

*Milan Čoh,
Matej Supej,
Milan Žvan,
Stojan Burnik*

Faculty of Sport, University of Ljubljana, Slovenia

BIODYNAMICAL PROFIL OF THE TAKE-OFF ACTION IN HIGH JUMP

1. INTRODUCTION

High jump is classified in the group of complex cyclic-acyclic movements where the main objective is to bring the jumper's centre of mass (CM) to a maximum height when crossing the bar. In terms of biomechanical characteristics, the high jump technique is defined by the following three interrelated phases: run-up phase, take-off phase and flight or bar clearance phase. According to studies conducted by some authors (Dapena, 1990, 1997, 2006; Bruggemann & Arampatzis, 1999), the take-off phase is one of the most important phases and generates a good performance in high jumping. In the take-off phase, the horizontal velocity of the jumper's CM transforms into vertical velocity. The take-off begins at the instant the jumper places their take-off foot on the ground. Dapena (1997, 2006) divides the take-off phase into the 'start of take-off phase' and the 'end of take-off phase'. The entire take-off phase from the instant the take-off foot touches the ground (touchdown) to the instant it loses contact with the ground (toe-off) lasts from 0.14 to 0.18 of a second. The optimum angle between the foot and the bar line is 20° to 25°. The distance from the take-off point to the bar is very individualised and depends on the velocity of the jumper, the run-up technique and the bar-crossing technique. As a rule, the distance between the take-off point and the bar is 0.90 m to 1.40 m (Dapena, 2006).

The start of the take-off phase lasts from the moment the take-off foot contacts the ground until the moment of maximum flexion (amortisation) in the knee of the take-off leg. In this phase the intensive transformation of the horizontal velocity into vertical velocity occurs as a consequence of the ground reaction force acting in backward and upward directions. The muscle activation regime of the knee extensors (m. quadriceps) is eccentric. The amortisation phase must be as short as possible to enable the fast transition from the eccentric to the concentric muscle contraction, which is a prerequisite for the efficient execution of the take-off. The ground reaction force in the amortisation phase is further intensified by the swing of the swinging leg and arms in the forward and downward directions. The second part of the take-off is associated with the concentric muscle contraction and lasts until the instant the take-off foot loses contact with the ground. The ground reaction force is mainly directed vertically upwards and is just appropriately eccentric with regard to the CM to facilitate appropriate torque impulses which generate the necessary angular momentum for the jumper's body to clear the bar. The most important factor of the end of the take-off phase is vertical velocity which generates the efficiency of the high jump (Dapena, 2006). Maximum vertical velocity is the consequence of the vertical ground reaction

force which the jumper develops at the time their foot contacts the ground. According to some studies (Dapena 1990, 2006; Arampatzis & Brüggemann, 1999; Isolehto et al., 2007; Ae et al., 2008), the vertical velocity of elite high jumpers at the end of the take-off phase equals $3.8 \text{ m}\cdot\text{s}^{-1}$ to $5.0 \text{ m}\cdot\text{s}^{-1}$. The amount of the vertical velocity at the end of the take-off phase largely depends on the jumper's horizontal velocity in the last two strides of the run-up (Dapena, 2006). Vertical velocity of the CM at the end of the take-off phase is negatively related with the horizontal velocity of the CM at the instant the take-off foot contacts the ground. In the initial amortisation phase of the take-off, the horizontal velocity of the jumper's CM decreases the most and the strongest ground reaction force develops.

The study aimed to identify the key dynamic parameters of the take-off action in high jumping using a direct measurement method, i.e. a force plate. The measurement of forces in the high jumper's take-off action in completely situational conditions is extremely rare in the methodology and technology of research of this kind. The analysis of dynamic parameters also considered kinematic parameters which had been established using a synchronised 3D kinematic system. Given that only one elite jumper participated in the study, the generalisation of the analysis results can only be limited. However, this is a very specific experiment where the results clearly have an important theoretical and practical value for biomechanical research of high jump technique modelling.

2. METHODS

The study involved (R.P.), a member of the national team of the Republic of Slovenia for the high jump (age: 29, body height: 1.94 m, body mass: 75.5 kg, BMI: 20.07, personal record in high jump: 2.31 m). At the 2008 Beijing Olympic Games, he placed 12th in the finals, with 2.25 m.

The subject executed ten high jumps, with the bar placed at a height ranging from 2.00 m to 2.25 m. The maximum height at which the jumper cleared the bar was 2.18 m. The recording was made using two synchronised cameras (SONY DVCAM DSR-300 PK). The angle between the optical axes of the cameras was 90° and between the cameras and the bar 45° . The biomechanical analysis of the take-off action was performed using the high-speed camera MIKROTRON MOTION BLITZ CUBE ECO-1 and the DIGITAL MOTION ANALYSIS RECORDER that is able to capture 6 seconds of movements at a frequency of 1,000 frames/second at a resolution of 640×512 pixels. This study was made using a frequency of 500 frames/sec. The analysed area of the last two strides and the take-off point was calibrated with a $1 \text{ m} \times 1 \text{ m} \times 2 \text{ m}$ reference scaling frame, and the calibration was based on eight reference angles. The length of the analysed movement was defined by the 'x' axis, the height by the 'y' axis and the depth by the 'z' axis. 3D software APAS (Ariel Dynamics Inc., San Diego, CA) was used to establish the kinematic parameters of the technique. A 15-segment model of the jumper's body was digitised and defined by 18 reference landmarks (according to M. Dempster via Miller and Nelson: Biomechanics of Sport, Lea &

Febiger, Philadelphia, 1973). The co-ordinates of the body landmarks were smoothed with a digital seventh-order Buterworth filter.

The dynamic parameters of the take-off action were established using a force plate (Kistler 9287, Winterthur, Germany, size: 900 x 600 mm) which was fastened at the take-off point and covered with a tartan mass. The sampling frequency was 1,000 Hz. The horizontal (X), vertical (Y) and lateral (Z) components of the ground reaction force were measured and smoothed with a digital second-order 500 Hz Buterworth filter. The high-frequency video recordings were synchronised with the measurements of forces, using a specially designed ‘TensioJump’ programme in the Matlab R2007a environment.

3. RESULTS AND DISCUSSION

Based on the parameters of the three-dimensional kinematic analysis (**Table 1**) we can establish that the jumper (R.P.) is a representative of the Power-Flop model of the high jump technique. His morphological characteristics (body height: 1.94 m, body mass: 75.5 kg) are very similar to the modern model of elite high jumpers, such as defined by the authors Isolehto, Virmavirta, Kyrolainen and Komi (2007) based on data on finalists at the 2005

Table 1: Kinematic parameters of the take-off action in high jump

VARIABLES	UNIT	R.P.
Result (R)	m	2.18
Height of the CM at the start of the take-off phase (H1)	m	0.96
Partial height of the CM at the start of the take-off phase (H1 %)	%	49.4
Height of the CM at the end of the take-off phase (H2)	m	1.33
Partial height of the CM at the end of the take-off phase (H2 %)	%	68.6
Highest point of the flight path (H3)	m	2.20
Horizontal velocity of the CM in the last two strides of the run-up (VR)	m.s⁻¹	7.15
Horizontal velocity of the CM at the start of the take-off phase (VhTD)	m.s⁻¹	6.64
Vertical velocity of the CM at the start of the take-off phase (VvTD)	m.s⁻¹	0.17
Horizontal velocity of the CM at the end of the take-off phase (VhTO)	m.s⁻¹	2.19
Vertical velocity of the CM at the end of the take-off phase (VvTO)	m.s⁻¹	4.33
Take-off time (Tt)	s	0.162
Take-off distance (TOD)	m	102
Knee lowest (KMAX)	°	141.6
Knee angle at the end of the take-off phase (KTO)	°	177.0
Angle velocity of the swinging leg	°/sec	870.2

World Championship in Athletics. One of the key parameters which directly influences the jump height is the position of the CM at the end of the take-off phase (H2). The maximum height of the CM at the end of the take-off phase largely depends on the jumper’s anthropometric characteristics (body height) and take-off technique

(efficient extension in the ankle, knee and hip joints and the trunk). The jumper's height H_2 equals 1.33 m, thus accounting for 68.6% of his body height. The difference between the minimum and maximum heights of the CM in the take-off phase is 0.37 m. This is less than established by Isolehto et al. (2007) on a sample of elite jumpers, i.e. 0.44 m. The partial change in the CM in the take-off action is mainly related to the transformation of the horizontal velocity into vertical velocity of the CM during the take-off phase. The vertical velocity at the end of the take-off phase is the key generator of the jump height (Dapena 1990; Hay, 1993; Bruggemann & Arampatzis, 1997; Greig, Yeadon, 2000; Isolehto et al., 2007; Ae et al., 2008). Our study subject's vertical velocity was $4.33 \text{ m}\cdot\text{s}^{-1}$. To maximise vertical velocity at the end of the take-off, the horizontal velocity of the CM at the start of the take-off phase is very important as it must be as high as possible (Dapena, 2006). During the take-off action, the horizontal component of velocity of the jumper's CM decreased by $4.45 \text{ m}\cdot\text{s}^{-1}$ and the vertical component increased by $4.16 \text{ m}\cdot\text{s}^{-1}$. Based on this decrease in horizontal velocity in the take-off action it can be established that the change is extreme. With elite jumpers, the decrease in velocity equals $3.47 \pm 0.28 \text{ m}\cdot\text{s}^{-1}$ (Isolehto et al., 2006). The shortcoming of our jumper (R.P.) is his too low velocity in the last two strides of the run-up ($7.15 \text{ m}\cdot\text{s}^{-1}$) and too low velocity of the CM at the start of the take-off phase ($6.64 \text{ m}\cdot\text{s}^{-1}$).

The horizontal velocity of the CM during the take-off action is extremely important as it correlates highly with the vertical velocity of the CM at the end of the take-off ($r = 0.79$) – Dapena et al., 2006. The jumper's take-off time was 0.162 sec. The duration of the take-off phase depends on the knee angles at the instant of touchdown and take-off as well as the knee angle at the instant of maximum amortisation. The take-off time is not a reliable criterion of a good or poor technique. It is not significantly correlated with the result of the high jump (Dapena, 1990). However, it is a valid criterion for assessing the Speed-Flop and Power-Flop techniques. Jumpers whose take-off time is short belong to the group of speed-floppers and those with a long take-off time to power-floppers. In view of the run-up velocity, horizontal velocity in the take-off action and the take-off time, our study subject is a power-flopper.

The transformation of the horizontal movement of the CM into the vertical movement of the CM is the most critical phase of the high jump, which is not only related to the kinematic but also the dynamic parameters of the take-off. The latter were established using a force plate which was incorporated in the ground and on which the jumper executed the take-off in the completely situational conditions of the Flop technique. The vertical (F_y), horizontal (F_x) and lateral (F_z) ground reaction forces were measured. In the vertical direction, the force has two maximums, and one minimum in between. The first maximum occurred 25 ms after the first contact with the ground and was slightly higher, measuring 4,213 N, the second occurred after 77 ms and was slightly lower, measuring 4,091 N (**Figure 1**).

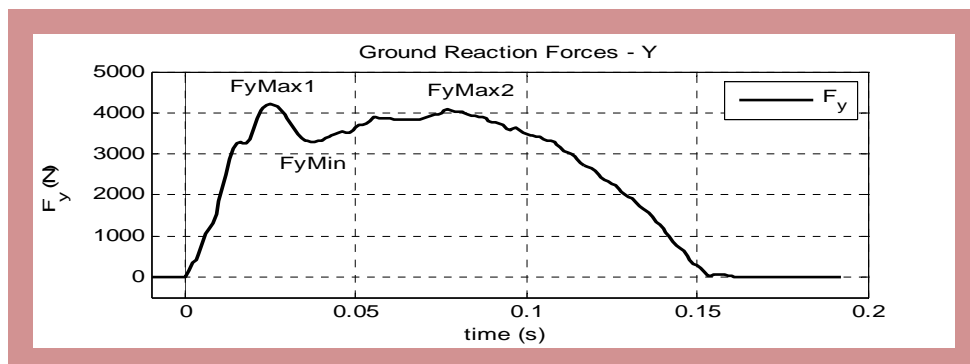


Figure 1: Ground reaction force in the vertical Y-direction

The total contact time on the force plate is 162 ms. The distance between the take-off point (touchdown) and the bar in the horizontal direction was 1.02 m. The subject's foot on the ground created a 19° angle with respect to the bar, which resulted in a strong pronation of the ankle joint. This is a consequence of the high force in the transversal direction of the foot as the maximum equals 1,806 N and occurs 51 ms after the first contact with the ground, i.e. at less than one-third of the take-off. In the longitudinal direction of the foot, the forces are even higher, at most equalling 3,763 N and occurring 25 ms after the contact with the ground, which coincides with the maximums of forces in the global system.

The calculated horizontal and vertical impulses of the force (**Table 2**) are high, thus indicating a high average force given the short take-off action (only 162 ms). A comparison of the kinematic and dynamic measurements is also interesting as it reconfirms the validity of both methods. The kinematic measurement results were as follows: the change in velocity of the CM in the vertical direction $\Delta V_v = 4.16 \text{ ms}^{-1}$ and in the horizontal direction $\Delta V_h = -4.45 \text{ m}\cdot\text{s}^{-1}$ (see Table 1). In accordance with the law, namely that a change in momentum equals the impulse of force, the dynamic measurements yielded the following: $\Delta V_v = 3.98 \text{ ms}^{-1}$ and $\Delta V_h = 4.34 \text{ ms}^{-1}$. The difference in the sign in the horizontal direction is a consequence of squaring; however, the differences are below 5%. The bulk of the error can be ascribed to the lower sampling of the kinematic measurements, and the rest is due to deficiencies of both methods.

Table 2: Parameters calculated by the TensioJumpAna programme from the force plate measurements

PARAMETERS	UNIT	R.P.
Vertical force Fy maximum (FyMax1)	N	4213
Time to reach FyMax1	s	0.025
Vertical force Fy min (FyMin)	N	3303
Time to reach FyMin	s	0.038
Vertical force Fy maximum (FyMax2)	N	4091
Time to reach FyMax2	s	0.077
Time to reach FxMax1	s	0.025
Contact time	s	0.162
Maximum in longitudinal force acting on the foot (FIMax)	N	3763
Time to reach FIMax1	s	0.025
Vertical force impulse (FIy)	Ns	448.3
Horizontal force impulse (FIz)	Ns	185.6

We also calculated the force impulse in the eccentric and concentric phases of the take-off in all three directions. In both phases, the largest force impulse was recorded in the vertical direction, followed by the longitudinal and transversal directions with regard to the bar. In the vertical direction, the force impulse was larger in the concentric phase (264.3 vs. 184), whereas in both of the horizontal directions it was larger in the eccentric phase. As expected, the energy efficiency of the take-off was negative, namely $e_{ef} = -4.8$ J/kg. In other words, the athlete loses energy proportionally to the increase in their velocity from zero to 3.1 ms^{-1} . The force impulse in the eccentric and concentric phases of the take-off is related to the modality of the neuromuscular activity. The eccentric-concentric cycle is the result of muscle stretching due to external force and muscle shortening in the second phase (SSC: stretch-shortening cycle; Komi & Gollhofer, 1997). In the eccentric phase, a limited quantity of elastic energy accumulates in the muscle-tendon complex to be used in the second phase. This portion of elastic energy that is accumulated in the muscle is only available for a specific time. The available time depends on the life span of the cross-bridges and lasts from 15 to 120 milliseconds (Deporte, Van Gheluwe, 1989; Enoka, 2003). The efficiency of an eccentric-concentric contraction also depends on the time of the transition. The longer the time, the less efficient is the contraction. In addition to the extent and velocity of the change in the muscle's length and the duration of the transition, the efficiency of an eccentric-concentric contraction largely depends on pre-activation. The latter defines the first contact of the take-off foot with the ground. Pre-activation prepares the muscles for stretching and is manifested in the number of attached cross-bridges and the change in the excitability of α -motor nerves. Both factors affect the short-range stiffness of the muscle. Greater muscle stiffness causes a marked extension of the ligaments and the tendon which, in turn, reduces the

consumption of chemical energy in the muscle. The reduced consumption of chemical energy is particularly important in those motor situations where specific movements must be made at a high velocity, such as in high jump, where the take-off lasts from 150 to 180 ms.

4. CONCLUSION

Based on this study it is possible to establish that efficiency in high jumping largely depends on the optimal take-off action. The take-off action is primarily defined by the horizontal velocity of the CM at the start of the take-off and the vertical velocity of the CM at the end of the take-off as well as by the duration of the take-off phase. In view of the results of the dynamic analysis, the jumper developed the highest ground reaction force in the eccentric phase of the take-off action. The ground reaction force in the vertical direction exceeded the jumper's body weight by 5.6 times. In the concentric take-off phase the maximum ground reaction force was 9% lower compared to the eccentric phase. It is also possible to identify large ground reaction forces in the horizontal and lateral directions, which are manifested in extreme loading on the ankle joint of the jumper's take-off leg in the take-off action.

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The aim of this study was to identify the key dynamic and kinematic parameters of the take-off action in the high jump. The authors studied a single elite athlete (personal record 2.31m) using a direct measurement method, i.e. a force plate, to measure the dynamic parameters and a synchronised 3D video system to measure the kinematic parameters. They were able to collect and calculate data on 49 variables. Given that the study was focused on just one athlete, generalisation of the results can only be limited. However, this was a very specific experiment where the results clearly have theoretical and practical value for biomechanical research of high jump technique modelling. Their findings include that the jumper studied developed the highest ground reaction force in the eccentric phase of the take-off. The ground reaction force in the vertical direction exceeded his body weight by 5.6 times. In the concentric phase, the maximum ground reaction force was 9% lower than in the eccentric phase. They were also able to identify large ground reaction forces in the horizontal and lateral directions, which are manifested in extreme loading on the ankle joint of the jumper's take-off leg during the take-off action.

Key words: high jump, technique, kinematic, dynamic, take-off action.

“Dan”, 16. februar 2010.

У СУСРЕТ НАУЧНИМ СКУПОВИМА ЦРНОГОРСКЕ СПОРТСКЕ АКАДЕМИЈЕ

Један аутор максимално на три рада

Како за учешће на научним скуповима Црногорске спортске академије, који ће се од 1. до 4. априла одржати у хотелу „Плажа“ у Херцег Новом влада велико интересовање, то организатори показивају заинтересованост да се један аутор може појавити највише на три рада и то на једном раду самостално а на осталима као коаутор или са коаутором. До сада смо обавили наслове 38 вистигах радова, а у данашњем објављујемо још осам: 39. Доц. др Ратко Павловић (Факултет физичког васпитања и спорта, Источно Сарајево); проф. др Наташа Бранковић, доц. др Александар Раковић (Факултет спорта и физичког васпитања, Ниш); „Структура морфолошког простора ученика“; 40. Проф. др Радован Чокорило (Факултет физичког васпитања и спорта, Источно Сарајево), проф. др Спасоје Бјелица (Висока школа за услужни бизнис, Источно Сарајево); „Подстицање психофизичке активности предшколског дјетета“; 41. Др Маја Штребач (Нови Сад); „Тржиште спортске опреме у ЕУ“; 42. Горан Вучковић (Криминалистичко – полицијска академија, Београд); Драган Радовановић (Универзитет у Новом Саду); „Разлике морфолошког статуса спортиста и неспортиста средњошколског узраста“; 43. Драган Радовановић (Универзитет у Новом Саду); Стево Поповић (Факултет спорта и физичког васпитања, Нови Сад); „Елементарне технике основних удараца руком у савременом каратеу“; 44. Мр Виктор Митревски (СОУ „Крсте Петков Масариќов“, Демир Хисар), доц. др Георги Георгиев (Универзитет „Св. Кирил и Методиј“, Факултет за физичку културу, Скопље), проф. др Насер Гашић (Факултет физичке културе и спорта, Приштина), проф. др Фадил Ника (Државни Универзитет у Тетову, Факултет физичке културе); „Квантитативне разлике у оскарку антропометријског простора код ученица средњих школа“; 45. Мр Адмир Коничанин (Гимназија, Техничка школа, Тутин), проф. др Давидо Адиминовић, мр Омер Шпиртовић (Државни Универзитет у Новом Пазару, Департаман за спорт и рехабилитацију); „Вјежбе и игре за исправљање кирфозе код дјеце предшколског узраста“; 46. Елмер Мебедовић, Бенада Мебедовић (Државни универзитет Нови Пазар), Ахмет Мебедовић (Медицинска школа Нови Пазар); „Вјежбе обликовања у структури часа трјесног вјежбања ...“ Т.Б.