Three Dimensional Kinematic Analysis of the Long Jump at the 2008 IAAF World Indoor Championships in Athletics

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ABSTRACT

A description of the technique used by elite jumpers gives insight into individual forms of organisation used to obtain high performance. These models eventually become references that help coaches and athletes to design their own strategies to achieve maximum mechanical efficiency. This paper presents the results of a biomechanical analysis of the men's and women's long jump finals the 2008 IAAF World Indoor Championships in Valencia by researchers from the University of Valencia (Department of Physical Education and Sports), the Institute of Biomechanics at the Polytechnic University of Valencia, and the University of Granada (Department of Physical Education and Sports). The methodology used is based on 3D video photogrammetry. The results show the characteristics of the jumper's individual models in the event. It has been observed that each jumper maintains an individual jumping pattern in relation to timing and in the values obtained in the different kinematic parameters under study. Detailed information on the kinematic parameters is provided.

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Introduction

Several studies have shown that performance in the long jump is directly related to different mechanical and muscular mechanisms that occur from the touchdown of the take-off foot through the take-off itself. Basically, the jumper's goal is to generate vertical velocity of his/her centre of mass (CM) at take-off without losing too much horizontal velocity of the CM. It is well known that the greatest gain in vertical velocity takes place during the compression phase, which is associated with a loss in horizontal velocity[1].

Different models have described the mechanical and technical features of the long jump. The deterministic model by Hay, Miller & Canterna[2] lays down a hierarchical structure with the factors that determine the jump distance, stressing the participation of the changes in the horizontal and vertical velocities of the jumper's CM during the take-off. An alternative approach is used by Alexander[3], whose model shows that the jump distance is a function of: a) the approach velocity; b) the angle of the take-off leg with respect to the ground at touchdown; c) the knee angle and, d) the muscular torque acting about the knee.

A description of the technique used by elite jumpers gives insight into individual forms of organisation used to obtain high performance. These models eventually become references that help coaches and athletes to design their own strategies to achieve maximum mechanical efficiency.

This paper describes the technical models used by a group of athletes who were finalists in the 2008 IAAF World Indoor Championships in Valencia. The aim of the study is to compare the jumpers' individual models in the light of the available documented biomechanical data on the long jump.

Method

Participants in the men's and women's long jump finals of the 2008 IAAF World Indoor Championships in Valencia, were assessed using 3D photogrammetric techniques with two synchronized high-speed video cameras at 125 Hz. For the calculation of the CM position, inertial parameters proposed by Zatsiorsky & Seluyanov[4] and adapted by Leva [5] were used.

During the final, all jumps were filmed and the best attempts by each athlete were subsequently analysed. The cameras were phase-locked and aligned with their optical axis at approximately 90° (side and front views). For spatial calibration, a modulated reference system (2.60m x 1.26m x 2.40m) was applied, and for the digitising process the software Kinescan digital 1.1, from the Institute of Biomechanics of Valencia, was used.

The DLT (Direct Linear Transformation) algorithm was used to calculate the 3D marker coordinates[6]. The kinematic parameters obtained on the marker coordinates (x,y,z) were transformed as variables of the study.

The biomechanical analysis for each athlete focused on the period of the last stride and the take-off phase. The most important factors for long jump performance occur during these decisive periods, which offer the best conditions for comparing athletes' techniques.

The main time periods were:

T1: Instant of the take-off of the last stride.

T2: Instant of touchdown (TD). Take-off foot lands on the ground.

T3: Instant of maximum knee flexion of the take-off leg (MKF).

T4: Instant of the take-off (TO). The foot leaves the ground (Instant of projection).

Three sub-phases in the reference instants mentioned above (T1, T2, T3 and T4) were considered.

Last stride (Ls): period between instants T1 and T2.

Compression phase (td-mkf): period between instants T2 and T3.

Extension phase (mkf-to): period between instants T3 and T4.

T1 T2 T3 T4

Figure 1: Representative instants of T1, T2, T3 and T4.

Table 1 shows the results of the male finalists, including both the official and effective distances. The best jump by every athlete was analysed, except those by Jeofry Mokoena and Mohamed Al Khuwalidi, in which case their second best jump was studied due to recording problems.

As can be seen, the effective distance (7.98±0.13m) is longer than the official result (7.90±0.13m) by 8cm, which means that the real values would have changed the competition's rresult. The jump analysed for the silver medallist, Jeofry Mokoena, (8.18m) would have earned him the gold medal. The rank would have stayed the same for the remaining athletes, save for Atanasov, who would have gone down one position in favour of the Jamaican jumper, Beckford.

Table 1: Basic data of sample for official and effective distance, men's final

Jumper	Official distance (m)	Effective distance (m)	Jump analysed
Tomlinson, Christopher (GBR)	8.06	8.11	Best
Mokoena, Jeofry (RSA)	8.05	8.18	2º Best
Al Khuwalidi, Mohamed (KSA)	8.01	8.05	Best
Garenamotse, Gable (BOT)	7.93	7.98	Best
Atanasov, Nikolay (BUL)	7.85	7.88	2º Best
Beckford, James (JAM)	7.85	7.93	Best
Starzak, Marzin (POL)	7.74	7.85	Best
Martinez, Wilfredo (CUB)	7.72	7.83	Best
Mean	**7.90**	**7.98**	
SD	**0.13**	**0.13**	

All jumpers performed the take-off on the board, though at different distances from the statutory foul line. The jumpers with the greatest gaps between official and effective distances were Mokoena, Starzak and Martinez, with 13, 11 and 11cm differences respectively, while the athletes who best adjusted their take-off to the foul line were Atanasov, Al Khuwalidi and Tomlinson, with 3, 4 and 5cm, respectively.

Table 2 shows the results of the women's final. In this case, all the leaps analysed were the athlete's best jumps.

The difference between official and effective distances in the women's final was 10cm (6.67±0.22m and 6.77±0.24m, respectively). This difference is slightly greater than that of the men's group, and the same applies to the standard deviation, which is almost double. This implies greater variability in comparison with the men.

Results

Phase timing

In the men's final, the results show that the compression phase (T2-T3) lasts between 40 and 56 milliseconds, while the duration of the extension phase (T3-T4) goes from 72 to 80 ms, the phase timing model used by all jumpers being fairly similar (Table 3).

On average, total take-off time for all of jumpers is 122 ms, the time used in the compression phase being shorter than that of the extension (45±6 ms and 77±4.1 ms, respectively). This means that jumpers use 37% of the total take-off time in the phase in which the knee extensor muscles work eccentrically, and 63% in the phase in which they work concentrically. Note that the winner's phase timing has the smallest inter-phase difference. In other words, he used 56 and 72 ms for compression

Table 2: Basic data of sample for official and effective distance women's final

Jumper	Official distance (m)	Effective distance (m)	Jump analysed
Gomes, Naide (POR)	7.00	7.10	Best
Maggi, Maureen (BRA)	6.89	7.07	Best
Simagina, Irina (RUS)	6.88	6.93	Best
Lesueur, Eloise (FRA)	6.60	6.70	Best
Montaner, Concepción (ESP)	6.57	6.70	Best
Radevica, Ineta (LAT)	6.54	6.63	Best
Costa, Keita (BRA)	6.48	6.55	Best
Josephs, Janice (RSA)	6.39	6.45	Best
Mean	**6.67**	**6.77**	
SD	**0.22**	**0.24**	

Table 3: Effective distance and phase timing during compression phase (T2-T3) and extension phase (T3-T4), men's final

Jumper	Effective distance (m)	t_(T2-T3) (ms)	t_(T3-T4) (ms)
Tomlinson, Christopher	8.11	56	72
Mokoena, Jeofry	8.18	48	80
Al Khuwalidi, Mohamed	8.05	40	80
Garenamotse, Gable	7.98	48	80
Atanasov, Nikolay	7.88	40	80
Beckford, James	7.93	40	72
Starzak, Marzin	7.84	40	80
Martínez, Wilfredo	7.83	48	72
Mean	**7.98**	**45.0**	**77.0**
SD	**0.13**	**6.0**	**4.1**
CV (%)	**1.6**	**13.3**	**5.3**

and extension, which accounts for 44% and 56% of the total time, respectively.

The compression phase is decisive for achieving the required braking so that the horizontal velocity built up in the approach run can be transformed into vertical impulse. In this phase the jumper accumulates elastic energy; the fact that it is so short proves the jumpers' extraordinary ability to complete such transformation.

Table 4 shows the results of the women's final. In this case, the total take-off time is 117 ms, which is slightly lower than that of men's. Their compression and extension times are also lower. As happens with men, compression time is shorter than extension time (52±6.05 ms and 65±6.68 ms, respectively), which indicates a phase timing model based on the use of 44.5% of the total take-off time in the compression phase (T2-T3), and 55.5% in the extension phase (T3-T4). As to the variability of results, it is higher in the compression than in the extension, variation coefficients being 13.3% and 5.3%, respectively.

Variability in results is higher in the values of the compression phase than in the extension, though inter-phase differences for women are lower than for men, the variation coefficient being 11.6% and 10.3%, respectively.

In comparative terms, the women's phase timing is different from that of the men. The women used a higher percentage of the total time in the phase in which the horizontal velocity of the approach was reduced, i.e. the compression phase. Even so, in the dynamic structure of the jump, men seem to use more

Table 4: Effective distance and phase timing during compression phase (T2-T3) and extension phase (T3-T4), women's final

Jumper	Effective distance (m)	t_(T2-T3) (ms)	t_(T3-T4) (ms)
Gomes, Naide (POR)	7.10	56	56
Maggi, Maureen (BRA)	7.07	56	72
Simagina, Irina (RUS)	6.93	56	64
Lesueur, Eloise (FRA)	6.70	56	64
Montaner, Concepción (ESP)	6.70	40	72
Radevica, Ineta (LAT)	6.63	56	56
Costa, Keita (BRA)	6.55	48	72
Josephs, Janice (RSA)	6.45	48	64
Mean	**6.77**	**52**	**65**
SD	**0.24**	**6.05**	**6.68**
CV (%)	**3.5**	**11.6**	**10.3**

appropriate models, as they manage to reduce their horizontal velocity more quickly.

Velocity variables

During the take-off, the horizontal velocity of the CM built up in the approach run is transformed into a vertical component thanks to the forces generated while the take-off foot is in contact with the ground. Many papers have proved that the jumper's increase in CM vertical velocity at take off has a decisive effect for jump distance[1, 7, 8, 9]. Figure 2 shows the trajectories of the CM's vertical and horizontal velocities at take-off, for the world champion, Tomlinson, in his best jump. As can be seen, these trajectories are in line with long jump theoretical postulates [1, 7] in such a way that the greatest increase in CM vertical velocity occurs in the compression period of the take-off (T2-T3). Complementarily, this increase is paralleled by a loss in CM horizontal velocity as a consequence of the breaking impulse exerted by the muscles when contracting eccentrically.

A) Velocity of the CM at take-off

Table 5 shows the velocity of the athlete's CM in the last stride of the appraoch (Vcg LS) and at take-off (Vcg T4). The velocity of the CM in the approach was measured during the last stride because this value is understood to better represent velocity when the athlete reaches the take-off point.

As shown, jumpers develop an approach velocity in the last stride ranging between 10.23 and 11.11 m/s, and the velocity of the CM at the instant of take-off ranges from 9.01 to 10.24 m/s. Overall, the jumpers' mean velocity in the take-off phase is reduced by 0.91 m/s, which implies an 8.7% loss. Variability levels are low in both cases, with a 4% variation coefficient.

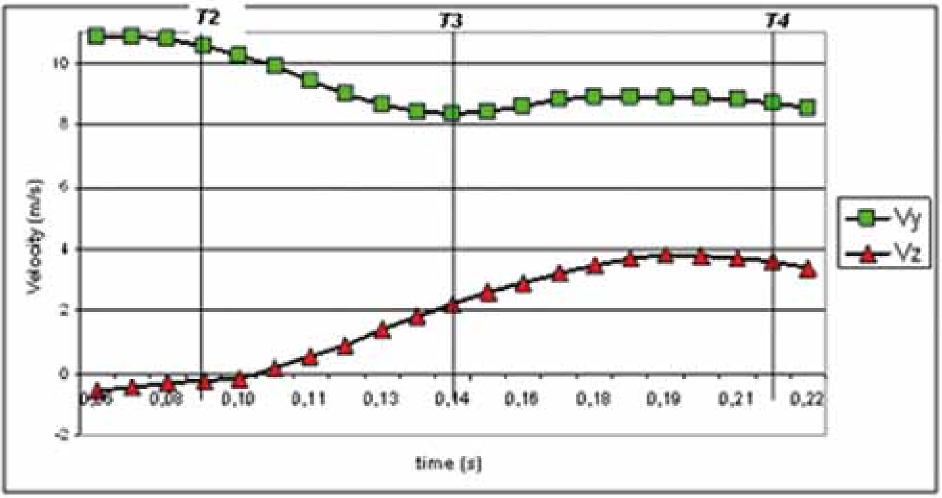

Figure 2: Trajectories of the horizontal (Vy) and vertical (Vz) components of the CM during the take-off phase (Tomlinson, 8.11 m)

Table 5: Effective distance and velocity of the CM during last stride (Vcg LS) and at the instant of take-off (Vcg T4), men's final

Jumper	Effective distance (m)	Vcg_ LS (m/s)	Vcg_T4 (m/s)
Tomlinson, Christopher	8.11	10.29	9.55
Mokoena, Jeofry	8.18	10.41	9.46
Al Khuwalidi, Mohamed	8.05	10.54	9.36
Garenamotse, Gable	7.98	10.46	10.24
Atanasov, Nikolay	7.88	10.44	9.43
Beckford, James	7.93	11.11	9.72
Starzak, Marzin	7.84	10.23	9.01
Martínez, Wilfredo	7.83	10.41	9.88
Mean	**7.98**	**10.49**	**9.58**
SD	**0.13**	**0.27**	**0.37**
CV (%)	**1.6**	**2.6**	**3.9**

Table 6 shows the results of the women's final. Women's average approach velocity comes to 9.48 m/s. The velocity of the CM at take off is 8.50 m/s on average. Therefore, overall, women's run-up velocity is reduced by 0.98 m/s in the take-off phase, a 10.3% reduction, which is larger than that of men.

The ratio between approach velocity and jump distance was significant and positive, i.e. the faster the approach velocity, the longer the jump distance, as also noted in the literature on this event (r: .739 $p < .05$). As is the case with men, variability remains low, the variation coefficient not exceeding 3%.

B) Horizontal velocity (Vy) during the take-off phase

The jumper's CM horizontal velocity during the take-off is reduced in the compression phase (T2-T3) and then increased again in the impulsion phase (T3-T4). Table 7 shows the values recorded in the men's final. Muscular activity during compression is one of the main causes of the braking of horizontal velocity, building up the elastic component in the eccentric contraction phase during the stretch-shorten cycle[10].

Mean values for horizontal velocity of the CM at instants T2, T3 and T4 are 10.24 m/s, 8.67 m/s, and 9.00 m/s, respectively, this confirming the previously described pattern.

Table 6: Effective distance and velocity of the CM during the last stride (Vcg LS) and at the instant of take-off (Vcg T4), women's final

Jumper	**Effective distance (m)**	**Vcg LS (ms)**	**Vcg_T4 (ms)**
Gomes, Naide	7.10	9.77	8.20
Maggi, Maureen	7.07	9.80	8.64
Simagina, Irina	6.93	9.29	8.48
Lesueur, Eloise	6.70	9.64	8.96
Montaner, Concepción	6.70	9.42	8.55
Radevica, Ineta	6.63	9.34	8.64
Costa, Keita	6.55	9.28	8.24
Josephs, Janice	6.45	9.30	8.27
Mean	**6.77**	**9.48**	**8.50**
SD	**0.24**	**0.22**	**0.26**
CV (%)	**3.5**	**2.3**	**3.0**

The loss in CM horizontal velocity during the take off is 1.24 m/s, a 12.1% reduction. Please note that the horizontal velocity loss in the take-off behaves like a relatively variable parameter (sd= 0.33 m/s - 27% in the calculated variation coefficient), which shows that each individual jumper has a differentiated pattern.

On the one hand, this velocity loss is due to the reduction in the compression phase, 1.57 m/s, which means a 15.4% reduction in horizontal velocity at instant T2 and; on the other, it is due to the upturn in horizontal velocity of the impulse phase, namely 0.33 m/s.

However, not all jumpers display this behaviour pattern in the compression and impulsion phases. Al Khuwalidi and Starzak do not show a velocity recovery in the impulsion. Conversely, though with a very low percentage, horizontal velocity keeps on decreasing, by 0.07 m/s in Al Khuwalidi's jump and by 0.24 m/s in Starzak's.

The male athlete with the greatest braking of horizontal velocity was the winner. Tomlinson reduced horizontal velocity by 2.17 m/s in the compression phase (T2-T3), a 20.2% reduction versus that at the start of the take-off (TD). As to variability, the loss in horizontal velocity at take-off stays within a relatively high range, as shown by the 26.7% variation coefficient (VC), this corroborating the idea that each jumper has a differentiated pattern when they brake to stop horizontal velocity at take-off.

Table 7: Effective distance and horizontal velocity of CM (Vy) at T2, T3, T4, and loss in horizontal velocity of CM during the take-off phase (Vz T2-T4), men's final

Jumper	**Effective distance (m)**	**Vy_T2 (ms)**	**Vy_T3 (ms)**	**Vy_T4 (ms)**	**Lost Vy T2-T4 (ms)**
Tomlinson, Christopher	8.11	10.75	8.58	8.90	1.85
Mokoena, Jeofry	8.18	9.94	8.63	8.76	1.18
Al Khuwalidi, Mohamed	8.05	10.05	8.96	8.89	1.16
Garenamotse, Gable	7.98	10.41	8.54	9.65	0.76
Atanasov, Nikolay	7.88	10.03	8.40	8.85	1.18
Beckford, James	7.93	10.53	8.91	9.17	1.36
Starzak, Marzin	7.84	9.89	8.64	8.40	1.49
Martínez, Wilfredo	7.83	10.35	8.68	9.38	0.97
Mean	**7.98**	**10.24**	**8.67**	**9.00**	**1.24**
SD	**0.13**	**0.31**	**0.19**	**0.39**	**0.33**
CV (%)	**1.6**	**3.0**	**2.2**	**4.3**	**26.7**

Table 8 presents the results of the women's final, also confirming a general reference pattern with mean horizontal velocity values of 9.07 m/s, 7.79 m/s, and 7.91 m/s for instants T2, T3 and T4, respectively. Thus, for women, we find a 1.17 m/s reduction in the horizontal velocity of the CM at take-off, i.e. a reduction of 12.8%, which is a slightly higher value that that reached by men, in percent terms. Also in this case, and as happens with men, the reduction in horizontal velocity behaves as a rather variable parameter (CV= 27%).

On the one hand, the horizontal velocity loss is due to the reduction in the compression phase, 1.28 m/s, a 14.1% reduction in horizontal velocity at instant T2 and, on the other, it is due to the upturn in horizontal velocity during the impulse, namely 0.13 m/s.

Three female jumpers do not follow the general pattern concerning the horizontal velocity trajectory during the take-off phase. Gomes, Montaner and Josephs continued to reduce their horizontal velocity during the impulsion 0.20 m/s, 0.09 m/s and 0.16 m/s, respectively.

The jumpers who managed to reduce their horizontal velocity to the greatest extent were Costa and Gomes. More particularly, during the compression they reduced horizontal velocity by 1.67 m/s and 1.55 m/s, respectively, which means 18.7% and 16.7% in relation to the values obtained at instant T2.

Table 8: Effective distance and horizontal velocity (Vy) of CM at T2, T3,T4, and loss in horizontal velocity of CG during the take-off phase (Vz T2-T4), women's final

Jumper	**Effective distance (m)**	**Vy_T2 (ms)**	**Vy_T3 (ms)**	**Vy_T4 (ms)**	**Lost Vy T2-T4 (ms)**
Gomes, Naide	7.10	9.31	7.76	7.57	1.74
Maggi, Maureen	7.07	9.40	7.90	8.05	1.35
Simagina, Irina	6.93	8.78	7.41	7.74	1.04
Lesueur, Eloise	6.70	9.48	8.40	8.45	1.03
Montaner, Concepción	6.70	9.08	8.05	7.96	1.12
Radevica, Ineta	6.63	8.78	7.74	8.13	0.65
Costa, Keita	6.55	8.92	7.25	7.70	1.22
Josephs, Janice	6.45	8.83	7.81	7.65	1.18
Mean	**6.77**	**9.07**	**7.79**	**7.91**	**1.17**
SD	**0.24**	**0.29**	**0.36**	**0.30**	**0.31**
CV (%)	**3.5**	**3.2**	**4.6**	**3.8**	**26.5**

C) Vertical velocity (Vz) during the take-off phase

The jumpers' CM vertical velocity during the take-off behaves in the opposite way of horizontal velocity. It increases considerably during compression (T2-T3), then continues rising during impulsion (T3-T4).

Table 9 shows the values from the men's final. Mean values for CM vertical velocity at instants T2, T3 and T4 are 0.24 m/s, 2.10 m/s, and 3.3 m/s, respectively, with a total gain in the vertical velocity of the CM at take-off of 3.4 m/s.

The highest gain in the vertical component is reached during the compression phase. The results show that the gain in vertical velocity during the compression is 2.2 m/s, i.e. 61.8% of the total obtained in the take-off.

In this case, and unlike what happens with the horizontal velocity loss, the increase in vertical velocity at take-off behaves with less variability, as understood from the 8.8% variation coefficient. This low degree of variability points to greater uniformity in the pattern used by jumpers to increase the vertical component of the take-off. This uniformity is reinforced by the high ratio between jump distance and vertical velocity gain, though it is not statistically significant (r: .63; p: .095). The jumpers with the highest vertical component are Mokoena and Tomlinson, with vertical velocity gains at take off of 4.04 and 3.67 m/s, respectively.

Table 9: Effective distance and vertical velocity (Vz) of CM at T2, T3,T4, and gain in vertical velocity of CM during the take-off phase (Vz T2-T4), men's final

Jumper	**Effective distance (m)**	**Vz_T2 (ms)**	**Vz_T3 (ms)**	**Vz_T4 (ms)**	**Gain Vz T2-T4 (ms)**
Tomlinson, Christopher	8.11	-0.19	2.84	3.48	3.67
Mokoena, Jeofry	8.18	-0.47	2.42	3.57	4.04
Al Khuwalidi, Mohamed	8.05	-0.09	2.14	2.92	3.01
Garenamotse, Gable	7.98	-0.10	1.79	3.42	3.52
Atanasov, Nikolay	7.88	0.04	2.08	3.23	3.19
Beckford, James	7.93	0.05	1.92	3.20	3.15
Starzak, Marzin	7.84	-0.19	1.83	3.24	3.43
Martínez, Wilfredo	7.83	-0.12	2.16	3.12	3.24
Mean	**7.98**	**-0.1**	**2.1**	**3.3**	**3.4**
SD	**0.13**	**0.2**	**0.3**	**0.2**	**0.3**
CV (%)	**1.6**	**200**	**14.3**	**6.0**	**8.8**

Table 10 shows the values of the women's final. Mean values for CM vertical velocity at instants T2, T3 and T4 are 0.23 m/s, 2.26 m/s, and 3.09 m/s, respectively, with a total gain in CM vertical velocity at take-off of 3.32 m/s, a value slightly lower than that of men.

The gain in the vertical component is also achieved in the compression phase, in line with the general pattern. In this case, jumpers had a vertical velocity gain in the take-off of 2.49 m/s, which is 68% of the total take off and a higher percentage than that reached by men.

If compared to men, the vertical velocity increase during the take-off behaves like a more variable parameter, as proved by the 21% variation coefficient. In the case of women, the existence of a high and significant relationship between jump distance and vertical velocity increase is confirmed (r: .77; p< .05). The jumper generating a greater vertical component during the take-off was Maggi, with a total gain of 3.63 m/s.

As far as variability levels are concerned, the women's parameters show more uniformity, especially in the vertical velocity gain during the take-off, with a 6.3% variation coefficient, two points less than the men's value.

Table 10: Effective distance and vertical velocity (Vz) of CM at T2, T3,T4 and gain in vertical velocity of CM during the take-off phase (Vz T2-T4), women's final

Jumper	**Effective distance (m)**	**Vz_T2 (ms)**	**Vz_T3 (ms)**	**Vz_T4 (ms)**	**Gain Vz T2-T4 (ms)**
Gomes, Naide	7.10	-0.24	2.81	3.15	3.39
Maggi, Maureen	7.07	-0.52	2.16	3.11	3.63
Simagina, Irina	6.93	-0.13	2.67	3.45	3.58
Lesueur, Eloise	6.70	-0.32	1.91	2.91	3.23
Montaner, Concepción	6.70	-0.19	1.82	3.11	3.30
Radevica, Ineta	6.63	-0.10	1.86	2.91	3.01
Costa, Keita	6.55	-0.23	2.37	2.93	3.16
Josephs, Janice	6.45	-0.07	2.47	3.16	3.23
Mean	**6.77**	**-0.23**	**2.26**	**3.09**	**3.32**
SD	**0.24**	**0.14**	**0.38**	**0.18**	**0.21**
CV (%)	**3.5**	**60.0**	**16.8**	**5.8**	**6.3**

Take-off parameters

In accordance with the projective nature of the jump, the parameters that condition the jumpers' trajectory in the flight phase are Velocity, Height and Angle of Projection of CM at the instant of projection (T4). Table 11 shows the values for each parameter in the men's final, the means being 9.58 m/s, 1.27 m and 20.7° respectively (Note that the value for the height of the CM is not standardised in respect of the athlete's height.

The three parameters are within a reasonably low variability range, with an 8% variation coefficient maximum. The angle of projection seems the most variable one, with a value of 7.8%.

Projection velocity is 9.58 ±0.37 m/s. Garenamotse reaches the highest projection velocity, 10.24 m/s, while Starzak has the lowest, 9.01 m/s.

As for the angle of projection, a value of 20.69° ±1.62° has been calculated. Differentiated patterns can be seen in this case. The jumper with the greatest angle is Mokoena, 23.2°, while Al Khuwalidi has the lowest, 18.7°.

The correlation coefficient between velocity and angle of projection of the CM is negative; the greater the projection velocity, the smaller the angle and vice versa, although it is not statistically significant (r: -.394; p: .334).

Table 11: Velocity, height and angle of projection of the CM at take-off (T4), men's final

Jumper	Effective distance (m)	Vcg T4 (ms)	Height CG–T4 (m)	Projection Angle CG–T4 (°)
Tomlinson, Christopher	8.11	9.55	1.33	22.2
Mokoena, Jeofry	8.18	9.46	1.34	23.2
Al Khuwalidi, Mohamed	8.05	9.36	1.26	18.7
Garenamotse, Gable	7.98	10.24	1.25	20.1
Atanasov, Nikolay	7.88	9.43	1.30	20.7
Beckford, James	7.93	9.72	1.21	19.8
Starzak, Marzin	7.84	9.01	1.22	21.9
Martínez, Wilfredo	7.83	9.88	1.21	18.9
Mean	**7.98**	**9.58**	**1.27**	**20.69**
SD	**0.13**	**0.37**	**0.05**	**1.62**
CV (%)	**1.6**	**3.8**	**3.9**	**7.8**

Table 12 shows the results of the women's final, with mean values of 8.50 m/s, 1.06m and 21.4° for velocity, height and angle of projection of the CM, respectively. It must be noted that the value of the CM height is not standardised and, consequently, differences exist between men and women caused by the greatest height of men versus that of women (1.85±0.05m, and 1.74±0.05m, respectively). But, if standardised values are considered, the women's CM at take-off is lower than that of men (0.61 and 0.68m, respectively).

As happens with men, the three parameters are within a reasonably low variability range for this type of actions, 2% and 8% variation coefficients. The angle of projection is the parameter with the highest variation coefficient, 7.5%.

Projection velocity is 8.50 ±0.26 m/s. Lesueur is the jumper with the highest projection velocity, 8.96 m/s, while Gomes, the winner, has the lowest value, 8.20 m/s.

As for the angle of projection, a value of 21.4° ±1.62° has been calculated. In this case, the athlete with the greatest angle is Simagina, who reaches 24°, while Lesueur has the smallest angle, 19°.

The correlation coefficient between velocity and angle of projection of the CM is higher than in men and negative; the greater the projection velocity, the smaller the angle and vice versa, although no statistical significance is reached (r: -.644; p: .085).

Table 12: Velocity, height and angle of projection of the CM at take-off, women's final(T4)

Jumper	**Effective distance (m)**	**Vcg T4 (ms)**	**Height CG–T4 (m)**	**Projection Angle CG–T4 (°)**
Gomes, Naide	7.10	8.20	1.12	22.6
Maggi, Maureen	7.07	8.64	1.05	21.1
Simagina, Irina	6.93	8.48	1.05	24.0
Lesueur, Eloise	6.70	8.96	1.05	19.0
Montaner, Concepción	6.70	8.55	1.04	21.3
Radevica, Ineta	6.63	8.64	1.08	19.7
Costa, Keita	6.55	8.24	1.04	20.8
Josephs, Janice	6.45	8.27	1.04	22.4
Mean	**6.77**	**8.50**	**1.06**	**21.4**
SD	**0.24**	**0.26**	**0.03**	**1.62**
CV (%)	**3.5**	**3.0**	**2.8**	**7.5**

Trajectories of the height of the CM and knee angle of the take-off leg

The analysis of the trajectories of the jumpers' CM height and knee flexion angle of the take-off leg is interesting. Figure 3 shows the trajectories of these parameters for the winning athlete. We can see that during compression the height of the CM is gradually increased even though the knee is flexed until the end of this phase (T3). This behaviour pattern is repeated in all jumpers, confirming their ability to coordinate the actions performed by bodily segments throughout this highly decisive phase.

The bracing and blocking action of the take-off leg must also be taken into account in order to reach maximum projection velocity, as it greatly reduces the horizontal velocity of the jumper's CM and increases its vertical velocity. The knee angle of the take-off leg is an indicator of the athlete's ability to transfer kinetic energy. This blocking action favours the transfer of kinetic energy. It seems evident that this action is decisive, considering that, in elite jumpers, 60% of the vertical velocity of the CM is generated during the compression phase [7].

Figure 4 shows take-off leg knee angle values at touchdown (T2), and maximum knee flexion (T3). As shown, the compression phase is similar in all jumpers as regards the degree of flexion. In general terms, jumpers flex their knee between 24° and 29° during the compression phase (25.8° ± 1.7°), their behaviour being very similar. The athletes whose knee were more stretched at the touchdown instant are Mokoena (170°) and Beckford (171°). Contrarily, Al Khuwalidi reached that point with his knee being more flexed (156°). The rest have a similar behaviour, with about 166° knee flexion.

In the case of women, the results show that the flexion-extension range of the knee in the compression phase is larger, from 16° to 28°. As illustrated by Figure 5, the jumper reaching the touchdown stage with the most stretched knee was Josephs (171°), while Montaner and Costa reach the TD instant with their knees in the most flexed position (156°). The remaining jumpers have a similar behaviour, with about 165° knee flexion.

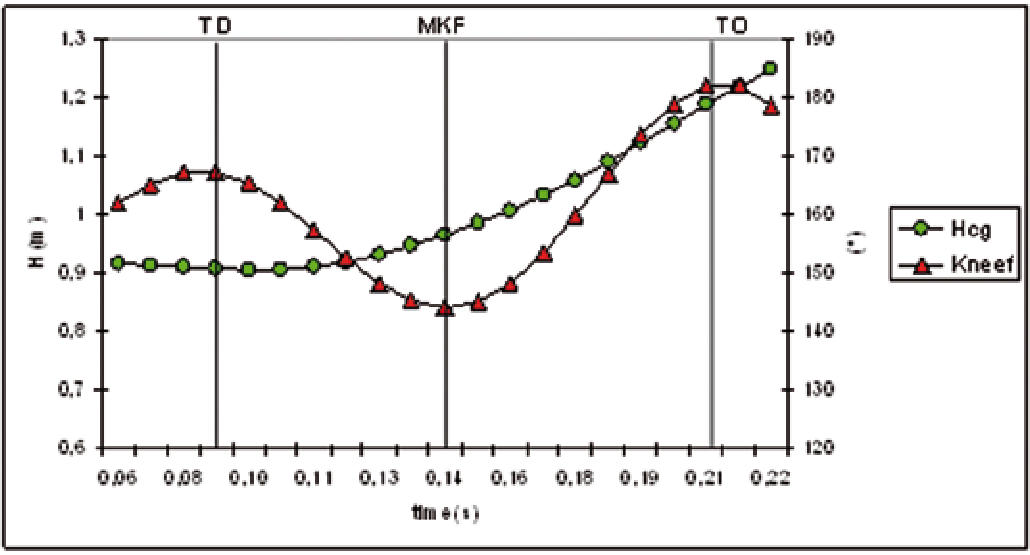

Figure 3: Height of CM and knee flexion during the take-off phase (TD-TO)

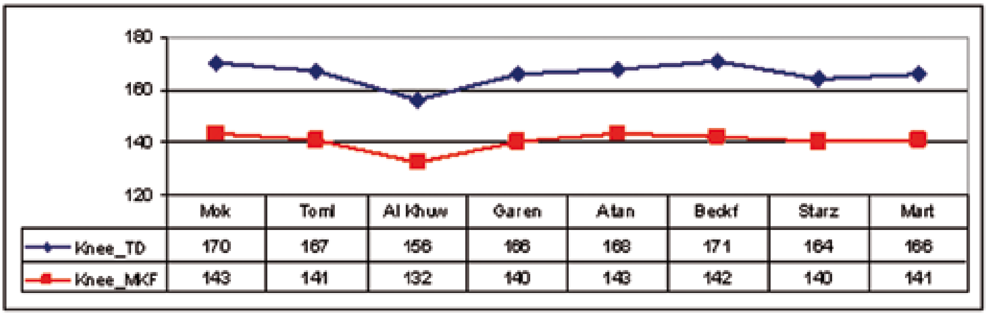

Figure 4: Knee angle of the takeoff leg at touchdown (T2), and maximum knee flexion (T3), men's final

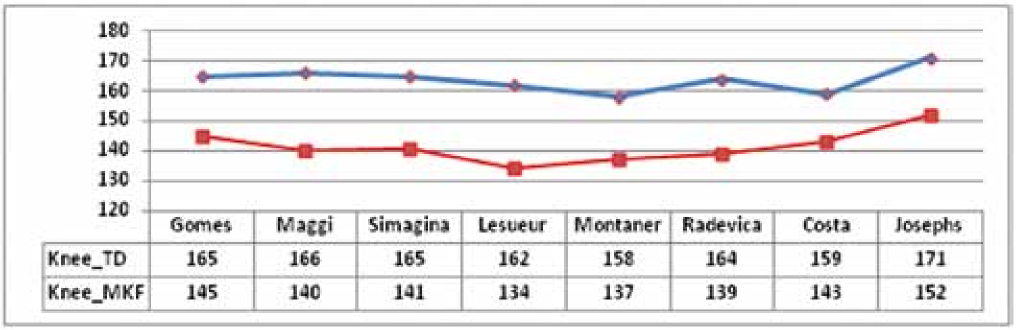

Figure 5: Knee angle of the takeoff leg at touchdown (T2), and maximum knee flexion (T3), women's final

Conclusions

As noted in the results, it has been observed that each jumper maintains an individual jumping pattern in relation to timing and the different kinematic parameters under study. Nevertheless, these individual patterns are conditioned by some minimum requirements needed to jump a long distance related with the position of the kinetic chain as well as the change of the velocity components of the athlete's CM during the take-off phase.

Athletes' individual models are an example of motor complexity, and numerous methodologies are required to analyse them. Descriptive studies such as the present work help to understand the dimensions involved in achieving performance in the long jump and to compare with jumpers with different performance levels.

We hope the information presented herein will be useful for long jump coaches and athletes and will contribute to the understanding of this event.

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