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BIOMECHANICAL CHARACTERISTICS OF TAKE OFF ACTION IN HIGH JUMP – A CASE STUDY

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Abstract The study aimed to establish the kinematic and dynamic parameters of the take-off action that generate the greatest efficiency in high jump. A biomechanical analysis was conducted using two synchronised cameras operating at a frequency of 50 Hz (SONY DVCAM DRS-300PK) and one high-speed camera with a 500 Hz frequency (MIKROTRON MOTION BLITZ CUBE ECO-1). The area of the last two strides of the run-up and take-off phases was defined with two Calibration Cubes measuring 1 x 1 x 2 metres. The kinematic parameters were established using the 3-D computer application APAS (Ariel Performance Analysis System). The 15-segment model of the body was digitised and defined by 18 reference points [16]. Numerical data were smoothed with a 16-level digital filter. The dynamic parameters were established using a force plate (Kistler 9287) which was fastened at the take-off zone. The horizontal (x), vertical (y) and lateral (z) components of the ground reaction forces were measured. The signal sampling frequency was 1000 Hz. It was established that the most important kinematic parameters of the high jump include the horizontal velocity of the jumper's CM at the beginning of the take-off phase and the vertical velocity of the jumper's CM at the end of the take-off phase, equalling 4.33 $m \cdot s^{-1}$. The efficiency of the take-off is related to the vertical ground reaction force which features two maximums. The jumper developed the first maximum of the vertical ground reaction force during the eccentric phase of the take-off, equalling 4213 N, whereas the second maximum was recorded in the concentric phase, measured at 4091 N. The lateral ground reaction force equalled 3053 N and was manifested in an extreme loading on the ankle joint of the jumper's take-off leg in the take-off action.

Key words: High jump, technique, kinematics, dynamics, tensiometry

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 McGinnis [14], the performance in high jump depends on the force impulse which causes a change in momentum in the vertical direction:

$$\sum F \, \Delta \, t = m \, (v2 - v1) \tag{1}$$

where:

- $\sum F$ = the sum total of vertical forces acting on the jumper
- Δt = the time of action of forces on the jumper during the take-off
- m = the jumper's body mass
- v1 = the vertical component of velocity of the CM at the start of the take-off
- v2 = the vertical component of velocity of the CM at the end of the take-off

According to studies conducted by some authors [1, 2, 7, 8, 9], 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. Darpena [5, 7] 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 [8].

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 [5, 10]. 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 [1, 4, 6, 8, 12], the vertical velocity of elite high jumpers at the end of the take-off phase equals 3.8 $m \cdot s^{-1}$ to 5.0 $m \cdot s^{-1}$. 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 [2, 5]. 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, while the strongest ground reaction force develops. The consequence of the reduced horizontal velocity is an increase in vertical velocity which defines the height of the flight trajectory of the jumper’s CM. In fact, the transformation is mainly due to the actual torque situation. The take-off point can be regarded as the centre of rotation around which the CM revolves due to the appropriate ground reaction force. The distance between the CM and the foot is considered the ‘lever arm’. This is what causes the transformation of horizontal velocity into vertical velocity.

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.

MATHERIALS AND METHODS

SUBJECTS

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.

MEASUREMENTS AND PROCEDURE

The measurements were carried out at the ‘Slovan’ athletic stadium at Kodeljevo in Ljubljana, Slovenia, in optimal weather conditions. 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° (Figure 1).

The camera frequency was 50 Hz and the resolution 720 x 576 pixels. 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 1000 frames/second at a resolution of 640 x 512 pixels. This study was made using the frequency of 500 frames/sec. The analysed area of the last two strides and the take-off point was calibrated with a 1 m x 1 m x 2 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 (Figure 2).

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 1000 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.

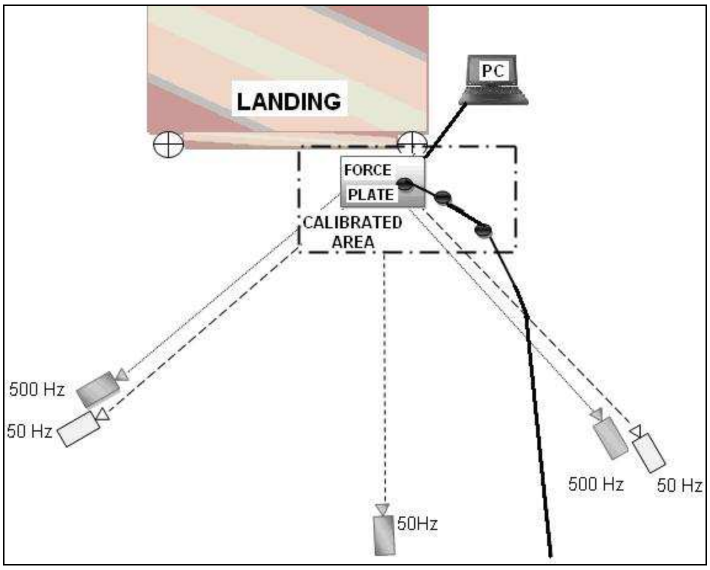

Figure 1. Camera position, coordinate system and the multi-phase calibration area

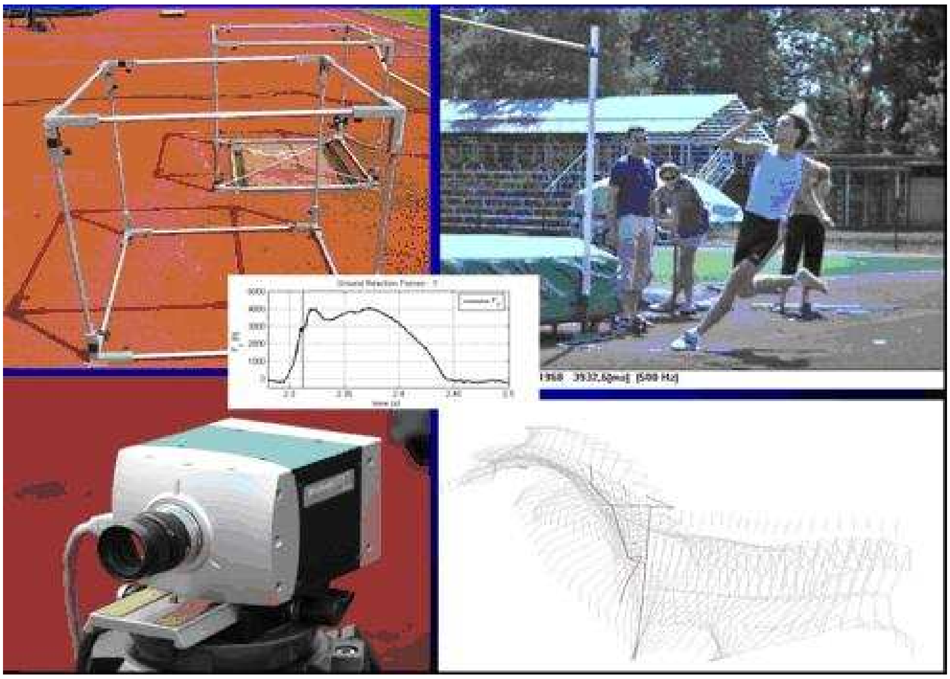

Figure 2. Measurement procedures of kinematic – dynamic analysis of the high jump

In addition, we investigated the projection of the horizontal ground reaction force in the longitudinal and transversal directions of the foot. The 'TensioJumpAna' programme was also developed in the Matlab R2007a environment where the following were calculated based on the measured forces: all local and global maximums and minimums, the time of their occurrence, force impulses and contact time. The force impulses were used in the calculation of the change in the momentum, i.e. the change of velocity in vertical and horizontal directions:

$$\Delta v_v = (\sum Fy\Delta t)/m \qquad (2)$$

$$\Delta v_h = (\sqrt{((\sum Fx\Delta t)^2 + (\sum Fz\Delta t)^2)} - \sum Fg\Delta t)/m \qquad (3)$$

where $\sum Fg\Delta t$ is the impulse of the weight force.

As the point of the maximum flexion in the knee of the take-off leg (141.6°) was eliminated from the kinematics, the respective areas of eccentric and concentric muscle contraction were possible to determine on the force diagram. Based on the above, we also calculated the force impulse in all directions for both take-off phases. Moreover, the energy efficiency of the take-off was calculated, representing a change in the specific potential and specific kinetic energy in the period from the start to the end of the take-off phase:

$$e_{ef} = (\Delta Ep + \Delta Ek)/m = gH2 - gH1 + v2^2/2 - v1^2/2 \qquad (4)$$

The analysis included the best jump only (2.18 m), which was completely processed by the 3 - D kinematics system.

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, BMI: 20.07) are very similar to the modern model of elite high jumpers, such as defined by the authors Isolehto et al. [12], based on data on finalists at the 2005 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 H2 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 that established by Isolehto et al [12] on a sample of elite jumpers, i.e. 0.44 m.

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)	$m \cdot s^{-1}$	7.15
Horizontal velocity of the CM at the start of the take-off phase (VhTD)	m·s	6.64
Vertical velocity of the CM at the start of the take-off phase (VvTD)	m·s	0.17
Horizontal velocity of the CM at the end of the take-off phase (VhTO)	m·s	2.19
Vertical velocity of the CM at the end of the take-off phase (VvTO)	m·s	4.33
Change in horizontal velocity of the CM during the take-off phase (Δ Vh)	m·s	- 4.45
Change in vertical velocity of the CM during the take-off phase (Δ Vv)	m·s	4.16
Take-off time (Tt)	s	0.162
Take-off distance (TOD)	m	102
Longitudinal axis of the foot with respect to the bar (E1)	^{0}	19
Knee angle at the start of the take-off phase (KTD)	^{0}	162.8
Knee lowest (KMAX)	^{0}	141.6
Knee angle at the end of the take-off phase (KTO)	^{0}	177.0
Angle velocity of the swinging leg	^{0}/sec	870.2

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 [1, 2, 4, 8, 12, 14]. Our study subject's vertical velocity was 4.33 $m \cdot s^{-1}$ (Figure 3).

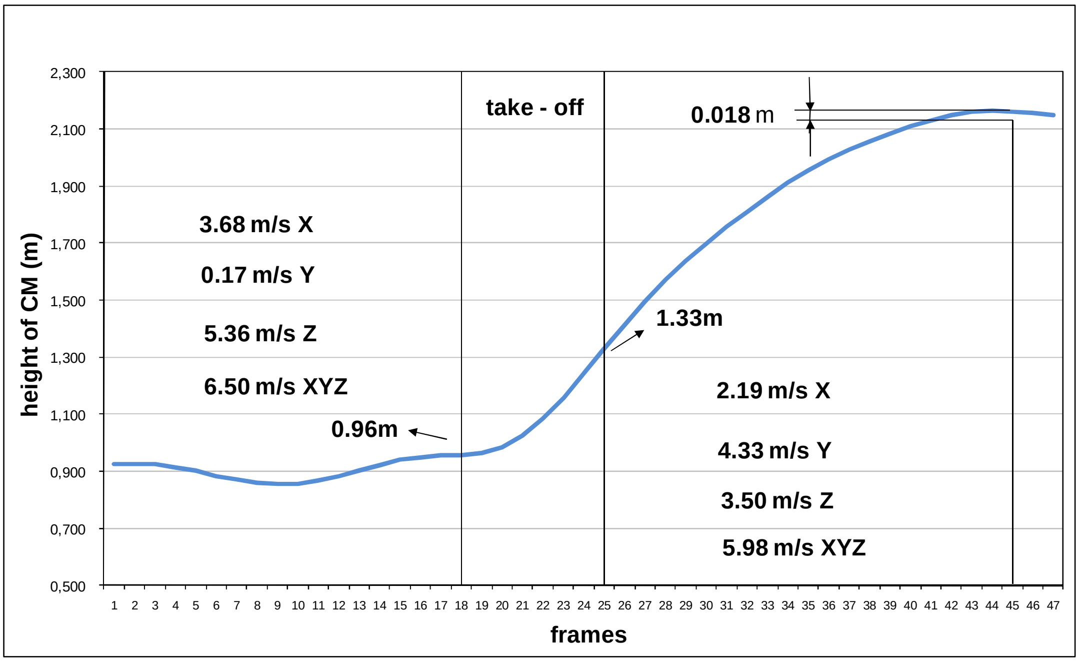

Figure 3. Parameters of the trajectory of the centre of mass in the take-off and flight phases

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 [5]. During the take-off action, the horizontal component of velocity of the jumper's CM decreased by 4.45 m·s^{-1} and the vertical component increased by 4.16 m·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 ± 0.28 m·s^{-1} [12]. The shortcoming of our jumper (R. P.) is his too low velocity in the last two strides of the run-up (7.15 m·s $^{-1}$) and too low velocity of the CM at the start of the take-off phase (6.64 m·s^{-1}). The finalists at the 2005 Helsinki World Championship in Athletics recorded a velocity in the initial phase of the take-off of 7.87 ± 0.34 m·s $^{-1}$ [12].

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) [5, 8]. 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 either a good or poor technique. It is not significantly correlated with the result of the high jump [5]. 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 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 (Fy), horizontal (Fx) and lateral (Fz) ground reaction forces were measured. In the vertical direction, the force has two maximums, and one minimum in between (Figure 4). 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 (Table 2).

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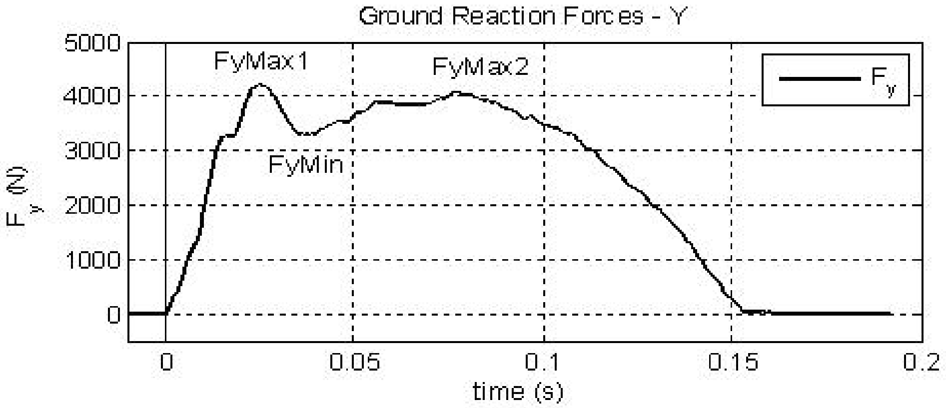

Figure 4. Ground reaction force in the vertical direction

In between is a local minimum, occurring after 38 ms and measuring 3.303 N. This form is the consequence of the amortisation of the eccentric and concentric phases. In each of the two horizontal directions only one maximum appears (Figures 5 and 6) as the amortisation through the jumper's skeleton is not so obvious here. The time of both maximums is not completely co-ordinated with the first maximum; however it comes close. In the 'x' direction, it occurs 27 ms after the contact with the ground and measures 3.053 N, whereas in the 'z' direction it occurs slightly earlier, after 25 ms, and is slightly lower, i.e. 2.708 N. The total contact time on the force plate is 162 ms.

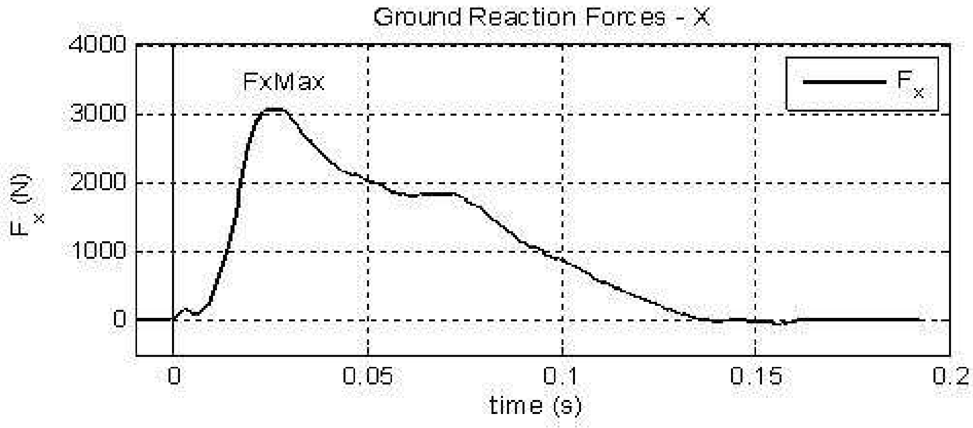

Figure 5. Ground reaction force in the horizontal x-direction

Table 2. Parameters calculated by the TensioJumpAna program 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
Horizontal force Fz maximum (FzMax1)	N	3053
Time to reach FzMax1	s	0.027
Horizontal force Fx maximum (FxMax)	N	2708
Time to reach FxMax1	s	0.025
Contact time	s	0.162
Maximum in transversal force acting on the foot (FtMax)	N	1806
Time to reach FtMax	s	0.051
Maximum in longitudinal force acting on the foot (FlMax)	N	3763
Time to reach FlMax1	s	0.025
Vertical force impulse (FIy)	Ns	448.3
Horizontal force impulse (FIz)	Ns	185.6
Horizontal force impulse (FIx)	Ns	237.2
Negative horizontal force impulse (FIx)	Ns	-3.22
Vertical force impulse in eccentric phase (FIye)	Ns	184
Horizontal force impulse in eccentric phase (FIxe)	Ns	122.8
Horizontal force impulse in eccentric phase (FIze)	Ns	111.5
Vertical force impulse in concentric phase (FIyc)	Ns	264.3
Horizontal force impulse in concentric phase (FIxc)	Ns	114.4
Horizontal force impulse in concentric phase (FIzc)	Ns	74.1
Change in vertical velocity calculated from force impulse (Δv_v)	$m \cdot s^{-1}$	3.98
Change in horizontal velocity calculated from force impulse (Δv_h)	$m \cdot s^{-1}$	4.34
Energetic efficiency of take-off (e_{ef})	J/kg	-4.8

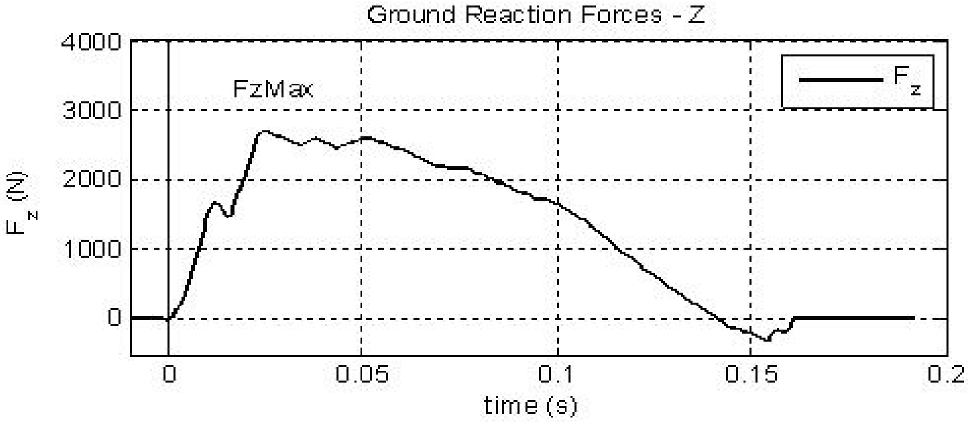

Figure 6. Ground reaction force in the horizontal z-direction

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 (Figure 7). This is a consequence of the high force in the transversal direction of the foot (Figure 8) 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.

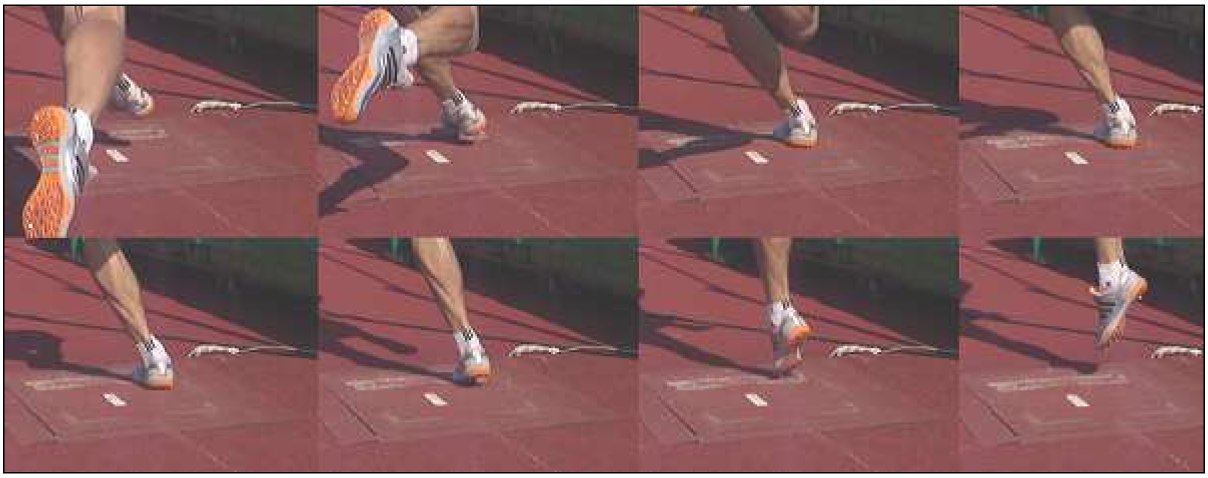

Figure 7. A strong pronation of the ankle joint at the take-off in high jump

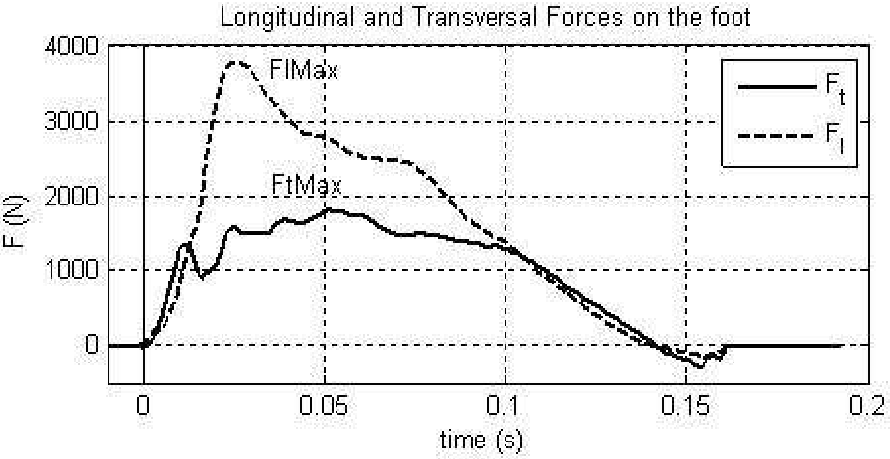

Figure 8. Longitudinal and transversal forces on the foot

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 Δ Vv = 4.16 $m \cdot s^{-1}$ and in the horizontal direction Δ Vh = - 4.45 $m \cdot s^{-1}$ (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: Δ Vv = 3.98 $m \cdot s^{-1}$ and Δ Vh = 4.34 $m \cdot s^{-1}$. 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.

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 (Table 2).

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 $m \cdot s^{-1}$. 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; 13).

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 [10, 11].

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 ά-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.

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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