Biomechanical analysis of the high jump at the 2005 IAAF World Championships in Athletics

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ABSTRACT

The purposes of this study were to determine how the maximum height of the jumper's centre of mass (CM) during the flight phase of the high jump is dependent on the kinematic variables of the take-off and to update current knowledge about the development and performance of the Fosbury Flop technique. The best jumps of the finalists at the 2005 IAAF World Championships in Athletics were filmed and analysed. The authors confirmed earlier findings that the vertical velocity and height of the CM at the end of the take-off phase together determine the height of the flight. The most important factor related to vertical velocity at the moment the take-off foot loses contact with the ground is the the CM position when the foot touches down for the take-off. CM height at this point is related more to arm technique than physique. The difference due to arm action can be 8cm if the jumper is 2m tall.

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Introduction

Richard "Dick" Fosbury (USA) won the gold medal in the high jump at the 1968 Olympic Games in Mexico City using a revolutionary new technique, which became known as the Fosbury Flop. Two major characteristics of the technique are a curved approach run and a back layout position for crossing the bar. In present day high jumping, the Fosbury Flop is the sole technique used by world-class high jumpers.

The high jump can be divided into three parts or phases: approach, take-off and flight (or bar clearance). The approach phase consists of a straight run-up, perpendicular to the plane of the uprights, followed by a curved section during the last four to six steps before the take-off. During this phase, the jumper builds up running velocity to between 7 and 8m/s. The purpose of the approach is to bring the athlete into an optimum position for take-off while moving at a velocity consistent with his/her strength and skill (HAY, 1993).

The take-off phase is defined as the period of time between the instant when the take-off foot first touches the ground (touchdown) and the instant when the toe looses contact with the ground (toe-off). The peak height of the jumper's centre of mass (CM) during the flight over the bar is dependent on the height and the vertical velocity of the CM at toe-off. This in turn is governed by the jumper's vertical velocity at the instant of touchdown and the vertical impulse transmitted via the take-off foot to jumper's body during the take-off phase. The height of the jumper's CM when the toe looses contact with the ground depends on his/her physique and body position at that instant. (HAY, 1973).

DAPENA et. al. (1990) found a positive relationship (r=0.79) between the horizontal velocity at the end of the approach and the vertical velocity of the CM the end of the take-off phase.

DAPENA and CHUNG (1988) suggest that a fast approach run can help the jumper to exert a larger vertical force to the ground. It is interesting to note that the fastest approach runs ever published from international events were at the 1997 IAAF World Championships, when the latest biomechanical analysis at the major championships was made (BRÜGGEMANN and ARAMPATSIS, 1997).

The present study is a part of series that includes previous investigations at the IAAF World Championships in Athletics in 1991 and 1997. The purposes were to determine how the maximum height of the CM during the flight phase is dependent on the kinematic variables of the take-off and to update current knowledge about the development and performance of the Fosbury Flop technique.

Methods

Subjects

Thirteen male high jumpers (height: 1.92 ± 0.05m, weight: 76.31 ± 8.13kg) were filmed during their competitive performances in the

Table 1:The physical characteristics of the finalists in the high jump at the 2005 IAAF World Championships in Athletics

Name	Height (m)	Weight (kg)	BMI	Result (m)
Yuriy Krymarenko (UKR)	1.85	62.0	18.1	2.32
Victor Moya (CUB)	1.96	80.0	20.8	2.29
Yaroslav Rybakov (RUS)	1.96	84.0	21.9	2.29
Mark Boswell (CAN)	1.89	66.0	18.5	2.29
Jaroslav Baba (CZE)	1.96	80.0	20.8	2.29
Nicola Ciotti (ITA)	1.87	75.0	21.4	2.29
Stefan Holm (SWE)	1.81	70.0	21.4	2.29
Vyacheslav Voronin (RUS)	1.90	78.0	21.6	2.29
Dracutin Topic (SCG)	1.97	77.0	19.8	2.25
Kyrikos Iannou (CYP)	1.93	66.0	17.7	2.25
Oskari Frösen (FIN)	1.94	86.0	22.9	2.20
Matt Hemingway (USA)	1.98	88.0	22.4	2.20
Andriy Sokolovskyy (UKR)	1.96	80.0	20.8	2.20
average	1.92	76.3	20.6	2.27
standard deviation	0.05	8.1	1.6	0.04

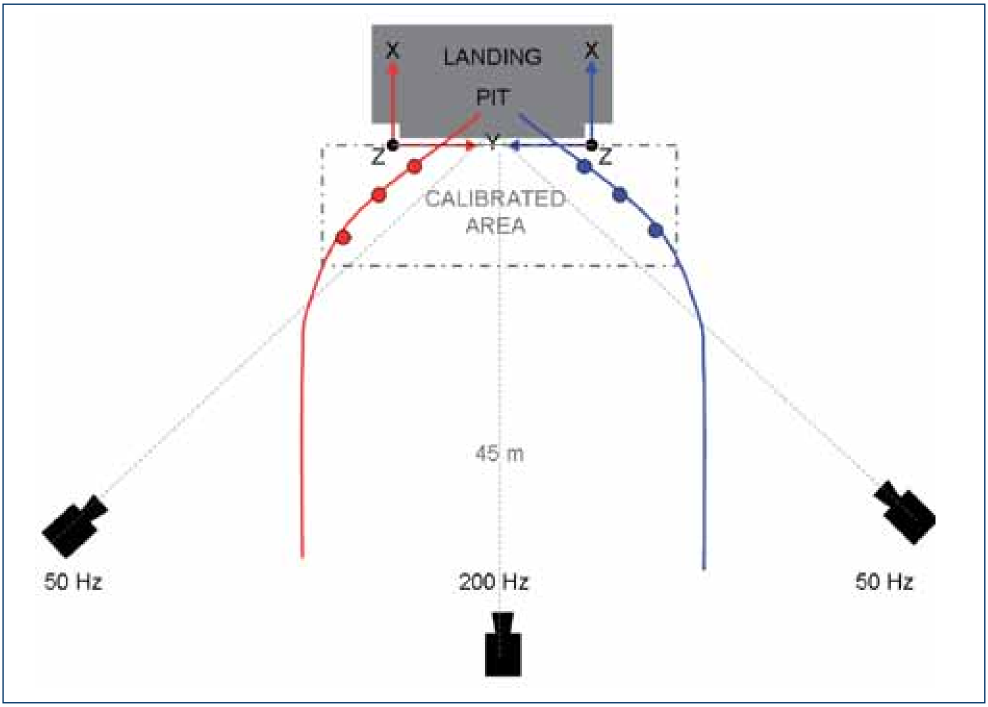

Figure 1: Camera positions, co-ordinate system and the multi phase calibration area used in the high jump at the 2005 IAAF World Championships in Athletics

men's high jump final during the 2005 IAAF World Championships in Athletics in Helsinki. The physical characteristics of the jumpers are presented in Table 1. The best valid jumps from each of the finalists were selected for the further analysis. The mean official result of the finalists was 2.27 ± 0.04m.

Data collection

Two Panasonic (NV-GS400) DV cameras were fixed outside the perimeter of the track. The distance to the mid-point of the bar was 45m and the angle between the optical axes of the cameras was 90° (Figure 1). The recordings of the jumps were made at 50 fields per second with a shutter speed of 1/2000 of a second. A third camera (JVC GR-DVL 9800), operating at the speed of 200 fields per second with the shutter speed of 1/250 of a second, was positioned perpendicular to the bar at a distance of 40m. The cameras were synchronised using the audio synchronisation method (BARROS et al., 2006), which records a synchronisation signal inserted onto the audio track through the camcorder's microphone jack.

The image space was calibrated by a multiphase (5 location) calibration procedure with the standard calibration frame. Peak Motus software uses a variation of the procedure published by CHALLIS (1995). This procedure was adapted by Peter Vint of Research Integrations, Inc.

Data reduction

The digital video signal was captured on to the Motus (Peak Performance, Inc.) motion analysis system. Fifteen body landmarks (wrist, elbow, shoulder, hip, knee, ankle, tip of the toe on both sides of the body and the head) for the two last strides of the approach and for the flight over the bar were manually digitised. The 3D model of the jumper's body consisted of 12 segments. Segment parameters used for determination of the body CM

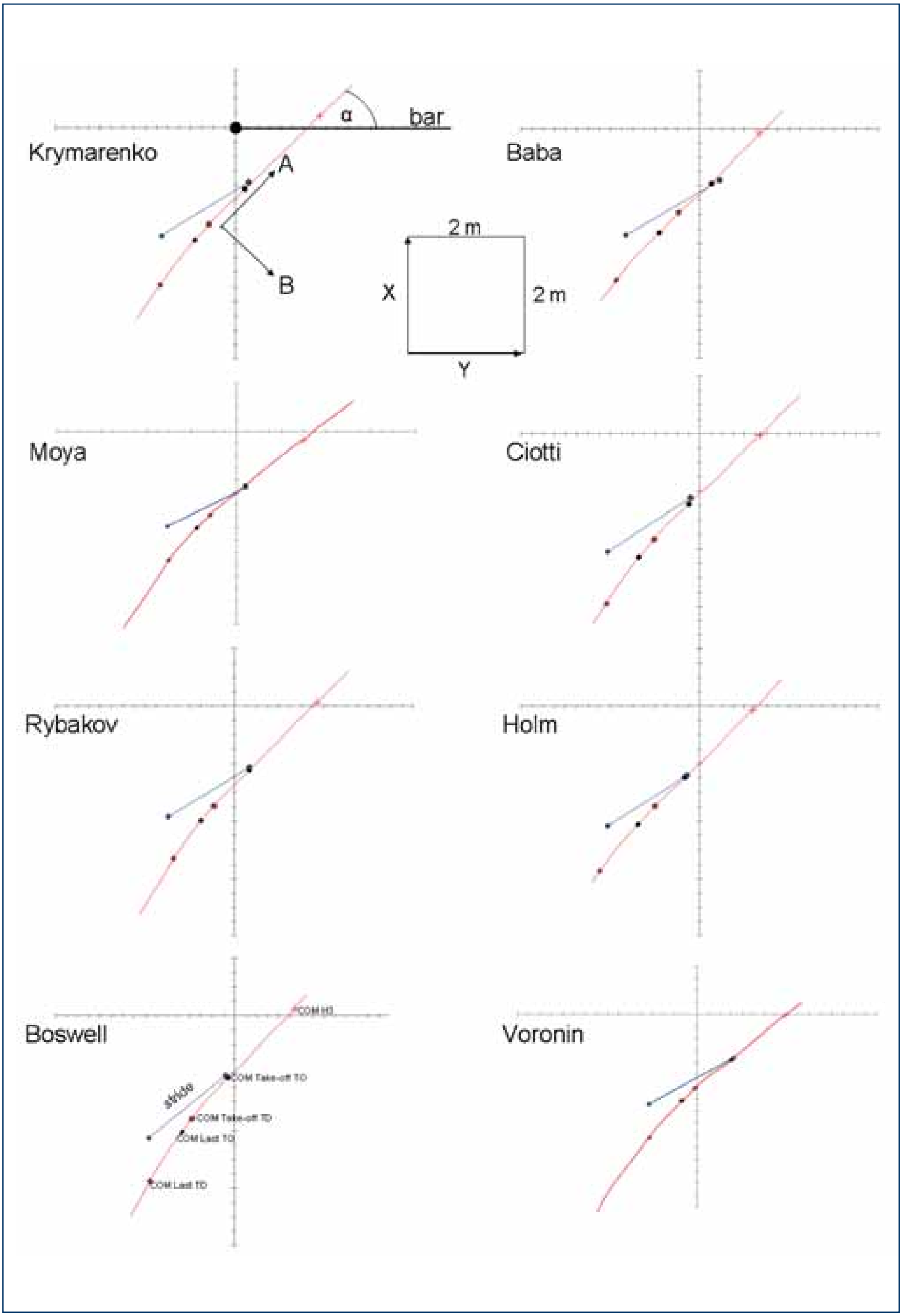

Figure 2: The overhead views of the paths of the centre of mass (CM) curves, XY – co-ordinates of the two last contacts and CM locations during the touchdown and toe-off phases of the eight best finalists in the high jump at the 2005 IAAF World Championships in Athletics.

were taken from the adjustment of Zatsiorsky-Seluyanov's segment inertia parameters made by DE LEVA (1996). The kinematic data was smoothed using a Butterworth fourth-order-zero-lag filter and a cut-off frequency of 14Hz based on residual analysis and qualitative evaluation of the data. Interpolating quintic splines were fitted to the digitised co-ordinate data to allow the estimation of data values at 0.005 second intervals (200Hz).

Co-ordinate system

Two different orthogonal co-ordinate systems were used: XYZ and ABZ (Figure 2). After the transformation, the XYZ co-ordinate system was related to the location of the uprights. The origin was the lowest point of the upright near the take-off point. The X- and Y-axes were in the horizontal plane, Y being parallel to the bar and X perpendicular to it. The Z-axis was vertical. The ABZ co-ordinate system was related to the horizontal direction of the CM during the take-off phase. The A- and B-axes were in the horizontal plane, A being parallel to the final path and B perpendicular to it. The Z-axis was vertical.

In the analysis, the partial heights (H1, H2 and H3) of the CM during the take-off phase refer to the height of the jumpers' CM at touchdown (TD), toe-off (TO) and peak height, respectively.

Results

Partial heights

The mean values of the partial heights during the TD and TO phases of the take-off were 0.93 ± 0.05m and 1.37 ± 0.05m, respectively. The height of the CM at the

Table 2: The height of the centre of the mass at the instant of touchdown (H1), toe-off (H2) and highest point of the flight path (H3) of the finalists in the high jump at the 2005 IAAF World Championships in Athletics (The values are also presented as a percentage of the standing height).

Name	H1 (m)	H2 (m)	H3 (m)	Result (m)	H1 %	H2 %	H3 %
Krymarenko	0.88	1.32	2.40	2.32	47.51	71.08	2.40
Moya	0.85	1.40	2.38	2.29	43.52	71.22	2.38
Rybakov	0.99	1.43	2.32	2.29	50.56	72.96	2.32
Boswell	0.88	1.36	2.31	2.29	46.46	72.06	2.31
Baba	0.93	1.41	2.33	2.29	47.40	71.79	2.33
Ciotti	0.86	1.34	2.33	2.29	45.83	71.76	2.33
Holm	0.87	1.28	2.32	2.29	48.07	70.72	2.32
Voronin	0.89	1.39	2.30	2.29	46.95	72.89	2.30
Topic	0.99	1.34	2.31	2.25	50.30	67.92	2.31
Iannou	0.98	1.36	2.29	2.25	50.67	70.47	2.29
Frösen	0.97	1.42	2.29	2.20	50.05	73.40	2.29
Hemingway	0.97	1.43	2.32	2.20	49.19	72.37	2.32
Sokolovskyy	0.97	1.40	2.24	2.20	49.44	71.33	2.24
average	0.93	1.37	2.32	2.27	48.15	71.54	2.32
standard deviation	0.05	0.05	0.04	0.04	2.15	1.41	0.04

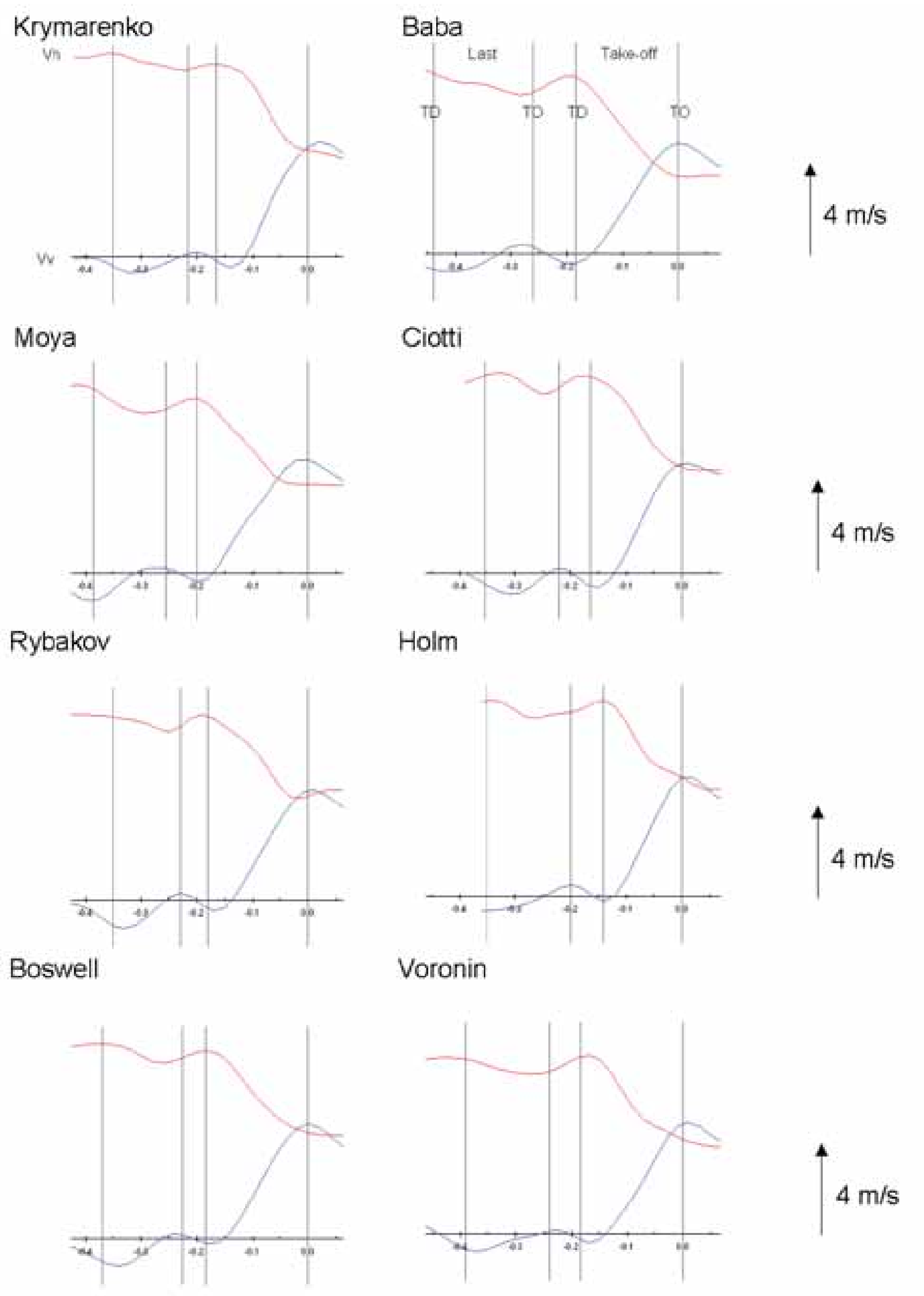

Figure 3: The horizontal (Vh) and the vertical (Vv) velocity curves of the eight best finalists in the high jump at the 2005 IAAF World Championships in Athletics.

Table 3: The vertical (Vv) and the horizontal (Vh) velocity values at the instants of touchdown (TD) and the toe-off (TO) during the take-off, the projection angle of the CM and the change of the horizontal velocity during the contact (ΔVh) of the finalists in the high jump at the 2005 IAAF World Championships in Athletics.

Name	Vh TD (m/s)	Vh TO (m/s)	Vh (?)	Vv TD (m/s)	Vv TO (m/s)	Angle (%)
Krymarenko	7.99	4.35	3.64	-0.45	4.61	51.68
Moya	7.36	3.75	3.61	-0.34	4.39	50.55
Rybakov	7.59	4.31	3.28	-0.45	4.18	51.87
Boswell	7.87	4.42	3.45	-0.20	4.32	51.37
Baba	7.28	3.27	4.01	-0.36	4.25	46.67
Ciotti	8.03	4.35	3.68	-0.48	4.40	50.07
Holm	8.11	4.73	3.38	-0.07	4.51	53.18
Voronin	7.31	3.75	3.56	-0.20	4.23	49.92
Topic	8.29	4.83	3.46	-0.64	4.36	51.54
Iannou	7.67	4.83	2.84	-0.17	4.26	56.34
Frösen	7.55	3.96	3.59	-0.24	4.12	48.91
Hemingway	8.10	4.62	3.48	-0.40	4.18	50.23
Sokolovskyy	7.99	4.83	3.16	-0.32	4.06	52.10
average	7.78	4.31	3.47	-0.33	4.30	51.11
standard deviation	0.34	0.49	0.28	0.16	0.15	2.27

highest point of the flight was 2.32 ± 0.04m (5.1 ± 0.33cm higher than the official bar height). These partial height values are often presented as a percentage value of the athlete's standing height. Table 2 summarises the results of commonly used partial heights.

Path of CM prior to and during the take-off and flight

The curves of the eight best jumpers' CM paths during the last two strides of the approach and the bar clearance are presented in Figure 2, which also shows the different phases separately. The vertical displacement of the acceleration path during the take-off phase was 0.45 ± 0.05m. The direction of the CM's motion during the take-off phase is first downwards, but after 22 ± 1ms it changes to upwards.

The mean take-off angle was 45.1 ± 3.5°. The angle between the path of the CM during the take-off phase (for the direction vector, see Figure 2) and the bar-line in the horizontal plane was 31.7 ± 0.2°. The highest point of the flight was 6.34 ± 0.03cm behind the bar-line and the bar clearance point was located 1.78 ± 0.08m from the upright. The vertical displacement of the CM during flight was 0.94 ± 0.07m.

Horizontal and vertical velocity components

Figure 3 shows the typical curves of the velocity components during the last two strides, take-off and flight phases of the eight best jumpers. At the TD instant of the take-off, the mean horizontal and vertical velocity values were 7.78 ± 0.34m/s and -0.33 ± 0.15m/s, respectively. At TO, the

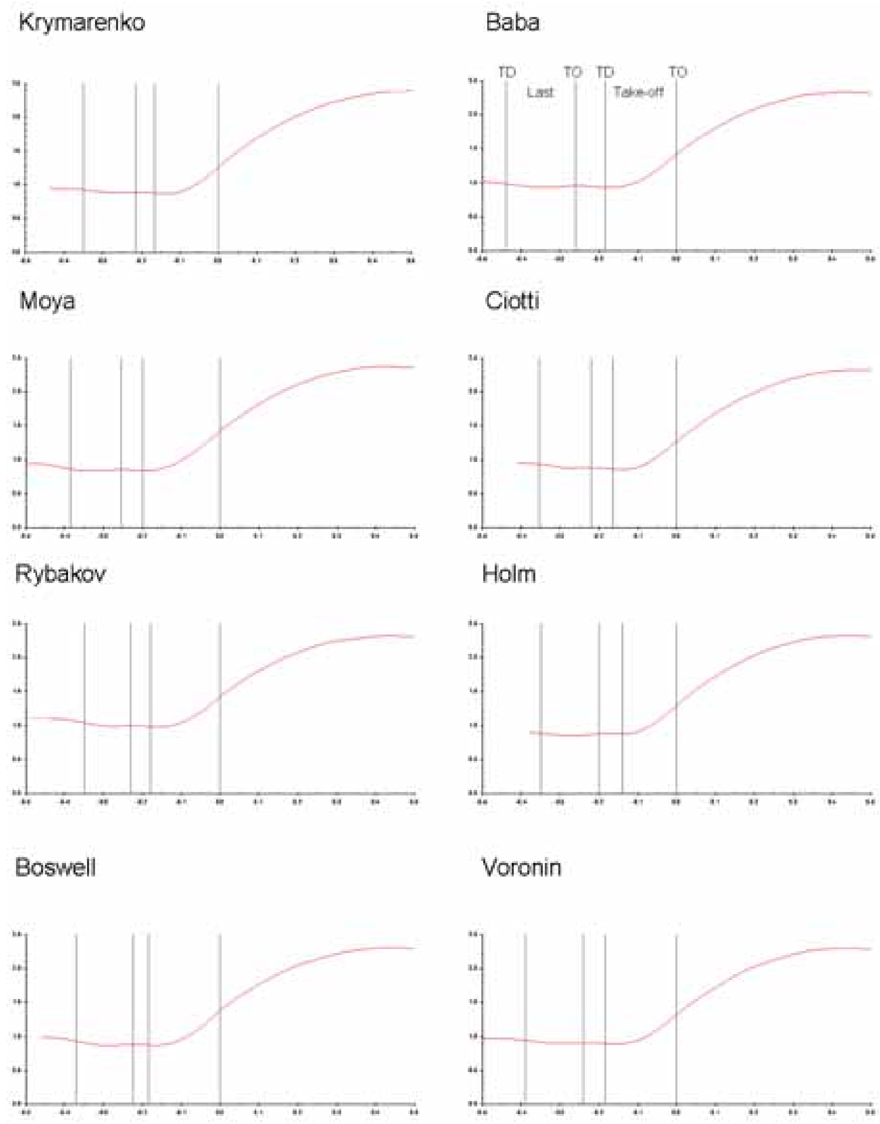

Figure 3: The height of the centre of mass (CM) during the last two contacts and the flight phase of the eight best finalists in the high jump at the 2005 IAAF World Championships in Athletics

horizontal velocity decreased to 4.31 ± 0.49m/s and the vertical velocity increased up to 4.30 ± 0.16m/s. Table 3 summarises the values of the velocity components during this critical phase of the jump.

Stride parameters

The mean contact times were 147 ± 16ms and 175 ± 20ms during the penultimate and take-off contacts, respectively. The flight time between the last contacts was 58 ± 14ms. The last stride angle was 28.5 ± 4.3°

Table 4: The support times during the last two contacts, flight time of the last stride, length of the last stride and it's projection angle to the y-axis (parallel with bar-line) of the finalists in the high jump at the 2005 IAAF World Championships in Athletics

Name	Stride Length (m)	Stride Angle (°)	Last (ms)	Flight Time (ms)	Take-Off (ms)
Krymarenko	2.01	32.11	0.135	0.060	0.170
Moya	1.92	24.78	0.150	0.050	0.200
Rybakov	2.16	31.82	0.140	0.040	0.190
Boswell	2.29	24.27	0.140	0.050	0.185
Baba	2.03	37.30	0.160	0.080	0.200
Ciotti	2.06	27.15	0.130	0.060	0.175
Holm	1.99	25.60	0.145	0.055	0.150
Voronin	2.11	26.94	0.155	0.050	0.190
Topic	2.25	28.37	0.115	0.085	0.135
Iannou	1.97	26.36	0.175	0.060	0.155
Frösen	2.12	25.42	0.165	0.055	0.180
Hemingway	1.99	25.66	0.160	0.070	0.180
Sokolovskyy	2.30	35.70	0.140	0.040	0.170
average	2.09	28.58	0.147	0.058	0.175
standard deviation	0.13	4.28	0.016	0.014	0.019

and the length of the last stride was 2.09 ± 0.13m. The mean perpendicular distance of the take-off contact from the closest upright was 1.02 ± 0.3m and 8.6 ± 0.4cm in the Y direction (see Figure 2). Figure 2 shows an overhead view of the footprints and the CM path during the last two contacts of the approach and in the airborne phase. The exact locations during the different stride phases for each jumper are also presented. Table 4 summarises the stride parameters.

During the TD instant of the take-off, the mean knee angle was 168 ± 14°, and it decreased (100 ± 15ms) to 143 ± 8.2°. At the end of the take-off phase, the knee angle was 174 ± 3.4°. Table 5 summarises how the knee angles change during the take-off phase.

The jumpers' inward and backward inclination values were calculated on the horizontal plane during the take-off contact. This method shows that during the TD phase of the take-off the body has a backward lean of 36.8 ± 2.1° but no inward lean at all. Both values are almost zero at the TO instant.

Discussion and Summary

The mean of the official results (2.27 ± 0.04m) in this competition is one of the poorest in the high jump at the IAAF World Championships in Athletics since the championships began in 1983. On the other hand, the mean height of the CM at the highest point of the flight was 2.32 ± 0.04m, which corresponds well to the earlier studies in which the jumps of only the best six to eight best jumpers were analysed.

From the technical point of view, the competition was interesting, because a number of variations of the Fosbury Flop technique were used. Chief among these were the "Power-Flop" and "Speed-Flop" but there were also different arm techniques, which include

Table 5: The knee angles at the instant of touchdown (TD) and the toe-off (TO) phases during the take-off and the lowest knee angle during the contact of the finalists in the high jump at the 2005 IAAF World Championships in Athletics

Name	Knee TD	Knee lowest	Knee TO
Krymarenko	171.94	146.23	177.97
Moya	163.83	135.41	169.16
Rybakov	168.49	141.80	173.51
Boswell	164.40	127.90	168.68
Baba	171.95	142.18	171.40
Ciotti	170.38	143.95	178.02
Holm	161.86	143.36	175.23
Voronin	166.81	142.79	168.92
Topic	173.90	163.50	177.96
Iannou	166.01	148.44	175.14
Frösen	172.41	144.70	175.27
Hemingway	166.51	138.07	175.45
Sokolovskyy	167.38	150.07	174.36
average	168.14	143.72	173.93
standard deviation	3.73	8.26	3.40

"normal running" arm action (Topic), "leading running" arm action (Holm), "fast double" arm action (Krymarenko) and "wide double" arm action (Baba).

The measurements of the parameters related to the approach show the fastest run-ups ever recorded. When comparing the values obtained to earlier studies (IIBOSHI et al., 1991; BRÜGGEMANN and ARAMPATZIS, 1997; DAPENA, 2000), it seems clear that nowadays, jumpers are increasing their horizontal approach velocity.

The present results show clearly that the vertical velocity and height of the CM at the end of the take-off phase together determine the height of the flight ($r=0.75$, $p<0.01$; $r=0.1.$, n.s, respectively). Thus, the vertical velocity of the jumper at the end of the take-off phase determines how high the CM will rise after TO. The most important factor related to the vertical velocity of TO is the low CM position at TD ($r=-0.70$, $p<0.01$). These findings are well in agreement with the theoretical findings of ALEXANDER (1990) and earlier experimental results (DAPENA, 1980; GREIG and YEADON, 2000).

The partial heights recorded in the present study are very close to the data reported by IIBOSHI et. al. (1991) as well as by BRÜGGEMANN and ARAMPATZIS (1997). These showed that CM height during the TD is related to arm technique more than physique. Topic, who used the [normal] running arm action, had the lowest value, 68% of body height, compared to the highest values (73%) for the jumpers who used a wide double arm action. The difference due to arm action can be 8cm, if the jumper is 2m tall. On the other hand, speed floppers like Topic have a shorter take-off time, greater knee angle and a higher horizontal velocity during the take-off phase than power floppers. Thus, high knee joint stiffness is crucial for the speed floppers who probably store more elastic energy to the muscle-tendon complex than the power floppers, whose take-off is based more on the concentric muscle action. The increased muscle activity of the leg extensors in the braking phase of the contact is also a prerequisite for efficient storage of elastic energy (KOMI and GOLLHOFER, 1997).

It can be concluded that different variations of the flop techniques enable the utilisation of the best physical capacity of the each individual jumper. Therefore, it seems that there is not a single, ideal technique for achieving good results and jumpers with different body types, physical characteristics and performance techniques have good possibilities to compete successfully in the highest level.

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