

3D Biomechanical Analysis of the Preparation of the Long Jump Take-Off

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ABSTRACT

The purpose of the present study was to describe the kinematics of the long jump approach and take-off and their effect upon the flight and the landing. Three digital video cameras, were used to capture the last two strides of the approach, the take-off phase, the flight and the landing of the eight jumpers participating in the men's long jump competition at the 2006 European Cup 1st League-Group B Event in Thessaloniki, Greece, on 17 June 2006. A 3D-DLT analysis was conducted for the two final strides of the approach and the take-off and a 2D-DLT analysis for the landing. Results indicate that all participants seemed to utilise the "longer penultimate-shorter last stride" ratio. Two types of approach were revealed, the "straight forward" and the "imbalanced". These approach types did not affect the long jumping technique, but the stride angles of the last stage of the approach were highly correlated ($r > .70$, $p < .05$) with the placement of the take-off foot on the board and with the lateral flight path of the Body Centre of Mass.

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Introduction

A long jumper performs the approach having in mind three requirements for a successful performance¹:

- a) the accuracy requirement (to place the toe of the take-off foot close to the take-off line),
- b) the velocity requirement (a large, subsequently controlled horizontal velocity of the body's centre of mass – BCM), and
- c) the position requirement (the jumper's body segments in a proper position and capable of making movements in order to develop the highest possible vertical BCM velocity with a minimum loss of horizontal BCM velocity).

The last two strides of the approach are crucial. More than 67% of the total adjustment to correct for prior errors in striding is made during the last two strides of the approach². Furthermore, elite long jumpers adjust their body position in order to prepare for take-off during the penultimate stride by increasing their stride length and thus lowering their BCM height³. The lowering of the BCM height leads to a larger vertical displacement of the BCM during contact at the board, resulting to a greater vertical take-off velocity and a smaller loss of horizontal velocity⁴.

The gain in BCM vertical velocity is primarily achieved by the action of the body moving or "pivoting" over the fixed foot of the touchdown leg and being forced upwards⁵. The forces applied from the foot on the take-off board causes a forward rotation about a transverse axis through the BCM⁶. This forward angular momentum must be controlled during the take-off and the flight by executing appropriate arm and leg movements in order to maintain the body positioning and thus to have an efficient landing^{7,8,9}.

Three-dimensional biomechanical analysis provides a fully detailed understanding of long jump technique. The achievement of the "pivoting" might be influenced by the positioning of the trunk relative to the touchdown leg in both the sagittal and frontal planes, making the joint action at the hip an important factor¹⁰. Furthermore, a small (near zero) sideways impulse is developed as a result of the positioning of the leg on the board⁶, indicating

that jumpers have to deal with a sideways deviation of their BCM flight path.

The purpose of this study was a) to present the three-dimensional analysis of the approach and take-off phases in the men's long jump and their effect upon flight and landing, and b) to comment on the results when they are compared with findings cited in the literature^{10, 11, 12, 13, 14, 15}.

Methods

Sample and data collection

The participants of the men's long jump competition at the 2006 European Cup 1st League-Group B Event, held in Thessaloniki, Greece, on 17 June 2006 were recorded with two digital JVC GR-DVL 9600EG (Victor Co., Japan) video cameras, operating at a sampling frequency of 50 fields/sec. The first camera was placed perpendicular to the plane of motion and recorded the last two strides of the approach and the take-off from the board. The second camera captured the same part of the jump, with the optical axes of the two cameras being approximately 60° apart.

For the execution of a 3D-DLT kinematic analysis¹⁶, the runway and the take-off area were calibrated placing at several positions a 2.5m 2.0m 2.5m frame with 24 control markers. The X-axis represented the direction of jumping along the runway; the Y-axis was perpendicular to the X-axis and parallel to the take-off board; the Z-axis was vertical to the X- and Y-axes (Figure 1). The accuracy of the 3D reconstruction was determined by Root Mean Square error. An error of 2.2mm, 1.5mm and 1.8mm was found for the X-, Y- and Z-axes, respectively.

Additionally, a third digital video-camera (Sony DCR-HC38, Sony, Minato, Tokyo, Japan) was placed high on the stands and recorded, from a head-on view and with a sampling frequency of 50 fields/sec, the jumpers' flight and landing in the sand pit. The pit was calibrated using reference marks, in order to identify the landing coordinates by using a 2D-DLT kinematic analysis¹⁶. X-axis represented the direction of the jumping, while Y-axis was perpendicular to X-axis. The synchronisation

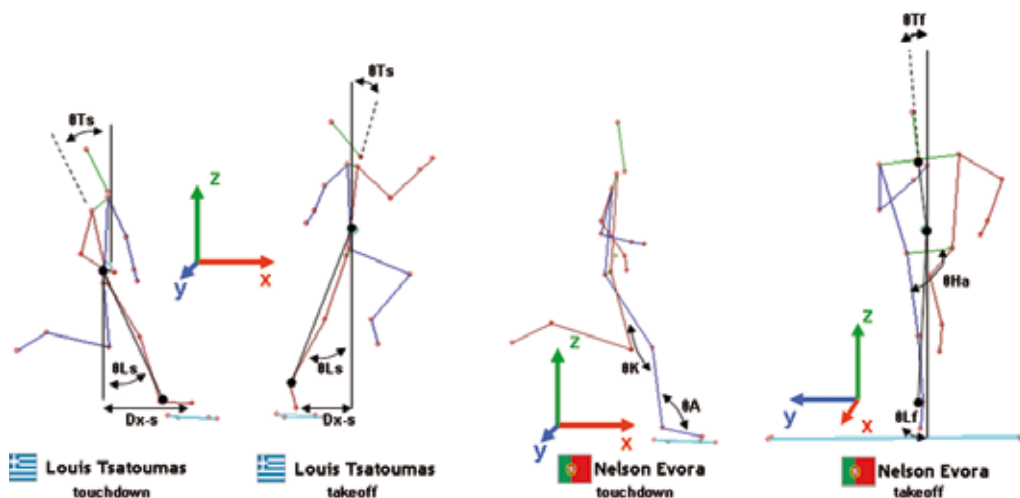


Figure 1: Graphical representation of the 3D kinematic parameters used (see Table 1 for the abbreviations shown). The arrow in each axis indicates the direction of positive values.

of the recorded videos from the three cameras was accomplished with the use of the audio band through the analysis software.

Data analysis

All trials were recorded and each athlete's best valid jump was selected for further analysis. Twenty-two anatomical points of the body (tip of the toe, 5th metatarsal, heel, ankle, knee, hip, shoulder, elbow, wrist, fingers on both sides of the body and the head) were manually digitised in each field. The coordinates of the BCM were calculated for every field using a combination of segment parameters and anatomical data^{17, 18, 19}. A 6 Hz cut-off frequency was selected for smoothing based on residual analysis²⁰. The biomechanical parameters, the methods for determining the parameters and the abbreviations used in the present study are presented in Table 1.

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-SD) were utilised for the presentation of the results. Additionally, a two-tailed Pearson correlation was used for the determination of the relationships among

the examined biomechanical parameters and the official distance. All statistical procedures were conducted using the SPSS 10.0 software (SPSS Inc, Chicago, IL).

Results

Competition results

Mean OFD was 7.40m (SD: 0.38; range: 7.00m – 8.05m). With the exception of Evora's winning jump, all other analysed jumps were performed with a head-on wind (Table 2).

Approach

All but one of the participants utilised the "long penultimate-short last" stride strategy. Sedoc did not alter his stride length, while Babicz shortened his last stride by 0.70m. On average, the last stride was 0.36m (SD: 0.21) shorter than the penultimate (Table 3).

The mean horizontal BCM velocity decreased from the penultimate to the last stride by 0.17m/sec (SD: 0.23). A slight velocity increment was recorded for Babicz (0.22m/sec) and Tsatoumas (0.02m/sec). As expected, the horizontal BCM velocity during the approach was highly correlated ($r = .78$, $p < .05$) with the effective distance (Table 4).

Table 1: Biomechanical parameters, the methods for determining the parameters and the abbreviations used in the study

Parameter (unit)	Abbreviation	Method for determination
Official Distance (m)	D_{OFF}	Distance in X-axis from the take-off line to the nearest break in the landing area made by any part of the body
Toe-to-board distance (m)	D_{TTB}	Distance in X-axis from the takeoff foot's toe to the take-off line
Effective distance (m)	D_{EFF}	The sum $D_{OFF} + D_{TTB}$
Instant of touchdown	TD	The first video field where the landing foot clearly contacted the ground
Instant of takeoff	TO	The first video field where the foot had clearly left the ground
Stride length (m)	$2LS, 1LS$	Distance at X-axis between toe-off point to the next touch down point of the approach strides
Horizontal velocity during the last strides (m/sec)	$V_{x2L_{TO}}, V_{x1L_{TO}}$	BCM velocity at X-axis at the instant of takeoff for the penultimate and last stride
BCM height (m)	$H_{TO}, 2L_{TO} \rightarrow 1L_{TD}, 1L_{TD} \rightarrow 1L_{TO}, 1L_{TO} \rightarrow BO_{TD}, BO_{TD} \rightarrow BO_{TO}$	BCM height at Z-axis at the instant of touchdown and takeoff for the penultimate, last stride and the takeoff
Horizontal velocity (m/sec)	V_{xTD}, V_{xTO}	BCM velocity at X-axis at the instant of touchdown and takeoff
Medio-lateral velocity (m/sec)	V_{yTD}, V_{yTO}	BCM velocity at Y-axis at the instant of touchdown and takeoff
Vertical velocity (m/sec)	V_{zTD}, V_{zTO}	BCM velocity at Z-axis at the instant of touchdown and takeoff
Takeoff angle in the sagittal (XZ) and frontal (YZ) planes (°)	$AngPr_{XZ}, AngPr_{YZ}$	Arc-tangent of vertical/horizontal and medio-lateral/vertical BCM velocity at the instant of takeoff, respectively
Sagittal touchdown and take-off distance (m)	D_{xTD}, D_{xTO}	Distance at X-axis from the athlete's BCM to the toe of the support leg at the instant of touchdown and takeoff, respectively
Lateral touchdown and take-off foot placement distance (m)	D_{yTD}, D_{yTO}	Distance at Y-axis from the athlete's BCM to the toe of the takeoff leg at the instant of touchdown and takeoff, respectively
Relative ankle touchdown velocity (m/sec)	rV_x	Ankle velocity at X-axis minus BCM velocity at X-axis at the instant of touchdown
Ankle angle (°)	$\theta A_{TD}, \theta A_{TO}$	Angle formed in the XZ-plane between the foot and the shank at the instant of touchdown and takeoff
Knee angle (°)	$\theta K_{TD}, \theta K_{TO}$	Angle formed in the XZ-plane between the thigh and the shank at the instant of touchdown and takeoff
Angle of leg placement in the sagittal (XZ) plane (°)	$\theta L_{sTD}, \theta L_{sTO}$	Angle formed in the XZ-plane by the downward vertical of the line connecting the body centre of mass and the ankle joint at the instant of touchdown and takeoff
Angle of leg placement in the frontal (YZ) plane (°)	$\theta L_{fTD}, \theta L_{fTO}$	Angle formed in the YZ-plane by the downward vertical of the line connecting the body centre of mass and the ankle joint at the instant of touchdown and takeoff
Sagittal (XZ) trunk inclination (°)	$\theta T_{sTD}, \theta T_{sTO}$	Trunk angle in the XZ-plane at the instant of touchdown and takeoff
Frontal (YZ) trunk inclination (°)	$\theta T_{fTD}, \theta T_{fTO}$	Trunk angle in the YZ-plane at the instant of touchdown and takeoff
Hip abduction/adduction angle (°)	$\theta Ha_{TD}, \theta Ha_{TO}$	Angle formed in the YZ-plane by the thigh of the support leg and the hip axis at the instant of touchdown and takeoff
Stride angle (°)	$\theta S_{2L}, \theta S_{1L}$	Projection angle to X-axis of the line connecting the XY – coordinates of the supports during the run-up
Flight angle (°)	θ_{FLIGHT}	Projection angle to X-axis of the line connecting the XY – coordinates of the takeoff and landing points
Lateral landing distance (m)	D_{yLAND}	Distance at Y-axis from the toe of the takeoff leg at the instant of takeoff to the landing point of the center of the hip axis.

Table 2: Participants, take-off leg (TOL), Official- (D_{OFF}), effective- (D_{EFF}), toe-to-board- (D_{TTB}) distances and wind velocity (W) for the analysed jump

ATHLETE	Nationality	TOL	D_{OFF} (m)	D_{TTB} (m)	D_{EFF} (m)	Trial (#)	W (m/sec)	SB* (m)
EVORA, Nelson	POR	right	8.05	0.02	8.07	1	0.0	8.05
TSATOUMAS, Louis	GRE	left	7.91	0.10	8.01	3	-1.0	8.30
SEDOC, Gregory	NED	left	7.36	0.13	7.49	4	-2.5	7.60
ŽUMER, Jan	SLO	left	7.34	0.13	7.47	3	-0.5	8.00
PUCELJ, Ivan	CRO	left	7.23	0.15	7.38	3	-1.5	7.88
TUDOR, Bogdan	ROM	left	7.17	0.11	7.28	4	-1.5	7.86
BABICZ, Pál	HUN	right	7.15	0.05	7.20	1	-1.7	7.52
IMRAK, Koray	TUR	left	7.00	0.07	7.07	2	-1.6	7.17
Mean (n=8)			7.40	0.10	7.50		-1.8	7.80
SD			0.38	0.04	0.36		0.8	0.35

* season bests for 2006, according to www.iaaf.org/statistics/toplists & www.iaaf.org/athletes/biographies & www.euromeetings.org/results (downloaded: 08 Jan. 2008). Evora's jump was a personal best

Table 3: Stride length (S) and projection angle (θ) to X-axis (parallel with the runway) and the differences observed (Δ) between the penultimate (2L) and the last stride (1L)

ATHLETE	D_{OFF} (m)	2LS (m)	1LS (m)	ΔS (m)	θS_{2L} (°)*	θS_{1L} (°)*
EVORA	8.05	2.19	2.06	-0.13	2.2	2.6
TSATOUMAS	7.91	2.56	2.22	-0.34	0.0	0.0
SEDOC	7.36	2.06	2.06	0.00	-0.5	-0.2
ZUMER	7.34	2.48	2.02	-0.46	2.1	3.0
PUCELJ	7.23	2.43	2.06	-0.37	0.8	1.5
TUDOR	7.17	2.49	2.05	-0.44	-0.5	-0.7
BABICZ	7.15	2.67	1.97	-0.70	0.3	0.5
IMRAK	7.00	2.22	1.80	-0.42	-2.3	-2.2
Mean (n=8)	7.40	2.39	2.03	-0.36	1.1	1.3
SD	0.38	0.21	0.12	0.21	0.9	1.2

* Mean refers to the absolute values of the parameter

Table 4: Horizontal (V_x), medio-lateral (V_y) and vertical (V_z) take-off velocity of the Body center of Mass and the differences observed (Δ) between the penultimate (2L) and the last stride (1L)

ATHLETE	D _{OFF} (m)	V _{x2Lto} (m/sec)	V _{x1Lto} (m/sec)	ΔV_x (m/sec)	V _{y2Lto} (m/sec)*	V _{y1Lto} (m/sec)*	V _{z2Lto} (m/sec)	V _{z1Lto} (m/sec)
EVORA	8.05	9.96	9.96	-0.08	-0.50	-0.39	0.02	0.26
TSATOUMAS	7.91	10.04	10.04	+0.02	0.47	-0.25	0.44	-0.09
SEDOC	7.36	9.93	9.93	-0.33	0.54	-0.13	-0.02	-0.12
ZUMER	7.34	10.35	10.35	-0.48	-0.08	-0.69	0.53	0.13
PUCELJ	7.23	10.14	10.14	-0.26	0.23	-0.33	0.41	-0.17
TUDOR	7.17	9.59	9.59	-0.37	0.28	0.07	0.31	0.19
BABICZ	7.15	9.26	9.26	+0.22	-0.44	0.17	0.60	-0.07
IMRAK	7.00	9.27	9.27	-0.09	0.63	0.00	0.52	0.17
Mean (n=8)	7.40	9.82	9.82	-0.17	0.24	0.25	0.35	0.04
SD	0.38	0.40	0.40	0.23	0.38	0.22	0.23	0.17

The overhead views of the BCM trajectories (Figure 2) and the foot placements during the last strides and the take-off revealed two types of approach. In the first, athletes use a “straight forward” movement to place the take-off foot on the board (i.e. Tsatoumas, Sedoc, Babicz). The other athletes seem to approach and take-off in an “imbalanced” way (i.e. Evora, Pucelj, Zumer, Imrak). A mean 1.1° (in absolute values; SD: 0.9) stride angle occurred during the last two strides of the approach. In most of the cases, the stride angle was slightly increased during the last stride of the approach.

Correlation analysis showed a strong negative relationship between horizontal and medio-lateral BCM velocity at the instant of the take-off of the last stride ($r = -.89$, $p < .01$). Furthermore, the stride angle was negatively related with the vertical BCM take-off velocity from the board ($r = -.93$, $p < .01$) and with the lateral BCM displacement during the take-off phase ($r = -.98$, $p < .01$). Finally, the stride angle was positively correlated with the flight angle ($r = .88$, $p < .01$).

Table 5: Body Center of Mass' height (H) at take-off and its alteration between the instants of touchdown(TD) and take-off (TO) for the penultimate(2L), the last stride (1L) and the contact on the board (BO)

ATHLETE	OFD (m)	2L _{TO} →1L _{TD} (flight, m)	1L _{TD} →1L _{TO} (support, m)	1L _{TO} →BO _{TD} (flight, m)	BO _{TD} →BO _{TO} (push-off, m)	H _{TO} (m)
EVORA	8.05	-0.10	0.01	-0.02	0.29	1.24
TSATOUMAS	7.91	-0.08	0.01	-0.05	0.28	1.24
SEDOC	7.36	-0.08	0.01	-0.03	0.25	1.21
ZUMER	7.34	-0.08	0.00	0.00	0.26	1.28
PUCELJ	7.23	-0.08	0.01	-0.04	0.28	1.22
TUDOR	7.17	-0.05	0.02	-0.03	0.33	1.28
BABICZ	7.15	-0.06	0.00	-0.03	0.23	1.19
IMRAK	7.00	-0.05	0.01	0.00	0.26	1.20
Mean (n=8)	7.40	-0.07	0.01	-0.03	0.27	1.23
SD	0.38	0.02	0.01	0.02	0.03	0.03

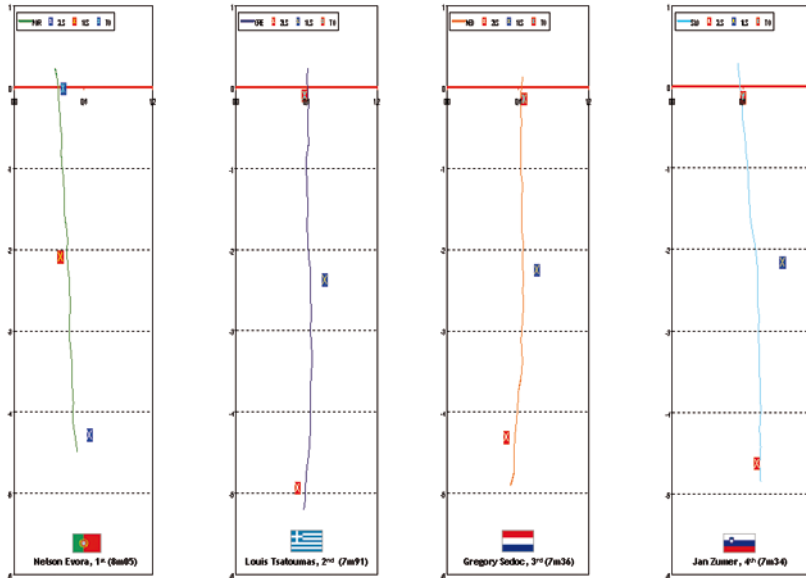


Figure 2a: Overhead views of the trajectory of the Body Center of Mass and the feet placements during the penultimate (2LS), the last stride (1LS) and the takeoff from the board (TO). Distances are in meters. Red foot-prints indicate support on the left foot, while blue footprints represent support on the right foot.

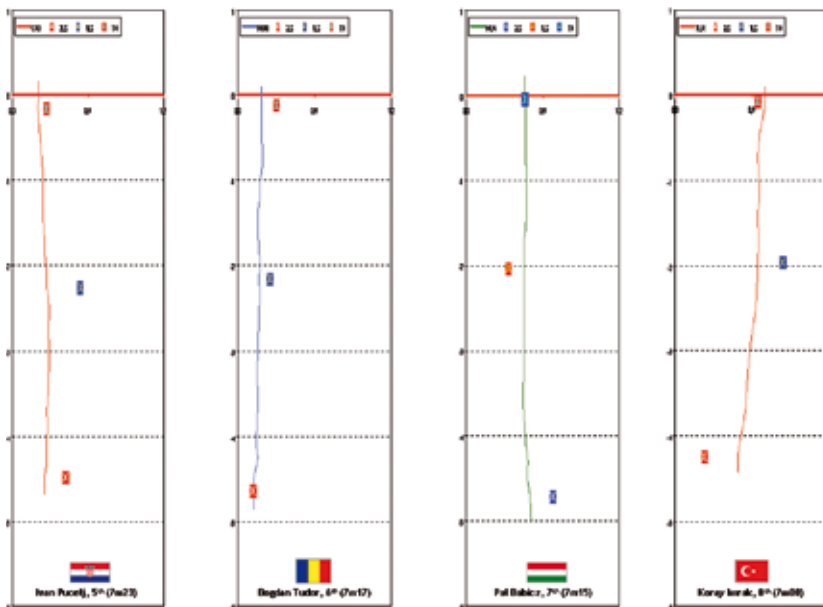


Figure 2b: Overhead views of the trajectory of the Body Center of Mass and the feet placements during the penultimate (2LS), the last stride (1LS) and the takeoff from the board (TO). Distances are in meters. Red foot-prints indicate support on the left foot, while blue footprints represent support on the right foot.

The utilisation of the “longer penultimate-shorter last stride” ratio led to the lowering of the BCMs during the flights prior to the last stride and the take-off (Table 5). BCM lowering was interrupted during the support phase of the last stride. The BCM lowering occurred du-

ring the flight prior the last support for the last stride was strongly correlated with the effective distance ($r = -.82, p < .05$). The highest values of BCM lowering for the analysed strides was recorded for Tsatoumas, (0.12m), while the lowest value was recorded for Imrak (0.04m).

Table 6: Angles of projection (AngPr), relative touchdown velocity (rVx), horizontal (Vx), mediolateral (Vy) and vertical (Vz) velocity of the Body Center of Mass at the instant of touchdown (TD) and take-off (TO) from the board

ATHLETE	D _{OFF} (m)	rV _X (m/sec)	V _X TD (m/sec)	V _X TO (m/sec)	V _Y TD (m/sec)*	V _Y TO (m/sec)*	V _Z TD (m/sec)	V _Z TO (m/sec)	AngPr (xz, °)	AngPr (yz, °)*
EVORA	8.05	-6.24	9.34	8.65	-0.37	-0.48	0.81	3.72	23.3	3.2
TSATOUMAS	7.91	-7.57	9.72	9.26	0.06	0.15	0.69	3.56	21.0	-0.9
SEDOC	7.36	-5.51	9.37	8.82	-0.01	-0.04	0.49	3.56	22.0	0.3
ZUMER	7.34	-6.08	9.75	8.99	-0.54	-0.56	0.53	3.15	19.3	3.6
PUCELJ	7.23	-4.70	9.47	8.48	-0.25	-0.41	0.01	3.81	24.2	2.8
TUDOR	7.17	-5.34	8.86	7.87	0.23	-0.09	0.37	3.70	25.2	0.7
BABICZ	7.15	-5.59	9.28	8.24	-0.02	-0.05	0.16	3.11	20.7	0.3
IMRAK	7.00	-5.25	8.54	7.92	0.27	0.49	0.78	3.58	24.3	-3.5
Mean (n=8)	7.40	-5.79	9.29	8.53	0.22	0.28	0.48	3.52	22.5	1.9
SD	0.38	0.87	0.41	0.50	0.18	0.22	0.81	0.26	2.1	1.5

* Mean refers to the absolute values of the parameter

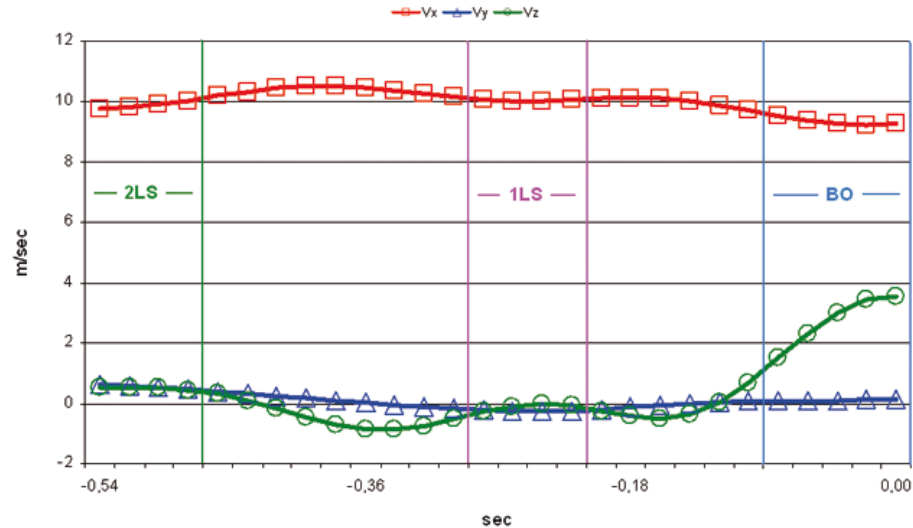


Figure 3: Horizontal (Vx), Medio-lateral (Vy) and Vertical (Vz) velocity of the Body Center of Mass during the penultimate (2LS), the last stride (1LS) and the contact on the board (BO) for the jumper placed 2nd (Louis Tsatoumas, PB: 8.66m).

Take-off

Average toe-to-board distance was 0.10m (SD: 0.04). Evora won the competition with a season best, notably with a TTB of 0.02m. The mean horizontal touchdown velocity at the board was 9.29m/sec (SD: 0.41). The mean horizontal and vertical BCM take-off veloci-

ties were 7.46m/sec (SD: 0.23) and 2.45m/sec (SD: 0.12), respectively (Table 6). A decrement of 8.2% (SD: 2.5) in average was observed in horizontal velocity during the take-off phase. A high correlation ($r = .73$, $p < .05$) was observed between horizontal take-off velocity and effective distance.

Table 7: Sagittal placement distances(Dx), lateral placement distances (Dy), ankle (OA) and knee (OK) joint angles for the take-off leg at the instant of touchdown (TD) and take-off (TO) from the board

ATHLETE	D _{OFF} (m)	D _{XTD} (m)	D _{XTO} (m)	D _{YTD} (m)*	D _{YTO} (m)*	θ _{A_{TD}} (°)	θ _{A_{TO}} (°)	θ _{K_{TD}} (°)	θ _{K_{TO}} (°)
EVORA	8.05	0.63	0.27	-0.01	-0.07	110	122	165	163
TSATOUMAS	7.91	0.56	0.37	0.03	0.03	109	133	172	178
SEDOC	7.36	0.64	0.26	-0.02	-0.01	107	126	162	167
ZUMER	7.34	0.69	0.43	0.03	-0.04	112	129	160	173
PUCELJ	7.23	0.77	0.31	-0.03	-0.06	114	127	166	166
TUDOR	7.17	0.73	0.26	-0.11	-0.12	119	123	170	172
BABICZ	7.15	0.69	0.32	0.01	0.00	107	133	168	170
IMRAK	7.00	0.59	0.23	0.00	0.06	108	130	159	175
Mean (n=8)	7.40	0.66	0.31	0.03	0.05	110.8	127.9	165.3	170.5
SD	0.38	0.07	0.07	0.03	0.04	4.1	4.2	4.9	5.0

* Mean refers to the absolute values of the parameter

The athletes who approached with a “straight forward” movement had lower medio-lateral BCM velocities at the instant of touchdown and take-off from the board (Figure 3). However, there was no indication that the medio-lateral BCM take-off velocity affected the effective distance ($r < .40$, $p > .05$).

The values relative to the BCM touchdown velocity of the take-off leg’s ankle (-5.79m/sec, SD: 0.87) indicated a rather “blocking” landing on the board²¹ for half of the participants. Relative ankle touchdown velocity was highly correlated with the effective distance ($r = .76$, $p < .05$). The toes of the take-off foot were, on average, placed 0.66m (SD: 0.07) ahead of the BCM projection to the X-axis and 0.03m (SD: 0.03) aside of the BCM projection to the Y-axis (Table 7).

An average 0.27m (SD: 0.03) vertical elevation of the BCM was recorded during contact on the board. The effective take-off distance ranged from 0.43m (Zumer) to 0.23m (Imrak). The knee joint was not fully extended at the instant of take-off (170.5°, SD: 5.0), while the ankle joint was at a mean angle of 128° (SD: 4.2) approximately.

The angular displacement of the take-off leg was almost symmetrical when referred to the vertical (Table 8). In the sagittal plane, the leg was placed at a 28.4° (SD: 4.3) angle. At take-off, the angle was 29.6°, (SD: 2.1). The respective leg placement angles for the frontal plane were 5.4° (SD: 1.6) at touchdown and 4.9° (SD: 1.7) at take-off. The hip joint was adducted by an absolute average of 4.4° (SD: 1.7) at the instant of touchdown. At the instant of take-off, the hip was abducted at an absolute average of 16.6° (SD: 5.1).

Table 8: Angle of placement of the take-off leg in the sagittal (θ_{LS}) and frontal (θ_{Lf}) plane and the hip abduction/adduction angle (θ_{Ha}) at the instant of touchdown (TD) and take-off (TO) from the board

ATHLETE	D _{OFF} (m)	$\theta_{LS_{TD}}$ (°)	$\theta_{LS_{TO}}$ (°)	$\theta_{Lf_{TD}}$ (°)	$\theta_{Lf_{TO}}$ (°)	$\theta_{Ha_{TD}}$ (°)	$\theta_{Ha_{TO}}$ (°)
EVORA	8.05	30	28	6	2	2	13
TSATOUMAS	7.91	24	29	4	5	7	16
SEDOC	7.36	23	30	8	6	5	22
ZUMER	7.34	35	33	4	6	6	20
PUCELJ	7.23	29	30	6	6	3	9
TUDOR	7.17	28	32	6	3	7	9
BABICZ	7.15	33	28	6	4	4	21
IMRAK	7.00	25	27	3	7	1	15
Mean (n=8)	7.40	28.4	29.6	5.4	4.9	4.4	15.6
SD	0.38	4.3	2.1	1.6	1.7	2.3	5.1

* Mean refers to the absolute values of the parameter

Table 9: Sagittal (θ_{Ts}) and frontal (θ_{Tf}) trunk inclination at the instant of touchdown (TD) and takeoff (TO) from the board, the BCM's flight path projection angle (θ_{FLIGHT}) to X-axis (along the pit) and the lateral landing distance (DyLAND).

ATHLETE	D _{OFF} (m)	$\theta_{Tf_{TD}}$ (°)	$\theta_{Tf_{TO}}$ (°)	$\theta_{Ts_{TD}}$ (°)	$\theta_{Ts_{TO}}$ (°)	θ_{FLIGHT} (°)	DyLAND (m)
EVORA	8.05	4	8	-5.7	15.1	-2.5	-0.34
TSATOUMAS	7.91	14	13	-0.4	8.7	1.3	0.17
SEDOC	7.36	12	11	-2.7	5.3	-0.7	-0.09
ZUMER	7.34	13	10	-5.2	8.9	-0.9	-0.23
PUCELJ	7.23	10	7	-2.5	4.0	-2.2	0.27
TUDOR	7.17	13	9	-1.0	7.3	-0.2	-0.02
BABICZ	7.15	3	9	-1.4	3.7	1.2	0.14
IMRAK	7.00	8	6	-3.7	10.0	2.3	0.27
Mean (n=8)	7.40	9.6	9.1	-2.8	7.9	1.4	0.19
SD	0.38	4.2	2.2	1.9	3.7	0.8	0.11

* Mean refers to the absolute values of the parameter

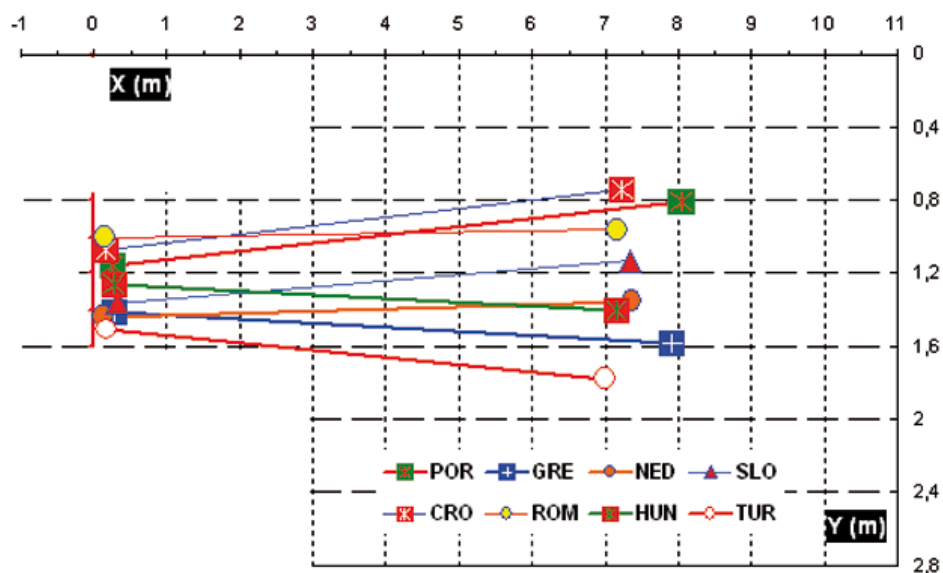


Figure 5: Overhead views of the take-off point and the landing mark in the sand pit (Note: the lines linking the data points are not intended to represent the actual BCM trajectory).

The athletes' trunks, slightly backwards at the instant of touchdown to the board (2.8°, SD: 1.9), shifted forward by approximately 10.7° (SD: 5.2) during the take-off phase (Table 9). However, an average amount of sideways trunk lean was observed during the start and the end of the take-off phase (9.9°, SD: 4.2 and 9.1°, SD: 2.2, respectively). Tsatoumas had the greatest inclination in the frontal plane in both touchdown and take-off from the board. Correlation analysis revealed that sagittal trunk inclination was highly correlated with hip angle at touchdown ($r = .81$, $p < .05$) and with horizontal BCM take-off velocity ($r = .74$, $p < .05$). The average angle of projection for the take-off was 22.7 (SD: 2.5). As for the frontal plane, the mean take-off angle (in absolute values) was 1.9° (SD: 1.5).

Flight phase and landing

The majority of the jumpers who covered the distance of the last two strides in an "imbalanced" way (Evora, Pucelj, Imrak) had the largest flight angles among the participants ($\Theta_{\text{FLIGHT}} > 2^\circ$). Although Tsatoumas and Babicz had a near zero stride angles, their flight angles were larger than 1° (Figure 4). The flight angle was highly cor-

related with the foot placement distance at the instant of take-off from the board ($r = .73$, $p < .05$).

Discussion

Mean official distance was smaller than other studies^{5, 11, 12, 13, 15, 22, 23, 24, 25, 26, 27} concerning international or national-level long jumpers (mean $D_{\text{OFF}} > 7.51\text{m}$). The head-on wind for the vast majority of the participants might be the reason why the jumpers achieved lower results than their seasonal bests. Another factor was the large toe-to-board distances. However, mean toe-to-board distance was in agreement with those reported in the 1988 Olympic Games²⁵ and the 1997 World Championships²⁴.

As found in previous studies^{11, 22, 23, 24, 25, 27} a "long penultimate-short last" stride strategy was applied. However, the length difference between the last two strides observed in the present study was in approximate two times greater than in other studies^{24, 25}. Another similarity during the approach was the decrement of the BCM horizontal velocity during the last two strides^{23, 24, 25, 26, 28}. The head wind was possibly responsible for the decrement of the mean

horizontal BCM velocity from the penultimate to the last stride by 0.17m/sec (SD: 0.23).

The analysed athletes lowered their BCM during the last two strides by an average of 0.09m. Most of the lowering (0.07m) occurred during the flight of the penultimate stride, as was also reported in the 2007 World Championship¹⁵. The lowering of the BCM contributed to the low position of the BCM and to the non-negative value of vertical BCM velocity in the beginning of the take-off, fulfilling the aims of the preparatory phase of the take-off²⁹.

Mean touchdown distance was greater than those reported elsewhere^{10,21}. The mean angle of leg placement (28.4°) was lower than those reported (32.2-37°)^{10,15}, but close to the 29° angle proposed from experimental data³⁰. The knee angle at the time instant to the board was 165°, as found in other studies^{10, 12, 15}. However, it seems that the absence of a minimum knee flexion, along with the large touchdown distance and the non-“active” movement of the take-off leg when it was placed on the take-off board, did not lead to an advantageous exploitation of the horizontal BCM touchdown velocity on the board ($r = .60$, $p > .05$).

The average horizontal BCM take-off velocity (8.53m/sec) was similar to those reported for the 1986 World Junior Championships medalists (8.57m/sec)⁴, the 1994 and 1995 UK National Championships (8.55m/sec)¹⁰ and for moderate level male athletes (≈ 8.48 m/sec)³¹. The average horizontal BCM take-off velocity in other major competitions has been reported as over 8.7m/sec^{12, 13, 15, 23, 24, 25, 26}.

Conversely, the average vertical BCM take-off velocity and the sagittal angle of projection were at the higher boundary of the range of values cited in the above-mentioned studies. Furthermore, the average medio-lateral BCM velocity at take-off was larger than reported elsewhere^{10, 11, 12}.

The average effective take-off distance (0.31m) was also smaller than recorded in various level competitions^{4, 5, 10, 23, 27}. Finally, the body segment angles were in reasonable agreement with those reported in previous three-dimensional studies of the long jump take-off^{10, 14, 15}.

Conclusion

Lateral deviation of the BCM path during the flight results to a 1-2cm shorter measured long jump, a crucial distance when an optimum jump is needed. There are indications that the penultimate stride plays a key role long jumping technique. Important biomechanical factors in during the penultimate stride are the maintenance of high horizontal velocity, the forward trunk motion, the powerful swing of the lead leg with the exploitation of gravity, the high force production during the forward push-off during, the balanced side-ward impulse and the short contact times^{3, 4, 27, 32, 33, 34}.

Summarising, the aim of the study was to provide information concerning 3D kinematical parameters during the approach, the take-off and the flight in the men's long jump. The small number of the jumpers analysed, along with the low sampling frequency, restricts a good clarity of the results. However, based on the findings of the present study we can state:

1. Long jump performance is mainly determined by the athlete's approach velocity and the lowering of the BCM height during the penultimate stride of the approach is an important technique element, in accordance with other studies^{3, 4, 5, 8, 23, 30}.
2. Based upon the magnitude of the last stride's projection angle to the approach, two types of approach are evident: a “straight forward” (near to zero angles referred to the mid-line of the runway) and an “imbalanced” movement (larger angles).
3. The stride angle has an effect upon vertical BCM take-off velocity, the lateral BCM displacement during the take-off phase and the BCM path during the flight.
4. The angle of the take-off leg placement in the frontal plane is correlated with the frontal torso inclination during the take-off phase from the board.
5. There is no indication that the medio-lateral BCM take-off velocity affects the effective distance.

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