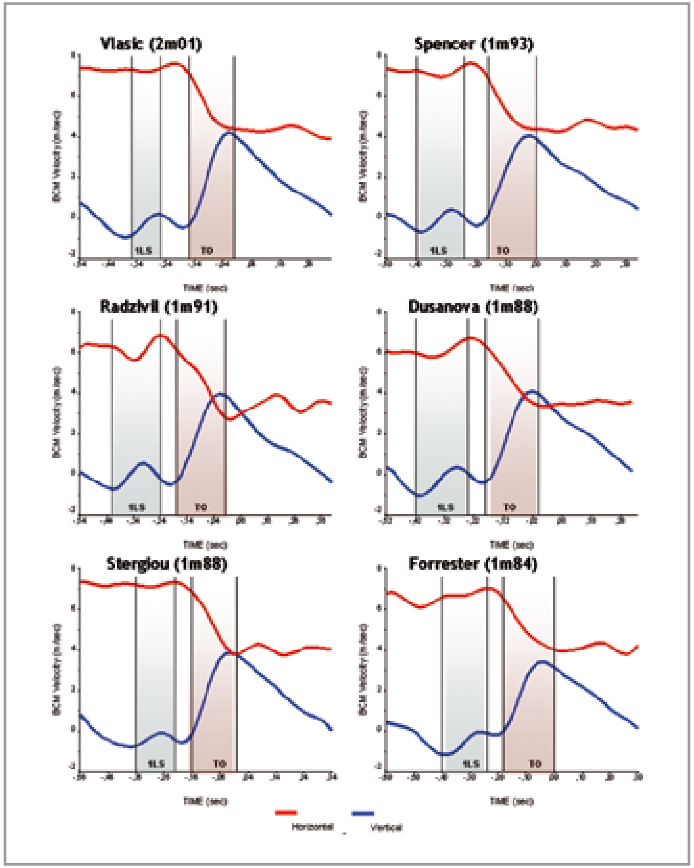

Figure 4: Horizontal and vertical velocity of the body center of mass (BCM) from the take-off of the penultimate stride until the maximum height of the body centre of mass achieved during the flight (The shaded areas between the vertical lines represent the support phases for the last stride (1LS) and the take-off (TO).)

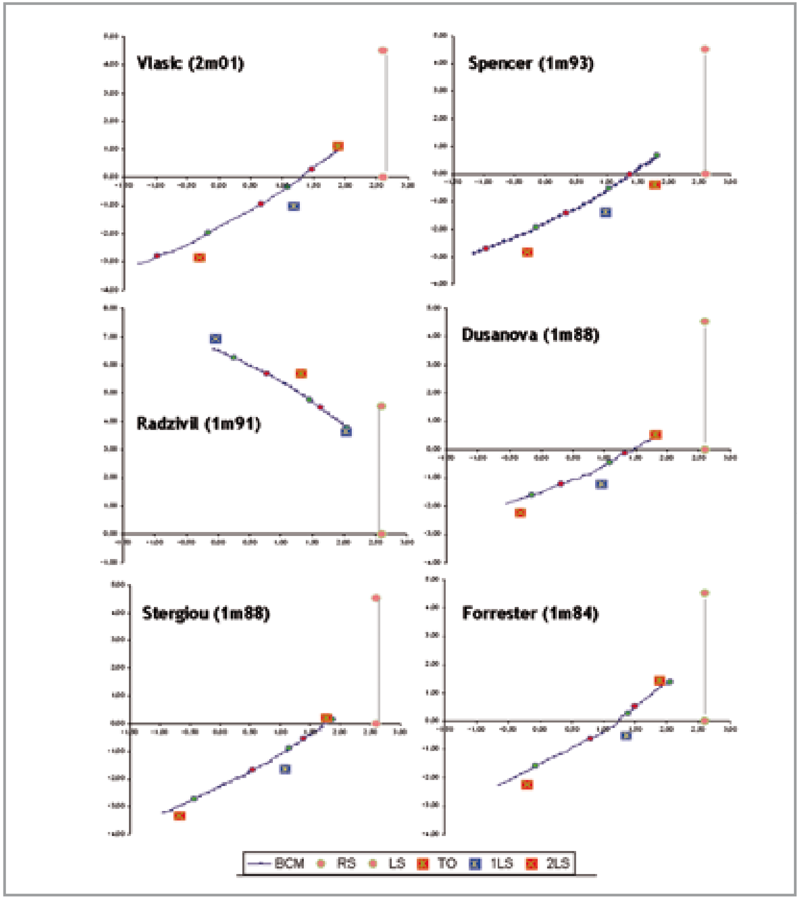

Figure 5: Overhead view of foot placements, i.e. support phase of the penultimate (2LS), the last stride (1LS) and the take-off (TO) and the trajectory of the body centre of mass (BCM) (RS and LS represent the right and left uprights, respectively. Red data points (•) represent the touchdowns, while green data points (•) represent the toe-offs.)

Table 7: The body centre of mass' height alteration between the instants of touchdown (TD) and toe-off (TO) for the penultimate (2L), the last stride (1L) and the take-off for the jump (J)

ATHLETE	$2L_{TD} \rightarrow 2L_{TO}$ (support, m)	$2L_{TO} \rightarrow 1L_{TD}$ (flight, m)	$1L_{TD} \rightarrow 1L_{TO}$ (support, m)	$1L_{TO} \rightarrow J_{TD}$ (flight, m)	$J_{TD} \rightarrow J_{TO}$ (support, m)
VLASIC	0.04	-0.05	-0.01	-0.06	0.42
SPENCER	-0.02	0.00	-0.01	-0.04	0.44
RADZIVIL	0.01	-0.04	0.01	-0.03	0.40
DUSANOVA	0.02	-0.05	-0.03	-0.02	0.41
KLYUGINA	-	-	-	-	0.47
STERGIOU	0.04	-0.06	-0.04	-0.03	0.40
FORRESTER	0.04	-0.06	-0.08	0.00	0.40
Mean (n=6)	*0.02*	*-0.04*	*-0.03*	*-0.03*	*0.42*
SD	*0.02*	*0.02*	*0.03*	*0.02*	*0.03*

** It was not possible to calculate BCM height for the last strides of Klyugina's analysed attempt because of a random incident during the filming of the event.*

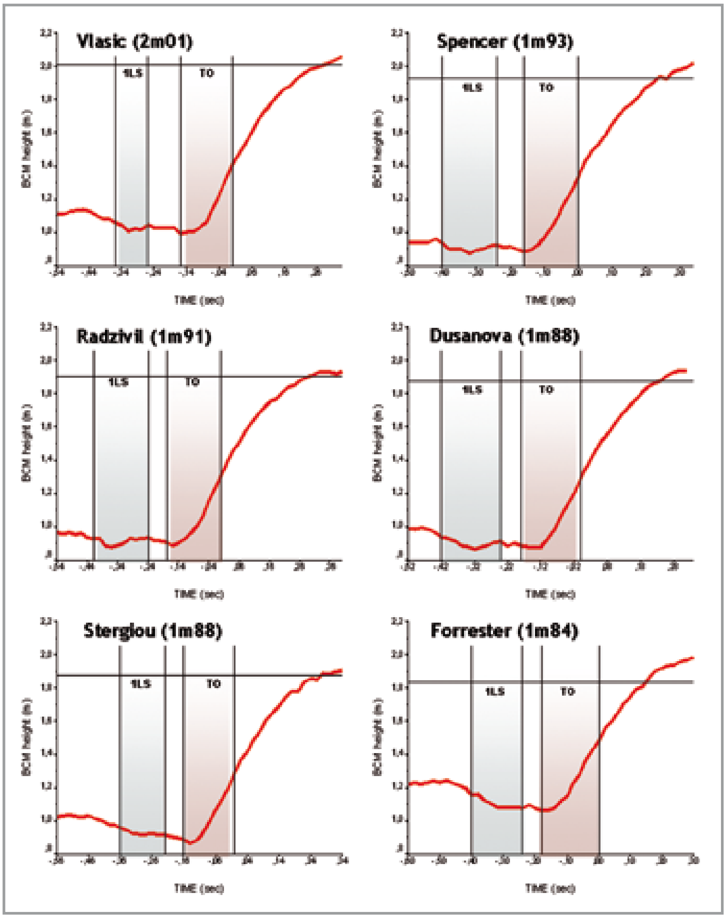

Figure 6: Body centre of mass (BCM) height from the toe-off of the penultimate stride until the maximum body center of mass height achieved during the flight (The vertical lines represent the support phases for the last stride (1LS) and the take-off (TO). The horizontal line represents the height of the bar.)

in Athletics and the Olympic Games[4,6,9,10,12]. The official height in the examined jumps could have been higher, since the average height of bar clearance was 0.08m ± 0.05. In general, the height of bar clearance was higher than the 0.05m observed in major competitions[4,6,9,10,12]. Four of the examined jumpers had an ineffective bar clearance (H3 > 0.06m), while the other three jumpers performed with a reasonable efficiency, as classified by DAPENA[23], bar clearance technique (0.03m < H3 < 0.06m). The horizontal BCM-to-bar distance at take-off, either close (Radzivil, Forrester) or far (Dusanova, Klyugina), along with the large BCM's angle of projection, might have created some difficulties for an efficient clearance of the bar[4,15,23].

The average horizontal approach (7.01m/sec ± 0.41) and take-off velocities (3.83m/sec ± 0.57) were similar to those reported in other competitions (7.10m/sec and 3.88m/sec, respectively[4,6,9]). In contrast, the mean vertical take-off velocity of the BCM was 3.78m/sec ± 0.31, lower than those reported in previous competitions (3.95m/sec)[4,6,9,10]. On the other hand, the mean vertical take-off velocity of the BCM was either identical to those observed before (3.7m/sec)[11,24] or greater compared to jumps at the same height (3.51m/sec)[25]. The transformation ratio of horizontal approach to vertical take-off velocity of the BCM was 0.57 ± 0.06, indicating a poorer transformation compared to the findings in the above mentioned studies, where the ratio was approximately 0.47. The poorer transformation found in the present study had an impact concerning the effectiveness of the jump, since the vertical take-off velocity has found to be the most important factor in high jumping[26]. The vertical velocity of the body segments during the take-off contributes to the vertical BCM take-off velocity and has been found to be higher in men than women[9,10,25]. It is worth mentioning that the jumpers examined in the present study had larger vertical velocities of the lead leg and the arms during the take-off phase, but also a greater deceleration upon the completion of the take-off than reported before[10]. The take-off angle found in the present study (51.6° ± 5.2) was larger than noted in the past[6,11,13,14,24].

The height of the BCM at the touchdown for the jump (1.00m ± 0.09) was notably higher than found previously (0.86m)[6,9,10]. Furthermore, the BCM at its lowest position during the take-off phase was at a height of 0.93m ± 0.07. Taking into consideration that the minimum knee angle during the take-off phase was an average 10° lower than found in the 1986 IAAF World Junior Championships[6], the higher BCM height could be attributed to lower backward trunk inclination, which is also an important body adjustment for the take-off[5]. However, it has been supported that the BCM height at touchdown does not reveal a performance-related trend, since the initial height at the take-off phase is not a performance-determining factor[10]. The overall vertical BCM displacement during the take-off phase was 0.42m ± 0.03, a value within the range observed in IAAF World Championships in Athletics[6, 10].

The average of the taken touchdown angle off leg (34° ± 3) was identical to the optimum suggested by GREIG & YEADON[28]. The range of motion of the take-off leg's knee (31° ± 6) was larger than those reported before (26°)[6]. The effectiveness of the magnitude of the knee flexion has been found to be related with factors such as strength and leg stiffness[11,16,25,28,29]. Although the minimum knee angle during the support of the last stride was an average 10° greater, the minimum knee angle during the take-off was an average 10° less than found in the past[6,16,24]. The higher knee flexion in the last support decreases the BCM height, but increases contact time. It has been suggested that the maintenance of BCM velocity is accomplished by using effective double arm techniques[30], which was used by the majority of the jumpers analyzed in the present study.

As expected[6,8,26,31,32], the stride angle was constantly decreasing as the jumpers reached towards the bar. The last stride (2.05m ± 0.12) was found to be longer than reported in the past (1.92m)[6,9]. The greater lowering of the BCM height during the last stride did result in lower vertical BCM touchdown velocity at the take-off phase for Stergiou and Forrester, as suggested by AE et al.[30].

Although the vertical of the BCM take-off velocity was lower, the vertical velocities of the body segments during the take-off were higher than those reported by BRÜGGEMANN & LOCH[10]. This could be attributed to the insufficient backward trunk inclination, since backward trunk inclination contributes, together with knee flexion, to the compensation of: 1) the large approach velocity, 2) the development of large vertical BCM displacement, and 3) gaining time for the coordination of the swing of the body segments[5]. The low BCM height at touchdown is advantageous concerning the effective stretch-shortening cycle during the take-off phase, allowing a larger vertical BCM displacement during the take-off phase, the development of greater vertical BCM take-off velocity and the efficient contribution of the swinging movement of the arms[25,33]. It has been reported that female high jumpers gain less than men from the arms' swing[10,25]. In general, in order to maximise the contribution of the arms and lead leg to high jump performance, it is essential to combine their coordinated movement at touchdown, their vigorous upward movement during the push-off, an optimum timing of their movements and the completion of their action just before take-off are important[34].

Finally, in the case of Vlasic, the results of the present study revealed that there was a consistency concerning the elements of her technique compared to her previous 2.00m jumps[13,14]. In detail, toe-to-bar distance and the height of the flight were identical (0.80m and 0.65m, respectively). Similar 2009 vs. 2003 values were observed concerning the lowest take-off leg knee angle (146° vs. 145°), the height of bar clearance (0.05m vs. 0.04m), the horizontal BCM take-off velocity (4.38m/sec vs. 4.33m/sec) and the horizontal velocity in the last steps of the approach (7.4m/sec vs. 7.5m/sec). The stride length for the penultimate (2.37m vs. 2.41m) and last stride (2.23m vs. 2.19m) were of the same magnitude. Her BCM height at touchdown and take-off was considerably lower in the past (0.99m vs. 0.95m and 1.41m vs. 1.38m, respectively). Significant alterations were observed concerning the horizontal and vertical BCM velocities at the touchdown for the jump (7.13m/sec vs. 6.50m/sec and -0.37m/sec vs. 0.04m/sec, respectively), the vertical BCM take-off velocity (4.09m/sec vs. 3.75m/sec) and the take-off angle (47.5° vs. 40.8°).

- In conclusion, the technique of the international-level female high jumpers analysed in the present study was characterised by:
- the slight dominance of double arm techniques,
- the similarity of the kinematic parameters of the last strides of the approach (i.e. horizontal velocity, stride length, stride angle, BCM height) to those reported in the past,
- the poor transformation of horizontal approach velocity to vertical take-off velocity, since a greater deceleration of the swinging limbs was observed at the completion of the take-off action,
- the variability observed in the relationship between the knee angle of the support leg and the vertical BCM velocity,
- the notable backward lean and inadequate knee extension of the support leg at the instant of take-off,
- the large take-off angle,
- the inefficient bar clearance.

In general, we can recommend that the athletes studied consider giving a greater emphasis to the key technique elements of the take-off phase and of the bar clearance.

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REFERENCES

1. SCHIFFER, J. (2009). The high jump. New Studies in Athletics, 34(3): 9-22.

2. TIDOW, G. (1993). Model technique analysis sheets. Part VIII: The Flop High Jump. New Studies in Athletics, 8(1), 31-44.

3. BRÜGGEMANN, G.-P. & ARAMPATZIS, A. (1997). Men's high jump. In: MÜLLER, H. & HOMMEL H. (Eds.), Biomechanical Research Project at the VIth World Championships in Athletics, Athens 1997: Preliminary Report. New Studies in Athletics, 12(2-3), 66-69.

4. RITZDORF, W.; CONRAD, A. & LOCH, M. (1989). Intra-individual comparison of the jumps of Stefka Kostadinova at the II World Championships in Athletics Rome 1987 and the Games of the XXIV Olympiad Seoul 1988. New Studies in Athletics, 4(4), 35-41.

5. HAY, J. G. (1985). The biomechanics of sports techniques (3rd edition). Englewood Cliffs, NJ: Prentice-Hall.

6. BRÜGGEMANN, G.-P. & CONRAD, T. (1986). High jump. In: SUSANKA, P., BRÜGGEMANN, G.-P. & TSAROUHAS, E. (Eds.), Biomechanical Research in Athletics: 1st World Junior Championships, Athens 1986 (pp. 121-148). Athens: S.E.G.A.S.-E.K.A.E.

7. CONRAD, A. & RITZDORF, W. (1990). Biomechanical analysis of the high jump. In: BRÜGGEMANN, G.-P. & GLAD, B. (Eds.), Scientific Research Project at the Games of the XXIVth Olympiad, Seoul 1988 (pp. 177–217). London: International Amateur Athletic Federation.

8. DAPENA, J. (1980). Mechanics of translation in the Fosbury-flop. Medicine & Science in Sports & Exercise, 12(1), 37-44.

9. DAPENA, J. (2000). The High Jump. In: ZATSIORSKY, V. (Ed), Biomechanics in Sport (pp. 284-311). Oxford: Blackwell Publishing.

10. BRÜGGEMANN, G.-P. & LOCH, M. (1992). The high jump. New Studies in Athletics, 7(1), 67-72.

11. IIBOSHI, A.; AE, M.; TKAMATSU, J.; NAGASAWA, M.; TANG, H.-P. & YUUKI, M. (1993). Techniques of elite high jumpers at the 3rd IAAF World Championships in Athletics. Abstracts of the XIV ISB Congress, Paris – France, Volume 1: 608-609.

12. KILLING, W. (2009). Zweimal bronze für Deutschlands Höhenjäger. Leichtathletik Training, 20(10-11), 26-35.

13. ANTEKOLOVIĆ, L.; BLAŽEVIĆ, I.; MEJOVŠEK, M. & COH, M. (2006). Longitudinal follow-up of kinematic parameters in the high jump - A case study. New Studies in Athletics, 21(4), 27-37.

14. BLAŽEVIĆ, I.; ANTEKOLOVIĆ, L. & MEJOVŠEK, M. (2006). Variability of high jump kinematic parameters in longitudinal follow-up. Kinesiology, 38(1), 63-71.

15. DOBRILA, I.; MEJOVŠEK, M.; HOFMAN, E. & ANTEKOLOVIĆ, L. (2002). Kinematic indicators of the high jump efficiency. Paper presented at the 3rd International Scientific Conference "Kinesiology-New Perspectives", Opatija, Croatia, 25-29.09.2002.

16. MALCOLM, P.; DE CLERCQ, D. & VAN LANCKER, W. (2009). Regression analysis on longitudinal kinematical data from one elite high jump athlete in competition. Paper presented at the 22nd Congress of the International Society of Biomechanics, Cape Town, South Africa, 05-09.07.2009.

17. KOLLIAS, I. (1984). Three-dimensional analysis of hammer throwing. Unpublished doctoral dissertation, University of Alberta, Canada.

18. PLAGENHOEF, S. (1985). Patterns of human motion: A cinematographic analysis. Englewood Cliffs, NJ: Prentice-Hall.

19. WINTER, D.A. (1990). Biomechanics and motor control of human movement (2nd edition). Toronto: John Willey & Sons Inc.

20. http://www.iaaf.org/statistics/toplists (April 15, 2010).

21. RITZDORF, W. (2009). Approaches to technique and technical training in the high jump. New Studies in Athletics, 24(3), 31-34.

22. TANSLEY, J. (2004). High jump biomechanics. In: DALES, G.G. & MEAD TRICARD, L. (Eds.), The 16th International Track & Field Coaches Association Congress Proceedings (pp. 198-205). Kalamazoo, MI: I.T.F.C.A.

23. DAPENA, J. (1992). Biomechanical studies in the high jump and the implications to coaching. Track & Field Quarterly Review, 92(4), 34-38.

24. ANTEKOLOVIĆ, J.; ANTEKOLOVIĆ, L.J. & JULARIĆ, J. (2009). Povezanost kinematickih parametara zaleta, odraza i visine skoka u vis. In: Zbornik radova 18. Ljetne škole kineziologa Republike Hrvatske „Metodicki orgamizacijski oblici rada u podrucjima edukacije, sporta, sportske rekreacije i kineziterapije" (ur. B. NELJAK), Porec od 23. do 27, pp. 88-92.

25. DAPENA, J.; McDONALD, C. & CAPPAERT, J. (1990). A regression analysis of high jumping technique. International Journal of Sport Biomechanics, 6(3), 246-261.

26. COH, M. & SUPEJ, M. (2008). Biomechanical model of the take-off action in the high jump: A case study. New Studies in Athletics, 23(4), 63-73.

27. GREIG, M.P. & YEADON, M. R. (2000). The influence of touchdown parameters on the performance of a high jumper. Journal of Applied Biomechanics, 16(4), 367-378.

28. AE, M.; NAGAHARA, R.; OHSHIMA, Y.; KOYAMA, H.; TAKAMOTO, M. & SHIBAYAMA, K. (2008). Biomechanical analysis of the top three male high jumpers at the 2007 World Championships in Athletics. New Studies in Athletics, 23(2), 45-52.

29. LAFFAYE, G. (2001). Fosbury-flop and performance's factors: a review. Science et Motricité, 42, 3-15.

30. AE, M.; SAKATANI, M.; YOKOI, T.; HASHIHARA, Y. & SHIBUKAWA, K. (1986). Biomechanical analysis of the preparatory motion for takeoff in the Fosbury Flop. International Journal of Sport Biomechanics, 2(1), 66-77.

31. DAPENA, J.; AE, M. & IIBOSHI, A. (1997). Closer look at the shape of the high jump run-up. Track Coach, 138, 4406-4411.

32. KOVÁCS, I.; SÓVÁGÓ, J. & TIHANYI J. (1996). Three-dimensional comparative analysis of individual techniques in high jump. Kalokagathia, 34(1/2), 67-82.

33. DAPENA, J. & CHUNG, C.S. (1988). Vertical and radial motions of the body during the take-off phase of high jumping. Medicine and Science in Sports and Exercise, 20(3), 290-302.

34. LEES, A.; ROJAS, J.; CEPERO, M.; SOTO, V. & GUTIERREZ, M. (2000). How the free limbs are used by elite high jumpers in generating vertical velocity. Ergonomics, 43(10), 1622-1636.should be very specialised and the length of the breaks between competitions will depend on the athlete's physical and mental preparation and on the calendar of events.