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Original Article

Key kinetic and kinematic factors of 110-m hurdles performance

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Abstract:
This study aimed at exploring the key kinetic and kinematic factors of 110-m hurdle clearance performance using three-dimensional (3D) analysis system. Ten national level athletes participated in this study. The kinematic analysis of the hurdling sequences was recorded using ten mutually synchronized digital cameras. Body markers were digitized using SkillSpector® software. Ground-reaction force was calculated by using rigid body inverse dynamics using the Smith's equations. All variables were combined into components through a principal component analysis. The retained components have been used in a multiple regression analysis. Twenty variables were retained as key hurdling performance determinants. Specifically, the horizontal and vertical velocity of the centre of mass (COM) and the lead-leg/trail-leg in all phases (i.e., take-off, flight, and landing), horizontal and vertical displacement of the COM, the lead-leg/trail-leg vertical displacement, and the flight-time at clearance are among the main hurdling performance determinants. Overall, to improve hurdling performance, greater horizontal velocity, lower vertical displacement at flight and lower contact-time at the take-off phases through a higher rate of force development are needed.
Key Words: - Motion analysis; inverse dynamic; hurdling; track and field

Introduction

Hurdling is a complex technical event that requires high levels of physical fitness (Iskra, 1995). In fact, sprint speed, inter-segmental coordination, reactive strength, and great technical skills are the most key physical fitness aspects that should regularly be developed and routinely implemented in training programs to succeed the race (Coh, 2003; Coh & Zvan, 2018). In particular, the technique of clearing the hurdle represents one of the most determinant elements defining the competitive result (López, Padullés, & Olsson, 2011; McLean, 1994; Sidhu & Singh, 2015). In this context, Iskra (1995) indicated that the improvement of the 110-m hurdle race technique represents one the central component of training.

Kinetic and kinematic analysis of 110-m hurdle clearance, in particular, may help understanding the critical factors that influence performance and assist coaches exploring the theoretical basis for hurdle running training (Salo, Grimshaw, & Viitasalo, 1999). Additionally, the kinetic and kinematic outcomes are widely used to help improving athletes' training and performance, alike (Coh, Jost, & Skof, 2000; Salo et al., 1999). Previous studies examined the kinematic analysis of Colin Jackson's clearance (World Record Holder) at the fourth hurdle in the 110m race (Coh,2003; Coh, Zvan, and Jost,2004; Coh and Zvan, 2018). Authors agreed that the horizontal velocity of the centre of mass (COM) at take-off and during clearance, the height of COM above the hurdle, the lead-leg's knee swing velocity, the flight-time, and the contact-time at the landing phase represent the key hurdling performance factors. In terms of kinetic factors, it has been demonstrated that the peak horizontal force at landing is paramount for an efficient hurdling (Coh and Iskra, 2012).

It is noteworthy that all previous biomechanical analyses of hurdling were carried out on only one to three hurdles (Iskra & Coh, 2006) with a large variation in the hurdles selected for analysis. For instance, previous research focused on only the first (Lee, 2004; Lee, Park, Ryu, & Kim, 2008; Salo, 2002; Xu, Wang, & Yan, 2005), the second (Iliew & Primakov, 1978; Mclean, 1994), the third (Lee, 2009; Salo, Peltola, & Viitasalo, 1993; Tsarouchas, Papadopoulos, Kalamaras, & Giavroglu, 1993), the fourth (Coh, 2003; Cooh et al., 2000; Li, Zhou, Li, & Wang, 2011; Ryu & Chang, 2011), the fifth (Coh & Zvan, 2018; Sidhu, 2016; Sidhu & Singh, 2015), the sixth (Li & Fu, 2000; Peak et al., 2011), the seventh (Shibayama, Fujii, Takenaka, Tanigawa, & Ae, 2011) the ninth (Iwkin, Jegorow, & Zukow, 1987; Salo & Scarborough, 2006), and the tenth hurdle (Lopez et al., 2011; Chow, 1998).

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Having in mind that previous studies have generally focused on only one to three hurdles, along with only a kinetic or kinematic analysis except Coh and Zvan (2018), further studies addressing both kinetic and kinematic factors over the whole 110-m hurdling race could be of high practical relevance. Clearly, this is a research area that needs further development. Therefore, in an attempt to fill this gap in the literature, the purpose of this study was to examine the key kinetic and kinematic factors related to the clearance technique (i.e., take-off, flight, and landing phases) over the entire 110-m hurdles race in national level sprint hurdle athletes. With reference to the relevant literature (Coh, 2003; Coh et al., 2000; Coh & Zvan, 2018; Iscra, 1995; Iskra & Coh, 2006; Salo et al., 1999), we hypothesized that greater velocity, lower vertical displacement at flight and lower contact-time at the take-off phases represent the key hurdling performance determinants.

Material & methods

Participants

Ten national level male athletes participated to this investigation (mean ± SD: age 20.82 ± 1.33 years; height 1.82 ± 0.04 m; body mass 75.04 ± 4.59 kg). They had 9.1 ± 1.3 years sprint hurdle training background. Their mean 110-m hurdles performance was 14.30 ± 0.13 second and the best performance was 13.90 second.
All procedures were approved by the Institutional Review Committee for the ethical use of human subjects at Ksar Said University. Written informed participant assent was obtained before the start of the study. All participants were informed about the experimental protocol and its potential risks and benefits before starting the study. Participants were allowed to withdraw from the study at any time without giving any reason.

Procedures

Three-dimensional (3D) kinematic analyses of the hurdling sequences were performed over the entire 110-m distance (i.e., 10 hurdles) with ten mutually synchronized [Time Code Synchronization, TC-Link] digital cameras [Sony DCR-PC108^E Mini-DV; 1 million pixels CCD, Shutter speed 1/4000th of a second and sample rate 60 Hz] with wide conversion lens [× 0.6; 45.5 × 29 mm]. Cameras were placed in pairs (i.e., 5 pairs) 7-m away and 1.50-m above the floor with an angle of 60° and 120° for the first and the second camera, respectively. Each pair of cameras permitted the analysis of two hurdles (figure 1).

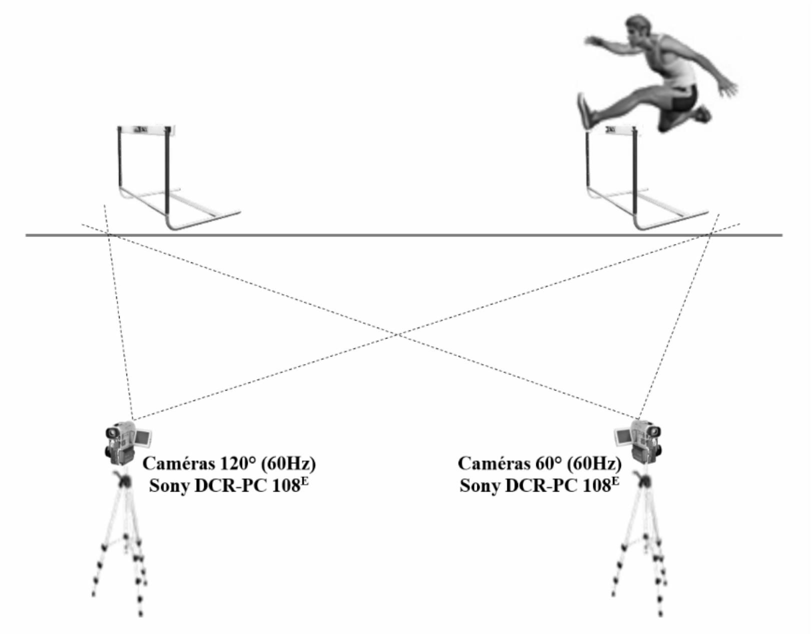

Fig. 1: Measurement procedure.

To collect kinematic athletes' clearance data, twenty markers were attached to the body of each participant for digitization. Body markers, using the Hanavan model modified by De Leva (1996), were digitized using the video-based data analysis system SkillSpector® 1.3.2 [Odense SØ – Denmark], (Bini, Jacques, Lanferdini, & Vaz, 2015; Lanferdini et al., 2016; Mkaouer, 2018; Mkaouer, Chaabene, Amara, Negra, & Jemni, 2018; Mkaouer, Jemni, Amara, Chaabène, & Tabka, 2013). Similarly, the body segments' COM was computed using the Hanavan model modified by De Leva (1996). Ground reaction force (F_t) was calculated using rigid body inverse dynamics via Smith's equation (Smith, 1983) [Equation 1a, 1b and 1c; Figure 1a and 1b] (Amara, Mkaouer, Chaabène, Negra, Hammoudi-Riahi, & Ben-Salah, 2017; Mkaouer, 2018; Mkaouer et al., 2013, 2018). The accuracy of force measurement via inverse body dynamic analysis using Smith's equation (Smith, 1983) has been recently validated by Mkaouer et al. (2018) (equation 1a, b and c; figure 2).

Equation 1.

$$\text{(a) } F_x(N) = m \cdot \left(\frac{v_2 - v_1}{t_1 + t_2} \right) \qquad \text{(b) } F_y(N) = m \cdot \frac{v_3}{t_2} \qquad \text{(c) } F_t(N) = \sqrt{(F_x^2) + (F_y^2)}$$

(1)

(F_t) resultant of reaction force in Newton; (F_x) horizontal force in Newton; (F_y) vertical force in Newton; (m) mass of the gymnast in kilogram; (t_1) amortization period in second; (t_2) time of pushing in second; (V_1) initial horizontal velocity "beginning of the amortization phase" in meter per second; (V_2) final horizontal velocity "end of the pushing phase" in meter per second; (V_3) final vertical velocity "end of the pushing phase" in meter per second.

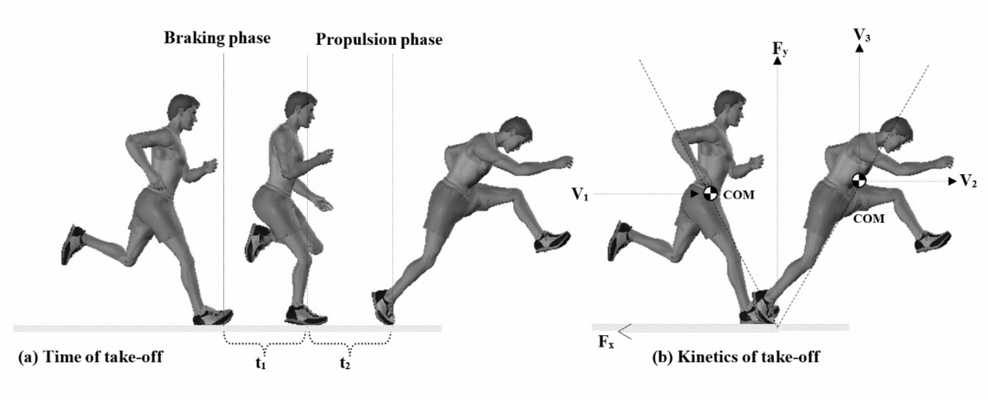

Fig. 2: Calculating method related to Smith (1983).

(COM) centre of mass; (F_x) horizontal force in Newton; (F_y) vertical force in Newton; (t_1) amortization period in seconds; (t_2) time of pushing in second; (V_1) initial horizontal velocity "beginning of the amortization phase" in meter per second; (V_2) final horizontal velocity "end of the pushing phase" in meter per second; (V_3) final vertical velocity "end of the pushing phase" in meter per second.

Three phases of clearance were analysed as follow: The take-off (i.e., the last braking and propulsion acts before the hurdle), the flight (i.e., the flying time/clearance above the hurdle) and the landing (i.e., the first braking and propulsion acts after the hurdle) phases.

The measurements were carried out on an outdoor athletic track. After 20-min of general and specific warm up (i.e., 10-min light jogging followed by 10-min specific hurdle technical skills), each athlete cleared 110-m hurdles twice from starting blocks. The between-repetition resting time was 1 h (Smirniotou, Katsikas, Paradisis, Argeitaki, Zacharogiannis, & Tziortzis, 2008). The hurdles' height (1.067-m) and intervals (9.14-m) were the same as an authentic competition. The best performance was retained for statistical analyses. The environmental conditions recorded during the experience were 25°C for temperature and w = 0.10 $m \cdot s^{-1}$ for wind velocity.

Statistical analysis

Data were reported as mean ± standard deviation (SD) and confidence intervals at 95% level (95% CI). Effect size (*d*) was calculated using GPOWER software "Bonn FRG, Bonn University, Department of Psychology" (Erdfelder, Faul, & Buchner, 1996). The following scale was used to interpret *d*: < 0.2, (trivial); 0.2 – 0.6, (small); 0.6 – 1.2, (moderate); 1.2 – 2.0, (large); and > 2.0, (very large) (Hopkins, 2002). Data were tested for normal distribution using Shapiro-Wilk's test. A paired sample t test was computed to assess any systematic bias in the body inverse dynamics calculation in the take-off phase between the two 110-m hurdle race performances. Pearson's correlation was used to determine relationships between races. The coefficient of determination (R^2) was calculated to determine the amount of explained variance between the two repetitions. Relative reliability of body inverse dynamics analyses was determined by calculating the intra-class correlation coefficient ($ICC_{1,3}$). We considered an ICC below 0.50 as poor, between 0.50 and 0.75 as moderate, between 0.75 and 0.90 as good, and > 0.90 as excellent (Koo & Li, 2016). Absolute reliability was analysed through the typical error of measurement (TEM). It was calculated by dividing the SD of the difference between scores by $\sqrt{2}$ (Hopkins, 2000) and expressed as coefficient of variation. Therefore, the outcomes of the motion tracking were introduced in an analysis of principal components (PCA) with the purpose of identifying the most representative factors of the total variables analysed according to each hurdle clearance phase (i.e., take-off, flight, and landing phases). The factorial analysis began by the calculation of the correlation matrix between kinetic and kinematic variables assessed with coefficient of determination (R^2). This matrix was submitted for the extraction of main components, followed by varimax rotation (Osborne & Costello, 2009). The factors were retained only if it is composed by two or more variables. Moreover, the first factor should be concentrated the greatest part of the tests with factorial weight above 0.80, cutting point adopted for the definition of the connection force between kinetic and kinematic variables (Ihalainen, Kuitunen, Mononen, & Linnamo, 2016;

Osborne & Costello, 2009). Stepwise regression was conducted between performance (i.e., best time in 110-m hurdles) and key factors retained from PCA. The significance level was set at $p \leq .05$. Data analyses were carried out using IBM SPSS Statistics Version 20 [IBM Corp., Armonk, New York, USA].

Results

Reliability outcomes of body inverse dynamics calculation using Smith's equation (Smith, 1983) is displayed in Table 1. The difference between the two race repetitions (i.e., 110-m hurdle clearance) was not statistically significant ($p > 0.05$). The dynamic variables measured by body inverse dynamics showed high absolute and relative reliability level (ICC > 0.90, TEM < 5%,).

Table 1. Short-term reproducibility of body inverse dynamics calculating at the take-off phase

	T-test (*p*)	ICC $_{(95\%)}$	TEM	TEM (%)	Cohen ***d***
Fx_{COM} (N)	0.581	0.982 (0.875-0.991)	6.58	0.296	$0.04^{‡}$
Fy_{COM} (N)	0.897	0.994 (0.959-0.997)	3.41	0.154	$0.01^{‡}$
Ft_{COM} (N)	0.699	0.987 (0.909-0.994)	6.89	0.219	$0.03^{‡}$
Px_{COM} (W)	0.291	0.996 (0.969-0.998)	9.95	0.059	$0.04^{‡}$
Py_{COM} (W)	0.309	0.998 (0.983-0.999)	2.73	0.058	$0.03^{‡}$
Pt_{COM} (W)	0.574	0.928 (0.881-0.986)	296.92	1.701	$0.10^{‡}$

(COM) centre of mass; (Fx) Horizontal reaction force; (Fy) vertical reaction force; (Ft) resultant of reaction force; (Px) horizontal peak power; (Py) vertical peak power; (Pt) resultant of peak power; (ICC) intra-class correlation coefficient; (TEM) typical error of measurement; (*d*) effect size; (‡) trivial effect size.

Overall, seventy-six variables (i.e., twenty-seven at take-off, twenty-two at flight-phase, and twenty-seven at landing) were analysed and factorized using the PCA (Table 2). Six factors (i.e., horizontal velocity, vertical velocity, horizontal displacement, vertical reaction force, vertical power, and vertical displacement) were retained for interpretation of the ratios between variables at the take-off (Table 3) and flight phases (Table 4). For the landing phase, seven factors were kept (Table 5) (Eigen values > 1.0). Moreover, after adopting 0.80 minimum correlation threshold, a total of twenty variables (e.g., the COM vertical and horizontal velocity, the vertical and horizontal velocity of knee and ankle, the vertical and horizontal displacement of COM in all phases, the take-off and landing angle, the contact-time, the vertical force and power at take-off and landing) were considered as key factors (figure 3).The outcomes summary of the step-wise multiple regressions analyses between the dependent variables (i.e., performance in 110-m hurdles) and the independent ones (i.e., key kinetic and kinematic factors) are shown in Table 6.

The equation generated by the regression model for performance prediction was calculated as follow (equation 2).

Equation 2.

$$\text{Perf.} = 17.922 - 0.001 \times Fy_{\text{COM at take-off}} - 0.881 \times Vx_{\text{ankle at landing}} \quad (2)$$

(Perf.) Performance in 110-m hurdles; ($Fy_{\text{COM at take-off}}$) vertical reaction force at take-off; (Vx) horizontal velocity of the trail-leg at landing.

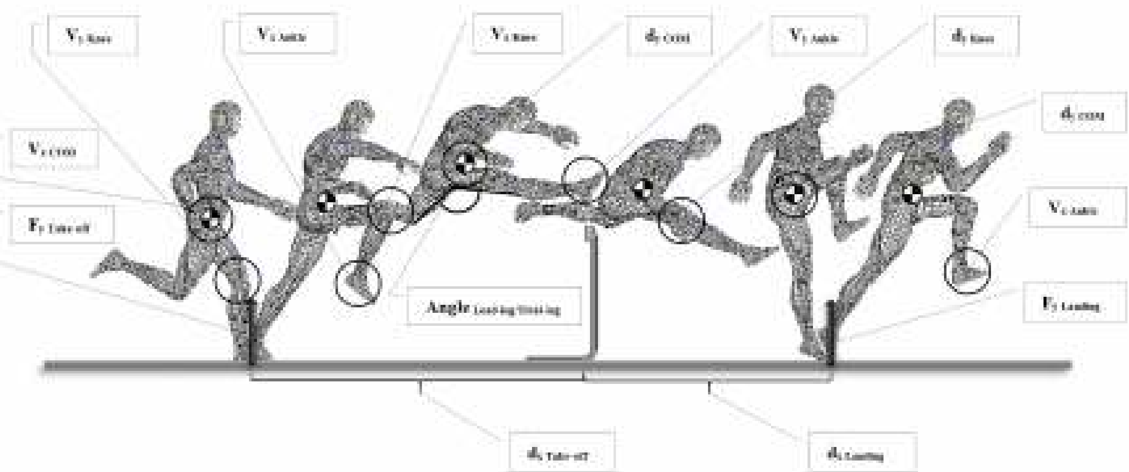

Fig. 3: Key factors of hurdle clearance.

Table 2. Descriptive statistics of the variables studied in take-off, flight, and landing phases

Variables	Take-off phase (Mean ± SD)	CV	Flight phase (Mean ± SD)	CV	Landing phase (Mean ± SD)	CV
Braking Angle (°)	62.02±1.17	0.04	---	---	76.49±1.80	0.04
Propulsion Angle (°)	68.04±2.51	0.04	---	---	63.76±1.32	0.04
Angle Knee Lead Leg (°)	96.05±2.41	0.13**	114.50±2.93	0.12**	143.48±2.44	0.06*
Angle Knee Trail Leg (°)	154.15±1.97	0.06*	30.87±2.26	0.17**	120.61±1.96	0.10**
Angle Hip Lead Leg (°)	93.84±4.20	0.18**	68.01±2.36	0.20**	176.18±3.88	0.07**
Angle Hip Trail Leg (°)	160.94±2.34	0.09**	45.24±2.43	0.23**	110.37±3.61	0.10**
Angle Lead Leg/Trail Leg (°)	---	---	88.49±3.53	0.17**	---	---
Vx COM ($m \cdot s^{-1}$)	7.41±0.29	0.07*	7.42±0.24	0.07**	7.27±0.19	0.07**
Vy COM ($m \cdot s^{-1}$)	2.08±0.03	0.10**	1.94±0.04	0.10**	1.61±0.08	0.18**
Vx Ankle Lead Leg ($m \cdot s^{-1}$)	16.64±0.50	0.10**	6.40±0.22	0.08**	0.56±0.09	0.36**
Vy Ankle Lead Leg ($m \cdot s^{-1}$)	2.94±0.61	0.45**	1.52±0.11	0.20**	3.17±0.30	0.23**
Vx Ankle Trail Leg ($m \cdot s^{-1}$)	3.72±0.26	0.23**	9.42±0.33	0.07**	13.25±0.37	0.10**
Vy Ankle Trail Leg ($m \cdot s^{-1}$)	4.75±0.32	0.07*	1.71±0.10	0.17**	3.80±0.24	0.21**
Vx Knee Lead Leg ($m \cdot s^{-1}$)	7.04±0.29	0.10**	6.50±0.22	0.07**	4.46±0.22	0.14**
Vy Knee Lead Leg ($m \cdot s^{-1}$)	3.92±0.30	0.29**	2.77±0.14	0.32**	2.59±0.20	0.04
Vx Knee Trail Leg ($m \cdot s^{-1}$)	5.10±0.76	0.23**	8.98±0.29	0.07**	9.12±0.36	0.08**
Vy Knee Trail Leg ($m \cdot s^{-1}$)	2.37±0.46	0.03	1.98±0.07	0.15**	2.19±0.22	0.18**
dx Hurdle (m)	1.87±0.11	0.07**	3.25±0.08	0.08**	1.37±0.14	0.11**
dx $COM/_{\text{Hurdle at Braking}}$ (m)	2.29±0.11	0.07**	---	---	1.13±0.15	0.15**
dx $COM/_{\text{Hurdle at Propulsion}}$ (m)	1.42±0.10	0.11**	---	---	1.87±0.16	0.09**
dy COM (m)	---	---	1.46±0.01	0.05*	---	---
dy COM at Braking (m)	1.08±0.01	0.07**	---	---	1.26±0.01	0.06**
dy COM at Propulsion (m)	1.25±0.01	0.06*	---	---	1.17±0.01	0.06**
dy Ankle Lead Leg (m)	---	---	1.19±0.02	0.06**	---	---
dy Ankle Trail Leg (m)	---	---	1.22±0.01	0.06**	---	---
dy Knee Lead Leg (m)	1.11±0.02	0.07**	1.34±0.01	0.06**	---	---
dy Knee Trail Leg (m)	---	---	1.42±0.02	0.07**	0.95±0.03	0.08**
Contact time (s)	0.12±0.01	0.07**	---	---	0.10±0.01	0.11**
Time of Clearance (s)	---		0.33±0.01	0.07**	---	---
Fx COM (N)	2220.11±199.30	0.03	---	---	731.43±94.32	0.04
Fy COM (N)	2218.08±297.97	0.04	---	---	1614.03±111.12	0.25**
Ft COM (N)	3157.32±283.57	0.04	---	---	1824.17±118.31	0.15**
Px COM (W)	16845.87±778.19	0.03	---	---	16328.72±942.40	0.05
Py COM (W)	4677.08±652.48	0.04	---	---	1374.01±164.67	0.20**
Pt COM (W)	17362.83±925.01	0.04	---	---	16368.76±764.66	0.25**

(COM) centre of mass; (Vx) horizontal velocity; (Vy) vertical velocity; (dx) horizontal displacement; (dy) vertical displacement; (Fx) Horizontal reaction force; (Fy) vertical reaction force; (Ft) resultant of reaction force; (Px) horizontal peak power; (Py) vertical peak power; (Pt) resultant of peak power; (*) Significant variation between the ten hurdles at $p < 0.05$; (**) Significant variation between the ten hurdles at $p < 0.001$.

Table 3. Take-off phase: Factor Loadings (varimax) – analysis of main components

Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Vx Ankle Lead Leg	**.95**	.08	.10	.03	.02	.25
Vx COM	**.92**	.17	-.21	.12	.24	.01
Braking Angle	**.88**	.27	.15	-.23	-.03	.16
Px COM	**.86**	-.19	.02	.40	.24	-.07
Vx Ankle Trail Leg	**.86**	.21	-.34	.29	.09	-.08
Vx Knee Lead Leg	**.85**	.28	-.30	-.06	-.14	.00
Fx COM	.77	-.31	.21	.43	.18	-.15
Vy Knee Trail Leg	.03	**.97**	-.16	-.09	.12	-.04
Vx Knee Trail Leg	.36	**.87**	-.14	.09	.22	-.17
Vy Knee Lead Leg	-.24	**.84**	-.23	-.07	-.38	.04
Vy Ankle Trail Leg	.36	**.83**	-.07	.15	.35	.07
Angle Hip Lead Leg	-.39	-.74	.50	-.08	-.19	-.03
dy Knee Lead Leg	.10	.62	-.39	.46	.44	-.04
Fy COM	-.01	-.26	**.94**	-.11	.09	-.06
Py COM	-.02	-.24	**.94**	-.13	.09	-.15
Angle Knee Trail Leg	-.06	-.43	**.81**	.31	-.07	.04
Vy Ankle Lead Leg	.06	-.41	-.71	.28	.41	.11
Propulsion Angle	-.33	-.15	.62	-.21	-.03	-.52
dx COM/Hurdle at Propulsion	.00	-.08	-.15	**.94**	.18	.17
dx Toe/Hurdle	.21	.02	-.13	**.93**	.18	.09
dx COM/Hurdle at Braking	.18	.17	.04	**.90**	.27	.05
Angle Knee Lead Leg	.10	.18	-.04	.11	**.90**	.10
Contact time	-.26	.10	-.12	-.24	**-**.79	.43
dy COM at Propulsion	.08	.37	.09	.45	.71	.08
dy COM at Braking	-.11	.18	-.30	.44	.65	.37
Vy COM	-.08	.07	.41	-.15	-.13	**-.84**
Angle Hip Trail Leg	.10	-.29	.46	.46	-.14	.66
Eigen value	**9.16**	**9.33**	**8.59**	**8.16**	**7.28**	**4.82**
% accumulated variance	**22.56**	**41.90**	**59.25**	**75.10**	**87.95**	**95.36**

(COM) center of mass; (Vx) horizontal velocity; (Vy) vertical velocity; (dx) horizontal displacement; (dy) vertical displacement; (Fx) Horizontal reaction force; (Fy) vertical reaction force; (Px) horizontal peak power; (Py) vertical peak power.

Dicussion

Previous investigations have focused on one and/or maximum three hurdles, along with either kinetic or kinematic analysis. Therefore, the current study can be considered unique in that it examined both kinetic and kinematic variables of the entire 110-m sprint hurdling performance.

Findings of this study showed that a greater horizontal velocity, an optimal ratio between take-off and landing distance in horizontal displacement, a better power and vertical reaction force, and a small vertical displacement are the major determinant factors to drive achieving high 110-m hurdles clearance performance level.

Results indicated that body inverse dynamics calculation using Smith's equation (Smith, 1983) showed high absolute and relative reliability level. The PCA outcomes generated six independent components that explained 94.96% of the total variance of all selected variables. These components are the horizontal velocity (22.74 %), the vertical reaction force (17.35 %), the horizontal displacement (16.25 %), the vertical displacement (13.42%), the vertical power (13.31 %), and the vertical velocity (11.89%). When applied for the take-off phase, results of the PCA extracted four independent components altogether explaining 75.10% of the total variance of all variables. These components are the horizontal velocity (22.56 %), the vertical velocity (19.34 %), the vertical reaction force and power (17.35 %), and the horizontal displacement (15.85 %). In terms of clearance phase, four independent components were retained explaining 76.59 % of the total variance of all selected variables. These components are the horizontal velocity (30.61 %), the vertical displacement (20.98 %), the COM vertical velocity (15.03 %), and the trail-leg vertical velocity (9.97 %). As to the landing phase, four independent components were retained for the landing phase which are the vertical displacement (19.30 %), the horizontal displacement (16.95 %), the horizontal velocity (14.25 %), and the vertical force and power (13.31 %). Together, these components exaplined63.81 % of the total variance.

Table 4. Flight phase: Factor Loadings (varimax) – analysis of main components

Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Vx Knee Lead Leg	**.94**	.02	-.05	.21	.23	.01
Vx COM	**.93**	.07	-.07	.21	.22	.12
dx Clearance	**-.90**	.25	.15	.18	.11	.11
Vx Ankle Trail Leg	**.90**	.28	.00	.21	.24	.10
Vx Knee Trail Leg	**.88**	.06	-.08	.26	.30	.14
Angle Lead Leg/Trail Leg	**.86**	.07	-.20	-.30	-.24	-.10
Vx Ankle Lead Leg	**.85**	-.17	.32	.03	.34	.10
dy Knee Trail Leg	.07	**.98**	-.04	-.11	-.10	-.01
dy Knee Lead Leg	-.14	**.87**	-.10	.30	.02	-.32
dy COM	-.32	**.83**	-.09	-.09	.09	-.02
dy Ankle Lead Leg	.49	.76	-.11	-.09	.26	-.15
Ang Hip Trail Leg	-.26	-.74	-.07	.12	.15	-.51
Vy Knee Lead Leg	-.03	-.10	**.89**	-.34	-.05	.19
Angle Knee Lead Leg	-.19	-.13	**-.82**	.36	-.26	.24
Angle Knee Trail Leg	-.41	-.03	.75	.26	-.28	-.05
dy Ankle Trail Leg	-.06	.56	-.70	-.32	.18	-.03
Angle Hip Lead Leg	-.32	-.28	.63	-.19	.09	.49
Vy COM	-.15	.20	.15	**-.90**	.08	-.05
Vy Ankle Lead Leg	.42	.54	-.24	.64	.08	.03
Vy Ankle Trail Leg	.33	-.17	-.27	.08	**.83**	.14
Vy Knee Trail Leg	.27	.29	.17	-.20	**.81**	.24
Time of Clearance	.10	-.12	.01	.13	.31	**.86**
Eigen value	**9.82**	**7.53**	**5.91**	**5.52**	**5.27**	**4.01**
% accumulated variance	**30.61**	**51.59**	**66.62**	**76.59**	**86.55**	**93.88**

(COM) center of mass; (Vx) horizontal velocity; (Vy) vertical velocity; (dx) horizontal displacement; (dy) vertical displacement; (Fx) Horizontal reaction force; (Fy) vertical reaction force; (Px) horizontal peak power; (Py) vertical peak power.

Moreover, by adopting 0.80 mean threshold of correlation (Ihalainen et al., 2016; Osborne & Costello, 2009), twenty variables were retained from the hurdles analysis as the most important factors determining 110-m hurdling performance. The most important factor was the horizontal velocity of the COM and the lead-leg/trail-leg in all phases (i.e., take-off, flight and landing phases). In this context, Shibayama, Fujii, Shimizu, and Ae (2008) showed that maintaining high horizontal velocity during hurdling seems to be one of the main factors in sprint hurdles. As a result, it is highly recommended to work on curtailing the loss of horizontal velocity while clearing the hurdle (Coh, 2004; Coh & Iskra, 2012).

In addition, results of the present study demonstrated that the vertical component of COM velocity and the lead-leg/trail-leg at take-off and at flight phase constituted key factors of optimum hurdle clearance. Coh and Iskra (2012) revealed that the take-off ensures an opposite transformation of the horizontal velocity of the COM into vertical velocity, the causal relationship between these two parameters is due to the change of COM direction of the movement at take-off. Generally, when running velocity increases all clearance actions happen quicker (Salo, 2002).

Outcomes showed that the horizontal displacement of COM before, during, and after clearing is a crucial factor for hurdling performance success. This is in line with Coh et al. (2004) who reported that the distance of the take-off and the landing are crucial for an efficient hurdle clearance. Previously published studies revealed that the optimal ratio between the take-off and the landing point is 60:40 (LaFortune, 1988; McLean, 1994; Salo & Grimshaw, 1998) which is comparable with the current findings (i.e., 58:42). In fact, the consequence of a correct position of these two points is a prerequisite for an optimal COM trajectory and a short duration of the flight phase. This ascertainment was strengthened by the present results showing that the vertical displacement of the COM, the vertical displacement of lead-leg/trail-leg, and the flight-time at clearance are the most decisive factors for an efficient hurdle. The take-off angle as well as the knee and the hip angle may also be regarded as influential factors in hurdle clearance (Shibayama, Fujii, Shimizu, & Ae, 2012). Previous studies demonstrated that the position of the COM over the hurdle and the flight-phase duration are defined by the take-off angle (Coh et al., 2004; Sidhu & Singh, 2015; Xu et al., 2005), indeed a lower angle is better. In addition, Salo (2002) showed that if the lead-leg knee angle during the take-off is slight, the lead-leg can be swung quicker forward and can better benefit of its elastic power at landing.

Table 5. Landing phase: Factor Loadings (varimax) – analysis of main components

Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
dy COM at Braking	**-.96**	-.04	.11	.09	.13	.15	.06
dy COM at Propulsion	**-.95**	-.18	.11	-.07	-.06	.11	-.06
dy Knee Trail Leg	**-.81**	-.23	.18	-.11	-.09	.21	-.40
Vy COM	.74	.27	.01	-.26	.42	.01	.22
Fx COM	.58	.26	-.01	.51	.07	.41	-.35
Braking Angle	.58	-.23	-.36	.20	.50	.28	-.10
dx Hurdle/Toe	.24	**.92**	-.21	.11	.08	-.11	.09
dx COM/Hurdle at Propulsion	.24	**.92**	-.18	.17	.09	-.03	.15
dx COM/Hurdle at Braking	.15	**.91**	-.28	.24	-.04	-.07	.02
Px COM	.12	-.67	.37	-.26	.37	.36	.04
Vx Knee Lead Leg	.03	.00	**.94**	-.01	.17	-.28	-.07
Vx Ankle Trail Leg	-.05	-.40	**.86**	.11	.06	.00	.08
Vx COM	-.33	-.34	**.81**	-.14	-.11	.11	-.18
Vx Knee Trail Leg	-.44	-.36	.77	-.08	-.06	.21	-.01
Fy COM	-.07	.12	-.06	**.93**	-.01	-.07	-.15
Py COM	.09	.26	-.06	**.89**	.13	.02	.16
Vy Ankle Lead Leg	.19	-.19	.24	-.15	**.88**	.10	.12
Vy Ankle Trail Leg	.13	-.29	-.09	-.50	-.75	.12	-.10
Contact time	-.56	-.05	.29	-.47	-.60	.13	-.06
Angle Hip Lead Leg	-.11	-.15	.19	.38	-.06	**.84**	.08
Vx Ankle Lead Leg	.31	.21	.22	.50	-.12	-.72	.07
Angle Knee Lead Leg	-.07	-.41	.00	-.33	-.43	.66	-.17
Angle Knee Trail Leg	.35	-.37	.30	.16	-.13	-.65	.42
Vy Knee Lead Leg	.38	-.39	-.33	-.44	.18	.50	-.03
Angle Hip Trail Leg	.33	.19	.00	.10	.02	.02	**.91**
Propulsion Angle	-.02	.34	-.23	-.02	.56	-.21	.67
Vy Knee Trail Leg	.41	.21	.06	.35	-.43	.09	-.65
Eigen value	**9.26**	**8.92**	**7.29**	**7.56**	**6.53**	**6.49**	**5.43**
% accumulated variance	**19.30**	**36.25**	**50.50**	**63.81**	**75.35**	**86.66**	**95.64**

(COM) center of mass; (Vx) horizontal velocity; (Vy) vertical velocity; (dx) horizontal displacement; (dy) vertical displacement; (Fx) Horizontal reaction force; (Fy) vertical reaction force; (Px) horizontal peak power; (Py) vertical peak power.

Table 6. Summary of the multiple regression between performance and key factors

Regression	R^2	B	Standard Error	Beta	t	Sig.
Constant		17.922	.198		9.332	.001
Fy COM at Take-off	.939	-.001	.000	-.912	-15.396	.001
Vx Ankle Lead Leg at Landing	.977	-.881	.257	-.203	-3.431	.01

Dependent variable: Performance, r = .989, R^2 = .977, estimated standard error (ESE) = .069, Cohen's f^2 = 1.65, $p < .01$; (Fy) vertical reaction force; (Vx) horizontal velocity.

Our findings indicated that the vertical force and power at take-off and at landing would be considered important factors to improve the 110-m hurdling performance. McLean (1994) revealed that the vertical component of the ground reaction force in landing represents a controlled lowering of the COM. In addition, Coh et al. (2004) reported that the braking time of the take-off phase should be as short as possible in order to sustain the horizontal velocity of the COM. In addition, Lopèz et al. (2011) showed that with an elevated ground reaction force, the hurdler could ensure a shorter ground contact time which is considered very important in hurdling process.

Salo (2002) showed that the best athlete is the one who can manage to perform rapid shift between horizontal and vertical velocity, in order to present a swifter attack, shorter clearance time, and accelerate the progression of the lead-leg before and after the hurdle. This quick shifting is related to the dynamic parameters (i.e., horizontal and vertical force) at take-off and at landing (Salo, 2002).

To determine the relationship between variables emerged from the PCA with the temporal performance recorded in the 110-m hurdles, a step-wise multiple regression analysis was used. The main results highlighted two key performance factors namely the vertical component of the force during the take-off (R^2 = 0.939; $p <$ 0.001) and the horizontal velocity of the lead-leg ankle at landing (R^2 = 0.977; $p < 0.01$) with $F_{(2, 7)} = 150.82$, $p <$ 0.001, ES = 1.65, (equation 2). Results of the regression study are in accordance with those of Sibayama et al. (2011) who showed that the decrease in the athletes' power performance induces a reduction in the horizontal velocity during the race. These facts could cause an increase in braking time and a subsequent deceleration of the first stride after the clearance.

This study has some limitations that need to be acknowledged. First, an integrated force plate into the track was not used. Second, an analysis of the inter-hurdle's interval was not performed. This has to be considered in future studies.

Conclusions

Results of the current study showed that six components and twenty variables were retained and considered as key factors in 110-m hurdle clearance. Among the key factors: (a) the horizontal velocity of the COM and lead-leg/trail-leg in all phases (i.e., take-off, flight and landing), (b) the vertical velocity of the COM and lead-leg/trail-leg at take-off and at flight phase, (c) the horizontal and vertical displacement of the COM, (d) the vertical displacement of the lead-leg/trail-leg and the flight-time at clearance, (e) the take-off angle, the knee angle in front of the hurdle and the hip angle at landing, and (f) the vertical component of force and power at take-off and at landing. In addition, outcomes of the regression analysis showed that some variables (i.e., lead-leg horizontal velocity, trail-leg vertical velocity, COM vertical and horizontal displacement) were force-velocity dependent. To sum-up, the study's hypothesis was confirmed in that greater velocity, lower vertical displacement at flight phase and lower contact-time at the take-off phase through a higher rate of force development are needed to improve 110-m hurdling performance. From a practical perspective, to optimise hurdling clearance performance, a quick shift between horizontal and vertical velocity has to be achieved. This can be done by minimising vertical displacement and clearance time over the hurdle. Further, high rate of force development is required to ensure shorter contact time at take-off phase. Moreover, a fast return of the trail leg at landing is crucial to achieve fast race recovery between hurdles. Future studies could analyse the 110-m hurdles per block of obstacles (i.e., from the 1st to the 4rd, the 5th to the 7th and the 8th to the 10th hurdles) following the phases of the race (i.e., acceleration, constant speed and deceleration).

Conflicts of interest

Authors declare no conflict of interest.

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