Biomechanical model of the take-off action in the high jump – A case study

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ABSTRACT

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.

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Introduction

The aim of this study was to identify the key dynamic parameters of the take-off action in the high jump in a single elite athlete using a direct measurement method, i.e. a force plate. The measurement of forces in a high jumper's take-off action in completely situational conditions is extremely rare in the methodology and technology of research of this kind. In addition to the analysis of dynamic parameters, the study also considered kinematic parameters, which were established using a synchronised 3D kinematic system.

Given that the study was focused on just one athlete, generalisation of the analysis results can only be limited. However, this was a very specific experiment where the results clearly have an important theoretical and practical value for biomechanical research of high jump technique modelling.

Description of the High Jump

The main objective of the high jump, which is classified in the group of complex cyclic-acyclic movements, is to bring the jumper's centre of mass (CM) to a maximum height when crossing the bar. In terms of biomechanical characteristics, high jump technique is defined by the following three interrelated phases: the run-up or approach phase, the take-off phase and the flight or bar clearance phase. According to McGINNIS (1999), performance in the high jump depends on the force impulse, which causes a change in momentum in a vertical direction:

$$\sum\sum F \Delta t = m (v2 - v1) \quad (1)$$

where:

- Σ F = the sum total of vertical forces acting on the jumper
- Δ t = the time between two consecutive force measurements (equals the inverse of force plate measurement frequency)
- 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 various authors (MORAVEC, 1986; JACOBY, 1987; DAPENA, 1988, 1992, 2006; BRÜGGEMANN & ARAMAPATZIS, 1997), the take-off is the most important phase. In the take-off, the horizontal velocity of the jumper's CM is transformed into vertical velocity, which determines the effectiveness of the jump (DAPENA, 2006). The take-off is considered to begin at the instant the jumper places the take-off foot on the ground (touchdown) and to last until to the instant the foot loses contact with the ground (toe-off). The entire phase 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 approach technique and the bar-crossing technique. As a rule, the distance is between is 0.90m to 1.40m (DAPENA, 2006).

DAPENA (1997, 2006) divides the take-off phase into the 'start of take-off phase' and the 'end of take-off phase'. The start of the take-off phase lasts from the when 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 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.

As stated above, the most important factor at the end of the take-off phase is the vertical velocity of the jumper's CM. Maximum vertical velocity is the consequence of the vertical ground reaction force that the jumper develops at the time the take-off foot contacts the ground. According to some studies (CONRAD & RITZDORF, 1990; DAPENA 1992, 2006; ARAMAPATZIS & 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 is 3.8 to 5.0m/s. 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 consequence of the reduced horizontal velocity is an increase in vertical velocity, which determines the height of the flight trajectory of the jumper's CM. In fact, the transformation is mainly due to the 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.

Methods

The study was conducted on Rozle Prezelj, a member of the national team of the Republic of Slovenia (age: 29, body height: 1.94m, body mass: 75.5kg, BMI: 20.07, personal record: 2.31m). At the 2008 Olympic Games in Beijing, he placed 12th in the final with 2.25m.

The measurements were carried out at the 'Slovan' athletic stadium at Kodeljevo in Ljubljana, Slovenia, in optimal weather conditions (Figure 1). The subject executed ten high jumps, with the bar placed at heights ranging from 2.00 to 2.25m. The maximum height at which he cleared the bar was 2.18m.

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 2). The camera frequency was 50Hz and the resolution 720 x 576 pixels. The biomechanical analysis was performed using the high-speed camera MIKROTRON MOTION BLITZ CUBE ECO-1 and the DIGITAL MOTION ANALYSIS RECORDER, which is able to capture six seconds of movements at a frequency of 1,000

Figure 1: Measurement equipment for the 3D kinematic analysis of the high jump

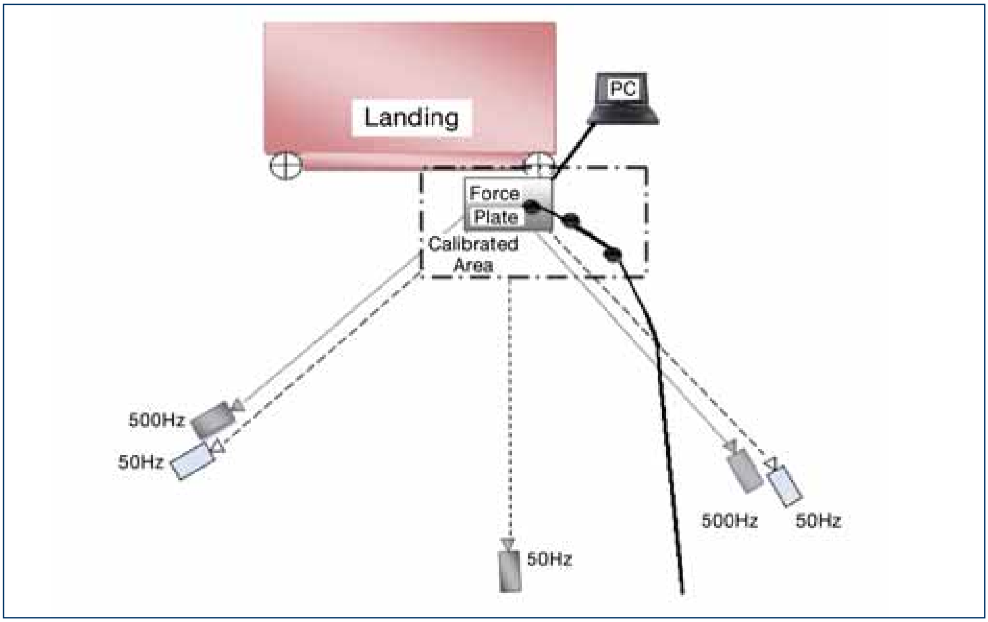

Figure 2: Camera position, coordinate system and multi – phase calibration area

frames/second and a resolution of 640 x 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 1m x 1m x 2m reference scaling frame and the calibration was based on eight reference angles (Figure 3). 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. APAS 3D software (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 DEMPSTER via Miller and Nelson: Biomechanics of Sport, Lea & Febiger, Philadelphia, 1973). The coordinates 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 (see Figure 3). The sampling frequency was 1,000Hz. The horizontal (X), vertical (Y) and lateral (Z) components of the ground reaction force were measured and smoothed with a digital second-order 500Hz Buterworth filter.

The high-frequency video recordings were synchronised with the force plate measurements using a specially designed ‘TensioJump’ programme in the Matlab R2007a environment. 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

Figure 3: Measurement of the ground reaction forces on the y, x and z axes using a force plate

change of velocity in vertical and horizontal directions:

$$\Delta V_v = (\Sigma Fy\Delta t)/m, \qquad (2)$$
$$\Delta V_h = (\nu(\Sigma Fx\Delta t)^2 + (\Sigma Fz\Delta t)^2)) - \Sigma Fg\Delta t)/m, \qquad (3)$$

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

As the point of maximum flexion in the knee of the take-off leg (141.6°) was eliminated from the kinematics, it was possible to determine on the force diagram the areas of eccentric and concentric muscle contractions. 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 was made of the best jump of the day (2.18m) and was completely processed by the 3D kinematics system.

Results and discussion

Based on the parameters of the three-dimensional kinematic analysis (Table 1), we can establish that the jumper is a representative of the Power-Flop model of high jump technique. His morphological characteristics are very similar to the modern model of elite high jumpers, such as defined by ISOLEHTO et al. (2007) based on data on finalists at the 2005 World Championship in Athletics.

One of the key parameters that directly influences 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

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	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 (∆Vh)	m/s	- 4.45
Change in vertical velocity of the CM during the take-off phase (∆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

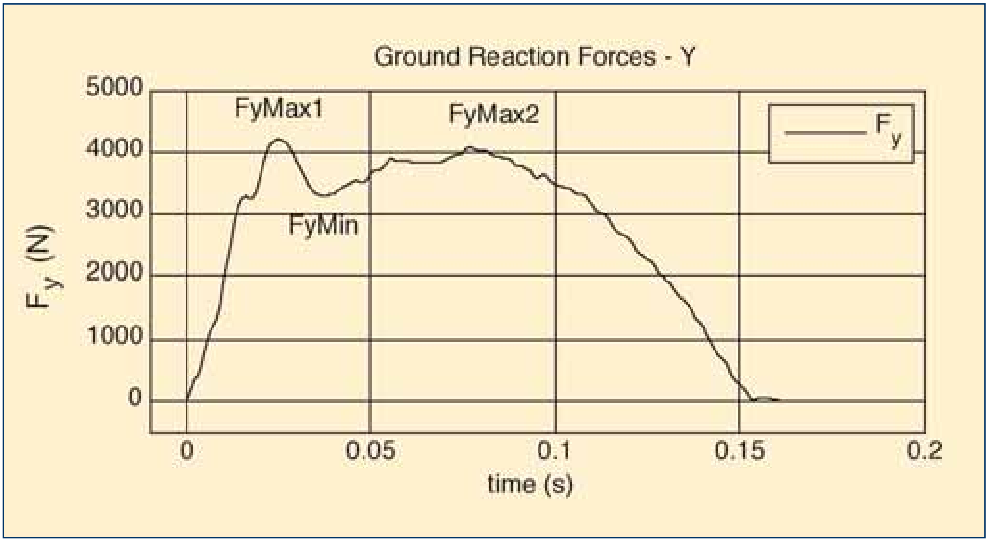

Figure 4: Ground reaction force in the vertical Y-direction

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

VARIABLES	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 (Fly)	Ns	448.3
Horizontal force impulse (Flz)	Ns	185.6
Horizontal force impulse (Flx)	Ns	237.2
Total horizontal force impulse (Flxz)	Ns	301.2
Negative horizontal force impulse (Flx)	Ns	-3.22
Vertical force impulse in eccentric phase (Flye)	Ns	184
Horizontal force impulse in eccentric phase (Flxe)	Ns	122.8
Horizontal force impulse in eccentric phase (Flze)	Ns	111.5
Vertical force impulse in concentric phase (Flyc)	Ns	264.3
Horizontal force impulse in concentric phase (Flxc)	Ns	114.4
Horizontal force impulse in concentric phase (Flzc)	Ns	74.1
Change in vertical velocity calculated from force impulse (ΔV_v)	m/s	3.98
Change in horizontal velocity calculated from force impulse (ΔV_h)	m/s	4.34
Energetic efficiency of take-off (eef)	J/kg	-4.8

trunk). The studied jumper's height H2 equals 1.33m, a thus accounts for 68.6% of his body height. The difference between the minimum and maximum heights of the CM in the take-off phase is 0.37m. This is less than the 0.44m established by ISOLEHTO et al. (2007) from their sample of elite jumpers. 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 CONRAD & RITZDORF, 1990; DAPENA 1992, 2006; HAY, 1993, ARAMAPATZIS & BRÜGGEMANN, 1999; ISOLEHTO et al., 2007; AE et al., 2008). Our subject's vertical

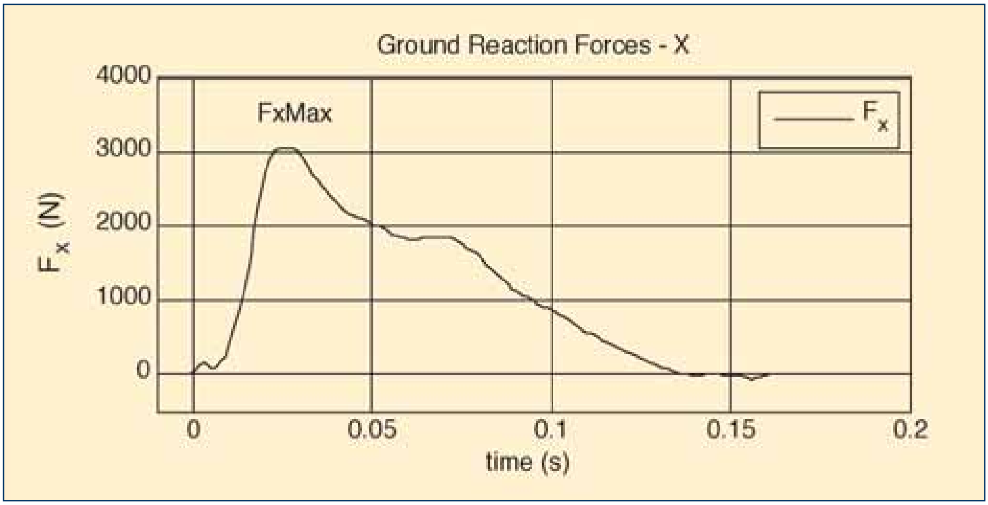

Figure 5: Ground reaction force in the horizontal X-direction

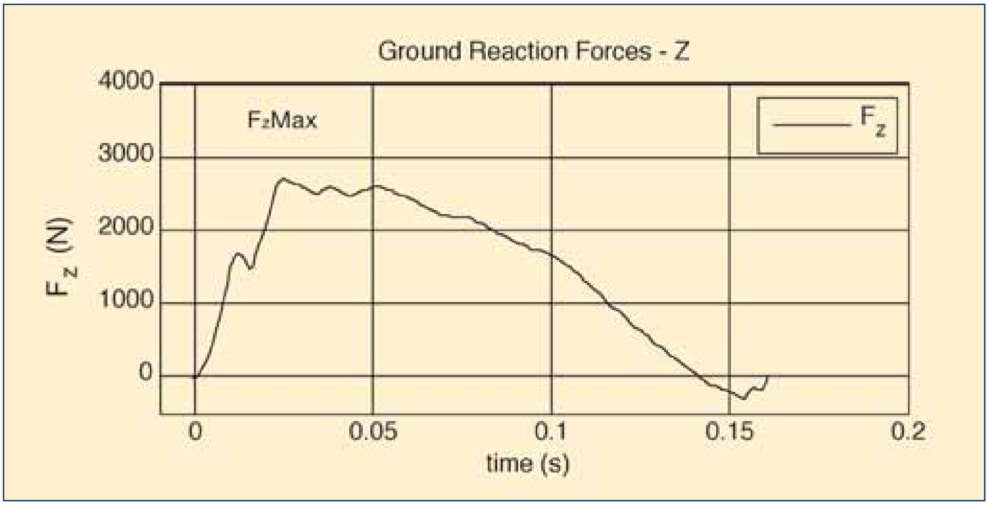

Figure 6: Ground reaction force in the horizontal z-direction

velocity was 4.33m/s. 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 great as possible (DAPENA, 2006). During the take-off action, the horizontal component of velocity of the jumper's CM decreased by 4.45m/s and the vertical component increased by 4.16m/s. 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 ± 0.28m/s (ISOLEHTO et al., 2006). The shortcoming of our subject is that the velocity of his CM is too low in the last two strides of the approach (7.15m/s) and at the start of the take-off phase (6.64m/s). The finalists at the 2005 World Championships in Athletics recorded a velocity in the initial phase of the take-off of 7.87 ± 0.34m/s.

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

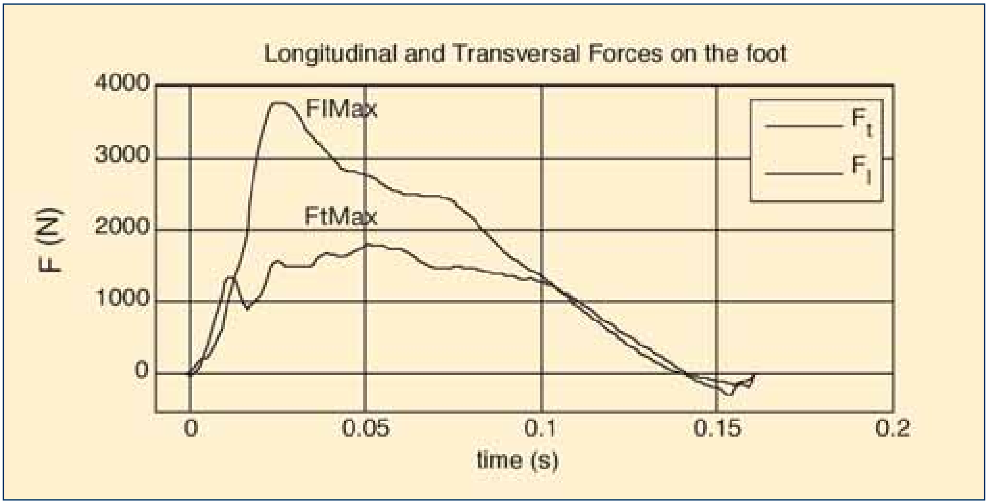

Figure 8: Longitudinal and transversal forces on the foot

The 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). Our subject's take-off time was 0.162sec. 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 approach velocity, horizontal velocity in the take-off action and the take-off time, our study subject is a power-flopper.

The transformation of the movement of the CM from horizontal to vertical is the most critical phase of the high jump and is related to the kinematic and 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 25ms after the first contact with the ground and was slightly higher, measuring 4,213N, the second occurred after 77ms and was slightly lower, measuring 4,091N (Table 2). In between is a local minimum, occurring after 38ms and measuring 3,303N. 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 coordinated with the first maximum, however it comes close. In the 'x' direction, it occurs 27ms after the contact with the ground and measures 3,053N, whereas in the 'z' direction it occurs slightly earlier, after 25ms, and is slightly lower, i.e. 2,708N.

The total contact time on the force plate was 162ms. The distance between the take-off point (touchdown) and the bar in the horizontal direction was 1.02m. 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 1,806N and occurs 51ms 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 3,763N and occurring 25ms 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 162ms). 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 = 4.16m/s and in the horizontal direction Δ Vh = – 4.45m/s (see Table 1). In accordance with the law that a change in momentum equals the impulse of force, the dynamic measurements yielded the following: Δ Vv = 3.98m/s and Δ Vh = 4.34m/s. 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} = –4.8J/kg. In other words, the athlete loses energy proportionally to the increase in velocity from zero to 3.1m/s. 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 & GOLHOFER, 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 120ms (CAVAGNA et al., 1965; 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 alpha 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 180ms.

Conclusion

Based on this study it is possible to confirm that effectiveness in high jumping largely depends on the 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 studied developed the highest ground reaction force in the eccentric phase of the take-off action. The ground reaction force in the vertical direction exceeded his 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 during the take-off action.

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