

Biomechanical determinants of elite high jump performance in Egypt: Part 1 - analysis of kinematic variables and performance

IBRAHIM I. ATTA¹, ABDULMALEK K BURSAIS², MOHAMMED S. ALIBRAHIM³, ANWAR AL-NUAIM⁴
^{1,2,3,4}Department of Physical Education, College of Education, King Faisal University, Al-Ahsa 31982, SAUDI ARABIA

Published online: November 30, 2024

Accepted for publication: November 15, 2024

DOI:10.7752/jpes.2024.11290

Abstract

This study extends previous research by examining the biomechanical factors influencing the performance of elite high jumpers during a 2020 competition. The study involved 16 athletes (mean height: 1.98 m, mean weight: 87 kg, mean age: 30 years). Biomechanical analysis was performed using six GoPro Hero 6 cameras set at 120 frames per second, capturing 48 jump attempts (three attempts per athlete). The three-dimensional biomechanical analysis program Skillspector was used to measure biomechanical variables, temporal analysis parameters, and moment variables, including the moments of takeoff initiation, maximum knee flexion of the takeoff leg, takeoff completion, flight initiation, and maximum body height during flight. Results. There were inverse relationships between height achieved and the braking time and the angle of the knee joint of the free leg at the takeoff, and direct relationships between height achieved and the vertical momentum and vertical kinetic energy of the body's center of gravity. Conclusions. Increasing the vertical kinetic energy at the beginning of takeoff would increase the lift force.

Keywords: biomechanics, performance, analysis, high jump, three-dimension

Introduction.

Implementing ideal biomechanics determines the success of an athlete's performance. The most important factors affecting performance and achievement level are the mechanical aspects that can be practiced during an athlete's training. Applying proper technique requires considering several aspects of biomechanics when training, including regularity in the process of teaching technique and the individual abilities of the athlete. This requires identifying the main performance variables and applying them during certain stages of the athlete's training (Leite, 2013; Dapena, 1992). The precision of mechanical energy transfer through the limbs is important, as it is the key to performance in the high jump. Therefore, analyzing the patterns of movement and the characteristics of the athlete's position and movements is essential for improvement (Schiffer, 2012; Dobbs et al., 2015).

The high jump consists of four technical stages. The first is the approach stage, where the jumper aims to reach the maximum speed that can be controlled while preparing for the takeoff stage. The takeoff phase, which represents the most important part of the high jump, aims to generate maximum vertical velocity. The third stage comprises the flight phase and clearing the crossbar. The final phase is the landing phase (Leite, 2013; Schiffer, 2012). High jumpers run in a curve during the approach, and the number of approach steps for elite high jumpers ranges from 10 to 12. The jumper completes the first part of the approach in a straight line, while the second part entails four to five steps in a curve with a radius of roughly 8 to 12 meters (Schiffer, 2012; Sado et al., 2020). The interval between the time when the takeoff leg contacts the ground and when it loses contact is the takeoff stage. The takeoff time ranges from 0.14 to 0.18 seconds. This stage is divided into the "beginning takeoff stage" and the "end takeoff stage." The beginning stage of the takeoff starts when the leg first contacts the ground and lasts until the knee joint reaches its maximum flexion. The end stage begins when the knee joint reaches its maximum flexion and lasts until the leg leaves the ground (Leite, 2013; Milan, 2010; Adashevskiy et al., 2013). The change from horizontal speed to vertical speed of the body's center of gravity during the beginning phase of the takeoff is directly related to the height of the jumper's center of gravity. The variable vertical speed of the body's center of gravity during the end of the takeoff is the determining factor for the height of the jump (Van Caekenberghe et al., 2021; Agar-Newman et al., 2015). After completing the takeoff stage, the parabolic path of the body's center of gravity is determined, and it cannot be changed by the jumper. This does not mean that the paths of the torso and limbs of the athlete's body have been determined during the flight phase. Rather, what cannot be changed is the point of the body's center of gravity, as this represents the average position of the joints and limbs of the competitor's body (Nicholson et al., 2019; Van Caekenberghe et al., 2021; Panoutsakopoulos et al., 2012). The flight phase is next in terms of importance in the high jump after the approach and takeoff, as most of the problems of clearing the crossbar arise due to suboptimal mechanics during the approach and takeoff phases (Dapena et al., 2006; Nicholson et al., 2022).

High jump results are determined to a large extent by the biomechanical characteristics of the athlete, including running speed, lift velocity, the angle of elevation of the body's center of gravity, the position of the body's center of gravity at the moment of leaving the ground, and the highest position of the center of gravity of the body while crossing the bar (Kim et al., 2015). In addition, the aforementioned factors related to the high jump must be identified, and the development and application of jump patterns are central issues in high jump training (Milan, 2010; Goldmann et al., 2015). At present, there is a dearth of studies related to identifying the most important biomechanical characteristics affecting the improvement in the high jump. This situation prompted the present study that was carried out during the Republic Championships in the Arab Republic of Egypt. The goal of the study was to determine the most important biomechanical indicators affecting the high jump for use in directing training programs and examining the biomechanics of the competitors (Schiffer, 2012; Rao et al., 2014; Dapena, 1992).

Materials and Methods

Participants

The study was conducted on elite athletes during the 2020 season at the Republic Championship. Sixteen athletes, each making three attempts, were filmed using 3D photography using six GoPro Hero 6 cameras set to a frequency of 120 frames/second. Basic and anthropometric measurements were taken for the competitors, where the mean height was 1.98 meters; the mean weight was 87 kg, and the average age was 30 years. The filming was done after the athletes had been informed of the research and goals and had given their approval. In addition, the study had the approval of the Egyptian Athletics Federation, and scientific research ethics approval was obtained from King Faisal University following the Helsinki Agreement (World Medical Association, 2013).

Procedures

The competitors were photographed using six cameras for three-dimensional analysis. Performance was examined by identifying and measuring biomechanical variables (kinetic and kinematic) throughout the various performance stages.

Measures

The study was conducted on elite high jumpers during the Republic Championships in 2020. Sixteen competitors were filmed during each of three attempts, for a total of 48 records. The 3D photography employed six GoPro Hero 6 cameras set to a frequency of 120 frames/second and positioned at a height of 120 cm. The scale of measurement was obtained from a three-dimensional drawing with dimensions of 1×1×1 meters where the jumpers were photographed (Fig. 1). The three-dimensional biomechanical analysis was performed using the motion analysis program Skillspector. The data were processed using SPSS version 26 for Windows. Statistical analyses were performed to calculate the correlations among the biomechanical variables affecting the level of achievement in the high jump.

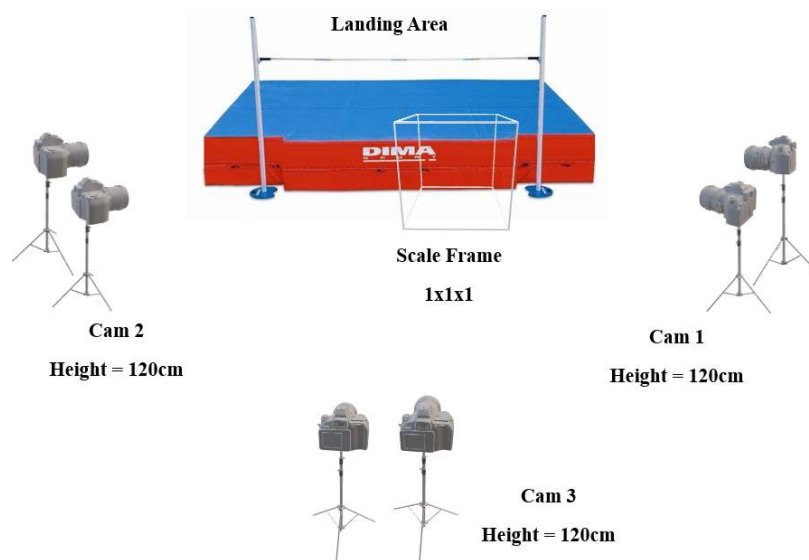


Figure 1. The positions of the cameras, a scale drawing, and a three-dimensional analysis of the performance of high jumpers during competition.

Statistical analysis

Means and standard deviations were calculated for each of the biomechanical variables (moments of the beginning of the take-off, maximum knee flexion of the take-off leg, end of take-off, start of flight, and maximum height of the body during flight).

Correlation coefficients were calculated to analyze the associations between the biomechanical variables, temporal analysis variables, and the moment variables listed above. Statistical analyses were performed with SPSS (version 26 for Windows; SPSS Inc., Chicago, IL, USA). The data are presented as mean $\pm$ standard deviation (SD).

Results

The temporal analysis of the performance stages, general biomechanical variables, and their correlation with the level of effectiveness and performance achievement of the high jump are presented in Table 1. The results of the biomechanical variables for the basic and additional forces and the body's center of gravity for the different performance stages are shown in Table 2. The correlations among the biomechanical variables of performance moments with the jumping heights are presented in Table 3.

Table 1. The mean, standard deviation, and correlation coefficients for the biomechanical variables and the time analysis of performance stages (n=48).

variables	m	SD	R
1 Achievement (m)	1.94	0.06	1
2 Speed of the body's COG (end of take-off) (m/s)	3.11	0.57	0.205
3 The angle of flight of the body's COG (degree)	59	3.20	.609*
4 Height of the body's COG (end of take-off) (m)	1.45	0.08	-0.293
5 Horizontal braking distance (m)	0.11	0.09	-.643*
6 Vertical braking distance (m)	0.09	0.09	0.137
7 net braking distance (m)	0.16	0.10	-0.335
8 Horizontal push distance (m)	0.26	0.09	-0.215
9 Vertical push distance (m)	0.33	0.11	0.017
10 Net push distance (m)	0.42	0.14	-0.071
11 The distance from the fourth to the last step (m)	1.35	0.12	-0.327
12 The distance from the third to the last step (m)	1.32	0.10	0.156
13 The distance from the second to the last step (m)	1.48	0.14	-0.185
14 The distance of the last step (m)	1.56	0.34	0.419
15 Average speed of the fourth-to-last step (m/s)	5.05	0.54	-0.249
16 Average speed of the third to last step (m/s)	5.51	0.69	-0.360
17 Average speed of the second to last step (m/s)	5.37	0.43	-0.351
18 Average speed of the last step (m/s)	7.54	2.07	0.094
19 The time of take-off of the fourth to last step (S)	0.17	0.01	0.337
20 Flight time of the fourth to last step (S)	0.10	0.01	-0.251
21 The time of the fourth to last step (S)	0.27	0.02	0.106
22 the rhythmic coefficient of the fourth to last step (Numeric value)	1.67	0.28	0.338
23 The time of take-off of the third to last step (S)	0.16	0.03	0.324
24 Flight time of the third to last step (S)	0.08	0.01	0.216
25 The time of the third to last step (S)	0.24	0.04	0.333
26 The rhythmic coefficient of the third to last step (Numeric value)	1.94	0.36	0.235
27 The time of take-off of the second to last step (S)	0.15	0.02	0.436
28 Flight time of the second to last step (S)	0.12	0.02	-0.039
29 The time of the second to last step (S)	0.28	0.02	0.220
30 The rhythmic coefficient of the second to last step (Numeric value)	1.30	0.31	0.177
31 Time of take-off of the last step (S)	0.16	0.03	0.453
32 Flight time of the last step (S)	0.05	0.01	0.273
33 Time of the last step (S)	0.21	0.03	.506*
34 The rhythmic coefficient of the last step (Numeric value)	3.55	0.69	0.139
35 Braking time (S)	0.08	0.02	-.559*
36 push time (S)	0.10	0.02	0.122
37 take-off time (S)	0.18	0.02	-0.348
38 Rhythmic coefficient of take-off (Numeric value)	0.77	0.34	-0.420

*.Correlation is significant at the 0.05 level (2-tailed)

**.Correlation is significant at the 0.01 level (2-tailed)

There were significant negative correlations between the variables of the horizontal braking distance at takeoff, the braking time of takeoff, and the level of performance ($r = -0.643$ and -0.559 , respectively; $P < 0.05$). There were significant positive correlations between the angle of flight of the body's center of gravity, the time of the last step, and the level of performance ($r = .609$ and $.506$; $P < .05$).

Table 2. The means and standard deviations of the biomechanical variables and the body's center of gravity for each of the four stages of the high jump ($n = 48$).

variables		beginning of take-off		Maximum flexion of the ascending leg		End of take-off		flying start		Maximum altitude during flight	
		m	SD	m	SD	m	SD	m	SD	m	SD
1	Links	Horizontal speed of the free leg (m/s)									
2		Vertical speed of free leg (m/s)									
3		The net velocity of the free leg (m/s)									
4	Kinematics	Horizontal speed of the right arm (m/s)									
5		Vertical speed of the right arm (m/s)									
6		The net velocity of the right arm (m/s)									
7	Additional Defenses	Horizontal speed of the left arm (m/s)									
8		Vertical speed of the left arm (m/s)									
9		The net velocity of the left arm (m/s)									
10	angle	Ankle joint angle of the free leg (deg)									
11		Knee joint angle of the free leg (deg)									
12		Hip angle of the free leg (deg)									
13	thrust	Right shoulder joint angle (deg)									
14		Right elbow joint angle (deg)									
15		The angle of the right wrist joint (deg)									
16	Additional kinematics	Left shoulder joint angle (deg)									
17		Left elbow joint angle (deg)									
18		The angle of the left wrist joint (deg)									
19	Kinematics of basic thrust	Angular velocity of the hip joint of the free leg (Deg/s)									
20		Horizontal speed of the take-off leg (m/s)									
21		Vertical speed of the take-off (m/s)									
22	Kinematics of the body's center of gravity	The net velocity of the take-off leg (m/s)									
23		Ankle joint angle of the take-off leg (deg)									
24		Knee joint angle of the take-off leg (deg)									
25	Kinematics of thrust	Hip joint angle for the take-off leg (deg)									
26		Angular velocity of the knee joint of the take-off leg (Deg/s)									
27		Height of the body's COG (m)									
28	Kinematics of the body's center of gravity	The horizontal velocity of the body's COG (m/s)									
29		The vertical velocity of the body's COG (m/s)									
30		The net velocity of the body's COG (m/s)									
31	Kinematics of gravity	Horizontal acceleration of the body's COG (m/s ²)									
32		Vertical acceleration of the body's COG (m/s ²)									
33		The net acceleration of the body's COG (m/s ²)									
34	Kinetics of the body's center of gravity	The horizontal momentum of the body's COG (kg.m/s)									
35		The vertical momentum of the body's COG (kg.m/s)									
36		The net momentum of the body's COG (kg.m/s)									
37	Kinetics of gravity	The horizontal force of the body's COG (Newton)									
38		The vertical force of the body's COG (Newton)									
39		The net force of the body's COG (Newton)									
40	Kinetics of the body's center of gravity	The horizontal potential energy of the body's COG (Jules)									
41		The vertical potential energy of the body's COG (Jules)									
42		The net potential energy of the body's COG (Jules)									
43	Kinetics of the body's center of gravity	Horizontal kinetic energy of the body's COG (Jules)									
44		The vertical kinetic energy of the body's COG (Jules)									
45		The net kinetic energy of the body's COG (Jules)									

Note: COG: Center of gravity; M: mean; SD: standard deviation

Table 3. The correlations between biomechanical variables and the height achieved (n = 48).

variables		beginning of take-off	Maximum flexion of the ascending leg	End of take-off	flying start	Maximum altitude during flight
1	Links	Horizontal speed of the free leg (m/s)	-0.371	0.083	0.473	0.385
2		Vertical speed of free leg (m/s)	-0.320	-0.281	-0.056	-0.236
3		The net velocity of the free leg (m/s)	-0.400	-0.193	0.088	-0.131
4	Additional Defenses	Horizontal speed of the right arm (m/s)	0.255	0.225	-0.249	-0.114
5		Vertical speed of the right arm (m/s)	-0.057	-0.349	0.093	0.402
6		The net velocity of the right arm (m/s)	0.178	-0.268	-0.090	0.065
7	Kinematics	Horizontal speed of the left arm (m/s)	-0.412	-0.442	0.014	0.108
8		Vertical speed of the left arm (m/s)	-0.068	-0.442	0.201	0.289
9		The net velocity of the left arm (m/s)	-0.380	-.508*	0.190	0.308
10	angle	Ankle joint angle of the free leg (deg)	-0.288	-0.465	.525*	0.173
11		Knee joint angle of the free leg (deg)	-.536*	-.537*	-.574*	-.527*
12		Hip angle of the free leg (deg)	-0.157	-0.060	-.549*	-.639*
13	thrust	Right shoulder joint angle (deg)	0.096	0.119	0.120	0.324
14		Right elbow joint angle (deg)	-.546*	-0.015	-0.070	-0.011
15		The angle of the right wrist joint (deg)	0.357	0.079	0.045	-0.133
16	Additional kinematics	Left shoulder joint angle (deg)	-.523*	-0.359	-0.182	-0.093
17		Left elbow joint angle (deg)	-0.133	0.069	-0.403	-0.038
18		The angle of the left wrist joint (deg)	0.080	0.236	-0.209	-0.174
19	thrust	Angular velocity of the hip joint of the free leg (Deg/s)	0.292	-0.063	.767**	-0.303
20		Horizontal speed of the take-off leg (m/s)	-0.401	0.198	0.445	.553*
21		Vertical speed of the take-off (m/s)	0.472	0.024	-0.277	-0.305
22	Kinematics of basic	The net velocity of the take-off leg (m/s)	-0.383	0.243	-0.021	-0.193
23		Ankle joint angle of the take-off leg (deg)	0.292	0.436	-0.350	-0.476
24		Knee joint angle of the take-off leg (deg)	0.192	0.283	-0.148	0.142
25	thrust	Hip joint angle for the take-off leg (deg)	-0.032	-0.086	-0.142	0.065
26		Angular velocity of the knee joint of the take-off leg (Deg/s)	-0.102	0.201	-0.283	0.209
27	of the body's center of gravity	Height of the body's COG (m)	-0.203	-0.261	-0.293	-0.147
28		The horizontal velocity of the body's COG (m/s)	-0.477	-0.277	0.251	0.095
29		The vertical velocity of the body's COG (m/s)	0.253	-0.169	-0.005	0.205
30	Kinematics of the body's center of gravity	The net velocity of the body's COG (m/s)	-0.461	-0.256	0.074	0.257
31		Horizontal acceleration of the body's COG (m/s ²)	-0.282	-0.207	-0.276	0.158
32		Vertical acceleration of the body's COG (m/s ²)	0.111	0.086	-.755**	-0.163
33	of gravity	The net acceleration of the body's COG (m/s ²)	0.085	0.087	-.785**	-0.102
34		The horizontal momentum of the body's COG (kg.m/s)	-0.471	-0.126	0.263	0.110
35		The vertical momentum of the body's COG (kg.m/s)	-0.178	-0.207	.673**	.814**
36	Kinetics of the body's center of gravity	The net momentum of the body's COG (kg.m/s)	-0.485	-0.252	.602*	.739**
37		The horizontal force of the body's COG (Newton)	-0.294	-0.237	-0.265	0.169
38		The vertical force of the body's COG (Newton)	0.139	0.113	-.761**	-0.155
39	of gravity	The net force of the body's COG (Newton)	0.114	0.113	-.780**	-0.089
40		The horizontal potential energy of the body's COG (Jules)	-0.305	-0.403	-0.405	-0.400
41		The vertical potential energy of the body's COG (Jules)	-0.047	-0.167	-0.122	-0.038
42	Kinetics of the body's center of gravity	The net potential energy of the body's COG (Jules)	-0.273	-0.387	-0.385	-0.354
43		Horizontal kinetic energy of the body's COG (Jules)	-0.454	-0.153	0.228	0.079
44		The vertical kinetic energy of the body's COG (Jules)	-0.090	-0.166	.700**	.856**
45	Kinetics of the body's center of gravity	The net kinetic energy of the body's COG (Jules)	-0.458	-0.235	.614*	.771**

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

There were significant negative correlations between the height achieved and the knee joint angle of the free leg, the angle of the right elbow joint, and the angle of the left shoulder joint at the moment of the beginning of the takeoff ($r = -.536$, $-.546$, and $-.523$, respectively; $P < 0.05$).

There were significant inverse relationships between the height achieved and the variables of the net velocity of the left arm and the knee joint angle of the free leg during the moment of maximum knee flexion of the takeoff leg ($r = -.508$ and $-.537$, respectively; $P < 0.05$). In addition, there were significant negative correlations between the height achieved and the variables of the knee joint angle of the free leg, the hip joint angle of the free

leg, the vertical acceleration of the center of gravity of the body, the net acceleration of the center of gravity of the body, the vertical force of the center of gravity of the body, and the net force of the center of gravity of the body during the moment at the end of the takeoff ($r = -.574, -.549, -.755, -.785, -.761$, and $-.780$, respectively; $*P < .05$, $**P < .01$). The height achieved was positively correlated with the ankle joint angle of the free leg, the angular velocity of the hip joint of the free leg, the vertical momentum of the body's center of gravity, the net momentum of the body's center of gravity, the kinetic energy of the body's center of gravity, and the net kinetic energy of the body's center of gravity ($r = .525^*$, $.767^{**}$, $.673^{**}$, $.602^*$, $.700^{**}$, and $.614^*$, respectively; $*P < .05$, $**P < .01$).

There were significant negative correlations between the height achieved and the variables of the knee joint angle of the free leg and the hip joint angle of the free leg at the moment of the beginning of the flight ($r = -.560$ and $-.639$, respectively; $P < .05$). There were significant positive correlations between the height achieved and the horizontal speed of the takeoff leg, the vertical momentum of the body's center of gravity, the net vertical momentum of the center of gravity, the vertical kinetic energy of the center of gravity, and the net kinetic energy of the center of gravity during the beginning of flight ($r = .553^*$, $.814^{**}$, $.739^{**}$, $.856^{**}$, and $.771^{**}$, respectively; $*P < .05$, $**P < .01$).

There were significant negative correlations between the height achieved and the knee joint angle of the free leg, the angle of the right shoulder joint, the vertical acceleration of the body's center of gravity, and the vertical force exerted on the body's center of gravity during the maximum height ($r = -.527^*$, $-.676^{**}$, $-.556^*$, and $-.576^*$, respectively; $*P < .05$, $**P < .01$). There were significant positive correlations between the height achieved and the variables of the vertical speed of the free leg, the horizontal speed of the right arm, the height of the body's center of gravity, the vertical momentum of the body's center of gravity, the vertical potential energy of the body's center of gravity ($r = .544^*$, $.595^*$, $.627^*$, $.541^*$, and $.535^*$, respectively; $*P < .05$, $**P < .01$).

Discussion

Previous studies have demonstrated that the variables related to the takeoff of the high jumper are among the most important factors that the athlete and coach should seek to improve in the training programs. The current study has highlighted the necessity of increasing the angle of flight of the jumper's center of gravity during the beginning of flight, since the objective is to achieve the maximum vertical height, and this is largely determined by the athlete's flight angle. One of the most crucial skills a high jumper must master is the ability to convert horizontal velocity into vertical velocity by adjusting the flight angle in a way that achieves the ideal vertical path to the bar (Rao et al., 2014; Sado et al., 2022).

One of the most important phases in the high jump is the takeoff stage. The goal of this stage is to convert horizontal velocity into vertical velocity. This requires a large amount of muscular force applied within a very short time; to achieve this, the jumper must shorten the braking distance while trying to increase the second part of the takeoff to raise the center of gravity of the body. The current study has demonstrated the necessity of shortening the horizontal braking distance to the body's center of gravity, as there was an inverse relationship between this variable and the height achieved (Dobbs et al., 2015; Becker, Will, 2015; Johnston et al., 2015).

There was an inverse correlation between the braking time and the height achieved. Braking represents the negative aspect of the takeoff, while the push represents the positive aspect of achieving a height. To succeed in clearing a height, it is necessary to reduce the braking time during the takeoff, as shown in previous studies of the high jump (Sattler et al., 2015; Goldmann et al., 2015).

The variables associated with the additional limbs (the arms and the free leg) played major roles and showed positive relationships with the vertical speed of the free leg and the horizontal speed of the right arm. We note the necessity of reducing the speed of the left arm during the moment of maximum flexion of the knee of the takeoff leg (Coh, Supej., 2008; Ae et al., 2008).

Since additional forces play an important role in addition to the basic push by the take-off leg, we highlight the necessity of increasing the angular velocities of the joint of the free leg at the end of the takeoff, directing the connection of the thigh, leg, and foot in the movement upward depending on the angle of the free leg (Table 3). Therefore, the jumper should control the angle of the free leg while not to a degree that reduces the velocity (Nicholson et al., 2018; Pleša et al., 2022).

Many studies have confirmed the importance of increasing the speed of the jumper during the beginning of flight. From this moment onward, the jumper's body is treated as a projectile. As this aspect of the jump is associated with better performance among top athletes, we stress the importance of increasing the horizontal velocity of the takeoff leg during the beginning of the flight (Van Caekenberghe et al., 2021; Kim et al., 2015; Kim et al., 2011).

The variable height of the body's center of gravity and the height achieved at the end of the flight are correlated, but to lift the body's center of gravity to the maximum height, the distance between the center of gravity and the crossbar should be as small as possible. From Table 2, the maximum height of the body's center of gravity during flight was 2.25 meters, whereas the greatest height that jumpers achieved was 1.94 meters, a disparity of 0.31 meters (Bermejo et al., 2011; Sado et al., 2018).

By monitoring the kinetics of movement, we note that there is a direct relationship between the vertical momentum of the body's center of gravity and the distances during the most important moments of the jump (the end of the ascent, the beginning of flight, and the maximum flight height). The momentum can be increased by

increasing the velocity. Increasing the momentum produced means an increase in the force exerted. Therefore, our results are in agreement with previous studies regarding the necessity of increasing the rates of momentum, speed, and force exerted to achieve maximum height (Nicholson et al., 2019; Mariano et al., 2021).

For ideal performance, the jumper should increase the amount of vertical kinetic energy and the net energy at the beginning and end of the flight. The jumper should increase the amount of vertical kinetic energy and the net energy of the body's center of gravity during the end of takeoff and the beginning of flight, as the results showed that there is a direct correlation between the height achieved and the vertical and net kinetic energy (Kim et al., 2014; Pavlovic, 2017; Solehto et al., 2007).

Practical implications

The current results can help coaches and athletes in developing the skills necessary to improve their level of performance. The findings can also aid researchers in conducting further studies. We highlight the following points and results that should be considered during training or when researching the high jump.

At the beginning of takeoff, there are significant inverse correlations between the height achieved and the variables of the knee joint angle of the free leg, the angle of the right elbow joint, and the angle of the left shoulder joint. During maximum knee flexion of the takeoff leg, there is a significant inverse correlation between the height achieved and the variables of the net velocity of the left arm and the knee joint angle of the free leg.

During the end of the take-off, there is an inverse correlation between the height achieved and the variables of the knee joint angle of the free leg, the hip joint angle of the free leg, the vertical acceleration of the body's center of gravity, the net acceleration of the body's center of gravity, the vertical force on the body's center of gravity, and the net force on the body's center of gravity.

There is a direct relationship between the height achieved and the variables of the angle of the ankle joint of the free leg, the angular velocity of the hip joint of the free leg, the vertical momentum of the center of gravity of the body, the net vertical momentum of the center of gravity of the body, the vertical kinetic energy of the center of gravity of the body, the net kinetic energy of the center of gravity of the body.

During the beginning of flight, there is an inverse correlation between the height achieved and the variables of the knee joint angle of the free leg and the hip joint angle of the free leg, and the existence of a direct correlation between the horizontal speed of the take-off leg, the vertical momentum of the body's center of gravity, the net momentum of the body's center of gravity, the vertical kinetic energy of the body's center of gravity, the net kinetic energy, and the center of gravity of the body.

During the maximum height of the body's center of gravity in flight, there is an inverse correlation between the height achieved and the variables of the knee joint angle of the free leg, the angle of the right shoulder joint, the vertical acceleration of the body's center of gravity, and the vertical force of the body's center of gravity. There were positive correlations between the height achieved and the variables of the vertical speed of the free leg, the horizontal speed of the right arm, the height of the center of gravity of the body, the vertical momentum of the center of gravity of the body, the vertical potential energy of the center of gravity of the body.

Study limitations

Although the current study has certain strengths, several limitations should be addressed in future research. In such studies, a larger sample size should be obtained for accurate results. All athletes participating in the current competition were used to collect the data, and 48 attempts were analyzed.

Secondly, in such studies, a larger number of cameras (6-12) could be used to capture the variables and conduct a three-dimensional analysis. In the present study, only six high-quality cameras were available to photograph the athletes (Panoutsakopoulos et al., 2012).

Finally, this is a descriptive and analytical study that aims to analyze biomechanical variables affecting the achievement during the performance stages of the high jump. The information can be provided to assist coaches and those interested in this field during the training process or can be used to conduct complementary studies for further development.

Conclusion

Performance in the high jump depends on several factors, the most crucial being the approach to the bar along a curve at speeds that can be controlled while positioning the takeoff leg in the proper spot and applying sufficient force to obtain the maximum height during flight. To achieve this, according to the results of the present study, the jumper must increase the vertical kinetic energy during the beginning of the takeoff while increasing the velocity of the limbs during the moment of maximum flexion and the beginning of the push to reduce the pressure on the take-off foot. Reducing the braking time during take-off and increasing the pushing time, increasing the stretch in the joints of the take-off leg at the end of the take-off, and maintaining the decrease in velocity during crossing the bar are all important factors that can help the jumper achieve maximum height.

Declarations

Ethics Statement

The filming was done after the competitors had been informed of the research and goals and had given their approval. In addition, the study received the approval of the Egyptian Athletics Federation and received

scientific research ethics approval from the Deanship of Scientific Research, King Faisal University, Saudi Arabia [Project No. KFUC-REC-2023-SEP-ETHICS1453] following the Helsinki Agreement (World Medical Association, 2013).

Informed consent to publish the data and images was obtained from the athletes involved in the research.

Funding statement

This work was supported by the Deanship of Scientific Research, King Faisal University, Saudi Arabia [Project No. KFUC242512].

Data availability statement

Data will be made available on request

Acknowledgments

Thanks to all the athletes who agreed to participate in the study. We thank the Egyptian Athletics Federation for their cooperation and for allowing the study to be conducted during the competition.

Conflicts of interest We declare no conflicts of interest.

References:

- Leite, W.(2013).Biomechanical analysis of running in the high jump. *Pedagogics, psychology, medical-biological problems of physical training and sports*, 17(2), 99-105. doi: 10.6084/m9.figshare.639261.
- Dapena, J.(1992).Biomechanical studies in the high jump and the implication to coaching, *Track & Field Quarterly Review*, George D. Gales, editor, 92(4), 7-8.
- Schiffer, J.(2012).Plyometric training and the high jump. *New Studies in Athletics*, 27(3), 9-21.
- Dobbs, C. W., Gill, N. D., Smart, D. J., & McGuigan, M. R .(2015).Relationship between vertical and horizontal jump variables and muscular performance in athletes. *The Journal of Strength & Conditioning Research*, 29(3), 661-671 , doi:10.1519/jsc.0000000000000694.
- Sado, N., Yoshioka, S., & Fukashiro, S.(2020).Non-extension movements inducing over half the mechanical energy directly contributing to jumping height in human running single-leg jump, *Journal of Biomechanics* October 113(2):110082. ,doi:10.1016/j.jbiomech.2020.110082
- Milan C.(2010).Biomechanical characteristics of take-off action in high jump-a case study. *Serbian Journal of Sports Sciences*, 4(4).
- Adashevskiy, V. M., Iermakov, S., & Marchenko, A. A.(2013).Biomechanics aspects of technique of high jump, *physical education of students*,vol.2, pp. 11-17, SSRN Electronic Journal. doi:10.2139/ssrn.2444335.
- Van Caekenberghe, I., Derave, W., Lenoir, M., Segers, V., Aerts, P., & De Clercq, D.(2021).Traditional high jump Gusimbuka Urukiramende: Could early 20th century African athletes beat Olympic champions?. *Journal of Sports Sciences*, 39(16), 1800-1806, , <https://doi.org/10.1080/02640414.2021.1898175>.
- Agar-Newman, D. J., & Klimstra, M. D.(2015).Efficacy of horizontal jumping tasks as a method for talent identification of female rugby players. *journal of strength and conditioning research*, 29(3), 737-743. , doi:10.1519/jsc.0000000000000683.
- Nicholson, G., Bennett, T. D., Bissas, A., and Merlino, S.(2019).Biomechanical Report for the IAAF World Indoor Championships 2018: High Jump Men. Birmingham, UK, International Association of Athletics Federations. Available online at: <https://www.iaaf.org/about-iaaf/documents/research>
- Panoutsakopoulos V, Kollias I, A.(2012).3D Biomechanical Analysis of Women's High Jump Technique, *New Studies in Athletics •IAAF*, 27(3), 31-48.
- Dapena, J., & Flickin, T. K.(2006).Scientific services project-high jump. Biomechanics Laboratory, Dept. of Kinesiology, Indiana University, USA,.
- Nicholson, G., Jongerius, N., Tucker, C. B., Thomas, A., Merlino, S., & Bissas, A.(2022).The association between hip-shoulder separation angles and technique characteristics in world-class high jumpers. *Frontiers in Sports and Active Living*, 4, 873526.doi: 10.3389/fspor.2022.873526.
- Kim, Y. S., Ryu, J. K., & Jang, J. K.(2015).The Kinetic Analysis of the Approach and Take-off Motion between Performance in Woman's High Jump, *Korean Journal of Sport Biomechanics*, 25(1), 1-10. <https://doi.org/10.5103/KJSB.2015.25.1.001>.
- Goldmann, J. P., Braunstein, B., Heinrich, K., Sanno, M., Stäudle, B., Ritzdorf, W., ... & Albracht, K.(2015).Joint work of the take-off leg during elite high jump,33rd International Conference on Biomechanics in Sports, Poitiers, France, June 29 - July 3. doi: <http://dx.doi.org/10.13140/RG.2.1.1547.0163>
- Rao, C. R., Kishore, Y., & Rao, J. R.(2014).Biomechanical Analysis of Centre of Mass Height during the Takeoff Phase In Fosbury Flop High Jump of National Level Participants. *International Journal of Modern Communication Technologies and Research*, (IJMCTR),2(10), 265758.
- Sado, N., Yoshioka, S., & Fukashiro, S.(2022).Curved Approach in High Jump Induces Greater Jumping Height without Greater Joint Kinetic Exertions than Straight Approach. *Medicine and Science in Sports and Exercise*, 54(1), 120-128. DOI: 10.1249/MSS.00000000000002761
- Becker J, Will F.W.(2015).Integrating biomechanical and motor control principles in elite high jumpers: A transdisciplinary approach to enhancing sport performance, *Journal of Sport and Health Science*, 4(4), 341-346. <https://doi.org/10.1016/j.jshs.2015.09.004>.

- Johnston, L. A., Butler, R. J., Sparling, T. L., & Queen, R. M.(2015).A single set of biomechanical variables cannot predict jump performance across various jumping tasks. *The Journal of Strength & Conditioning Research*, 29(2), 396-407. <https://doi.org/10.1519/jsc.0000000000000779> .
- Sattler, T., Sekulić, D., Spasić, M., Perić, M., Krolo, A., Uljević, O., & Kondrič, M.(2015).Analysis of the association between motor and anthropometric variables with change of direction speed and reactive agility performance. *Journal of human kinetics*, 47, 137. doi: 10.1515/hukin-2015-0069. PMID: 26557198; PMCID: PMC4633249
- Coh, M., & Supej, M.(2008).Biomechanical model of the take-off action in the high jump: a case study. *New Stud in Athletics, IAAF*, 23(4), 63-73.
- Ae, M., Nagahara, R., Ohshima, Y., Koyama, H., Takamoto, M., & Shibayama, K.(2008). Biomechanical analysis of the top three male high jumpers at the 2007 world championships in athletics. *New Studies in Athletics*, 23(2), 45-52.
- Nicholson, G., Bissas, A., & Merlino, S.(2018).Biomechanical report for the IAAF world championships 2017: high Jump Men's,in 2017 IAAF World Championships Biomechanics Research Project, July, UK (International Association of Association of Athletics Federations). Available online at: <https://www.iaaf.org/about-iaaf/documents/research> (accessed July 2018).
- Pleša, J., Kozinc, Ž., & Šarabon, N.(2022).A brief review of selected biomechanical variables for sport performance monitoring and training optimization. *Applied Mechanics*, 3(1), 144-159. <https://doi.org/10.3390/applmech3010011>.
- Kim, E. H., Bae, Y. S., Kim, S. S., Kwon, M. S., Wi, U. R., KIm, K. M., & Lee, J. M.(2011). Biomechanical analysis of men's high jump medalists in iaaf world championships, daegu 2011. *Korean Journal of Sport Biomechanics*, 21(5), 573-584. <http://dx.doi.org/10.5103/KJSB.2011.21.5.573>.
- Bermejo, J., Palao, J. M., & Elvira, J. L.(2011).Effect of age on high jump take off biomechanics. In *ISBS-Conference Proceedings Archive*.
- Sado, N., Yoshioka, S., & Fukushima, S.(2018).Hip abductors and lumbar lateral flexors act as energy generators in running single-leg jumps. *International journal of sports medicine*, 39(13), 1001-1008. doi:10.1055/a-0749-8846.
- Mariano, A. S., Tomazini, F., Rodacki, C., Bertuzzi, R., De-Oliveira, F., & Lima-Silva, A. E.(2021). Effects of caffeine on performance during high-and long-jump competitions. *International Journal of Sports Physiology and Performance*, 16(10), 1516-1521. doi: 10.1123/ijsp.2020-0755.
- Pavlovic, R.(2017).The differences of kinematic parameters high jump between male and female finalists World Championship Daegu, 2011. *Turkish Journal of Kinesiology*, 3(4), 60-69.
- Solehto, J., Virmavirta, M., Kyrolainen, H., & Komi, P.(2007).Biomechanical analysis of the high jump at the 2005 IAAF World Championships in Athletics. *New Studies in Athletics*,22(2)17-27.