Principal Component Structure and Sport-Specific Differences in the Running One-Leg Vertical Jump

G. Laffaye[1]
B. G. Bardy[1]
A. Durey †[2]

Abstract

The aim of this study is to identify the kinetic principal components involved in one-leg running vertical jumps, as well as the potential differences between specialists from different sports. The sample was composed of 25 regional skilled athletes who play different jumping sports (volleyball players, handball players, basketball players, high jumpers and novices), who performed a running one-leg jump. A principal component analysis was performed on the data obtained from the 200 tested jumps in order to identify the principal components summarizing the six variables extracted from the force-time curve. Two principal components including six variables accounted for 78% of the variance in jump height. Running one-leg vertical jump performance was predicted by a temporal component (that brings together impulse time, eccentric time and vertical displacement of the center of mass) and a force component (who brings together relative peak of force and power, and rate of force development). A comparison made among athletes revealed a temporal-prevailing profile for volleyball players, and a force-dominant profile for Fosbury high jumpers. Novices showed an ineffective utilization of the force component, while handball and basketball players showed heterogeneous and neutral component profiles. Participants will use a jumping strategy in which variables related to either the magnitude or timing of force production will be closely coupled; athletes from different sporting backgrounds will use a jumping strategy that reflects the inherent demands of their chosen sport.

Key words
Force · Fosbury · volleyball · handball · basketball

Introduction

Vertical jumps are common movements in a wide variety of sports and are often ranked in four general categories: the *squat jump*, in which the subject begins the jump from a low position with bent knees; the *drop jump*, in which the subject falls onto the ground from a particular height; the *counter-movement* jump, with the use of a downward motion followed by an upward motion; and the *running one-leg jump*, in which the subject runs and jumps on one leg, e.g., in long or high jumping.

During the last two decades or so, many researchers have contributed to discover the relationship between physical or anthropometical factors and jumping performance [6,10,15], but have failed to reach a real agreement on (i) the variables that can accurately predict the vertical performance, and (ii) the accuracy of the prediction. Such investigations are typically based on correlation or regression analyses. For instance, multiple regression models having a relatively high level of reliability were used in the prediction of the jumping height (Fosbury-flop) from given physical and technical qualities [10]. Other authors [2,4] have shown that during vertical jump, force pattern could be a good predictor of performance by using a multiregression analysis.

Affiliation
[1] Motor Control and Perception Laboratory, UPRES EA 4042, University Paris XI, Orsay, France
[2] Laboratory of Aerodynamics and Biomechanics, University of the Mediterranean, Marseille, France

Correspondence
Guillaume Laffaye · Center for Research in Sport Sciences · University of Paris Sud XI · Batiment 335 · 91405 Orsay Cedex · France · Phone: +33169156287 · Fax: +33169156222 · E-mail: cglaffaye@aol.com

Accepted after revision: July 20, 2006

Bibliography
Int J Sports Med 2007; 28: 420–425 © Georg Thieme Verlag KG · Stuttgart · New York ·
DOI 10.1055/s-2006-924507 · Published online November 16, 2006 ·
ISSN 0172-4622

Table 1 Sample and task characteristics: mean (SD)

Sample characteristics	*High jumpers*	*Volleyball players*	*Basketball players*	*Handball players*	*Novices*
Number	5	5	5	5	5
Level	2.01 m (0.04)	3rd national division	3rd national division	3rd national division	none
Age (y)	24.4 (3)	26 (6.9)	22.8 (2.9)	24.3 (4.8)	24.5 (4.2)
Height (m)	1.84 (0.03)	1.85 (5.6)	1.86 (8.7)	1.83 (9.4)	1.83 (3.2)
Mass (kg)	77.5 (7)	79.4 (6.3)	73.8 (9.4)	75.8 (7.6)	72.5 (8.2)
Vertical jump performance (m)	65.2 (4.1)	55.2 (4.0)	50.2 (3.3)	55.4 (4.3)	48.3 (5.4)

Aragon-Vargas and Gross [2] have proposed different levels of predictability, from force pattern to complex multisegmental model and have demonstrated that force pattern is the more accurate predictor of performance. Laffaye et al. [11] have shown that a minimum value of leg stiffness (11.5 kN/m) is necessary to jump high in a one-leg vertical jump task. Ae et al. [1] showed that an excessive knee and ankle flexion at take-off decreases the performance, mostly because the flexion time has to be as short as possible in order to allow an efficient stretch-shortening [9]. Dimitriev [5] indicated that a high flexion of the knee dramatically decreases the jump performance. Another factor involved is obviously the role played by the free segments. In the throw-and-fix technique, which consists of accelerating the free segments upward and then blocking them quickly, the adduction of the free knee contributes 56% of the overall vertical velocity [13]. These actions performed with an optimal timing increase the effectiveness by about 12% [14]. Vint and Hinrichs [16] confirmed the role played by the free segments and suggested that there was no difference in vertical performance between a one-foot and two-foot jump. However, different strategies were employed: the one-foot jump benefited from an increased take-off height due to the role of the free swinging leg, while greater flight heights were achieved during two-foot jumps. So, this shows that timing factors have crucial contributions during the jump.

Moreover, this theoretical background suggests that classical methods used to investigate jumping performance are only based on kinematics analysis or multiple regressions of time and force parameters. But recently, a new method has been proposed [8] in order to understand the jumping structure, using a principal component analysis (PCA). Kollias et al. [8] compared the squat jump of different sport categories (track athletes, soccer, volleyball, and handball players) and showed that 73% of the total variance could be explained by two principal components: a temporal factor linking together contact time, time to the peak of force, and rate of force development (but with a negative loading); and a force factor linking peak of force and peak of power. The PCA model allowed the understanding of the redundant variables involved in the squat jump performance and appeared to be an adequate method for capturing the differences between participants. It is an alternative to classical multiple regression analyses, in which the independent variables correlated with the dependent variables are included in the model, but not the uncorrelated variables. The PCA method allows the understanding of the link between all variables, summarized in a fewer number of factors (or principal components).

In the present contribution, we are concerned by the generalization of the results obtained by Kollias et al. [8] in another type of jump: the one-leg vertical jump. Is the model specific to the squat jump or does a common motor pattern exist in the two jumps? Are the individual signatures of the jumpers (track athletes, volleyball and handball players) transferable from the squat jump to the one-leg jump?

Finally, this theoretical background suggests that (i) timing and force factors can be good candidates to predict performance in various types of vertical jump, and (ii) a principal component analysis can be an interesting alternative to achieve a global view of the structure of specific jumps [2,4,7].

So, the hypotheses of this study are (i) similar characteristics will be identified between the inherent structure of the squat jump and the one-leg vertical jump, (ii) participants will use a jumping strategy in which variables related to either the magnitude or timing of force production will be closely coupled, and (iii) athletes from different sporting backgrounds will use a jumping strategy that reflects the inherent demands of their chosen sport.

Materials and Methods

Twenty-five male subjects were grouped in five different categories: Fosbury-flop athletes, handball players, volleyball players, basketball players and novices, as shown in Table 1. All experts were skilled at the regional level, had at least five years of practice in their respective sports, and were in good physical condition.

All participants were submitted to a preliminary one-leg maximum vertical jump test. The test consisted of running over 5 meters, then jumping on one foot in order to touch a target with the top of the head. The target was a smooth ball (25 cm in diameter), tied to the end of a thread going over a pulley that the experimenter could manipulate. The maximum height was assessed with a precision of ± 1 cm.

After this preliminary test, the target was located at a height equal to 95% of the maximum height, and each subject was instructed to run, jump, and touch the ball with the head. The task stopped when each subject touched the target eight times. The eight trials were recorded (kinetics and kinematics), giving 40 jumps (5 participants × 8 trials) for each group.

At each trial, we collected and recorded both the kinetics and the kinematics of the jump. For the kinetic data, an (AMTI OR6-5 (AMTI, Watertown, MA, USA) force plate was positioned at the end of the run-up, with its upper surface at ground level. The sampling frequency was 600 Hz.

For the kinematic data, the motion of the segments was recorded in three dimensions with a six MCAM camera 640 VICON infra-red motion analysis system (Vicon, OMG Companies, USA), at a sampling rate of 120 Hz.

In total, 32 passive reflecting markers were positioned on various parts of the body, using the anthropometric model of Chandler et al. [3] in order to construct a 3-D human body model. A light-emitting diode was used to synchronize the six cameras together with the force plate, triggered by a 5V signal.

The total ground contact period was analysed, including take-off, aerial and landing phases. Six biomechanical variables that have been previously identified in the literature as strong predictors of jumping performance [2,4,8] were calculated from the kinematic and kinetic data. These parameters were: a) peak vertical force scaled to body weight (RF_{max}), b) peak power scaled to body weight (RP_{max}), c) maximum rate of force development (RFD_{max}), d) impulse contact time (TIME), e) time-to-peak force (TF_{max}), and f) vertical displacement of the mass center during the take-off phase (H_{COM}).

The mechanical power (RP_{max}) was obtained by multiplying the vertical ground reaction force by the vertical velocity of the center of mass and scaled to body weight (BW). The maximum rate of force development (RFD_{max}) was calculated as the first time derivative of the vertical ground reaction force. The jump height was defined as the vertical height traveled by the C.M. between the end of take-off and the apex of the jump. The vertical displacement of the center of mass (H_{COM}) was calculated from the kinematic data during the force application stage (see Fig. **1**).

The principal components analysis (PCA) was performed on the data obtained from the 200 tested jumps (8 jumps × 25 subjects) in order to identify the principal components summarizing the six variables. The PCA was obtained from the STATISTICA package (version 5.5, Statsoft, Inc.) using the procedure described by Kollias et al. [8]. The number of principal components in the pattern matrix extracted by the PCA was chosen with an eigenvalue greater than 1. The original matrix was rotated to extract the appropriate variables, using a normalized $VARI_{max}$ rotation (orthogonal rotation). This rotation allowed an earlier labelling of the principal components. In order to characterize the jumping profiles for each sport group, the individual jumps (averaged over trials) were plotted in a plane containing the two principal components. In addition, a partial correlation matrix was done within the variables (with $p < 0.05$).

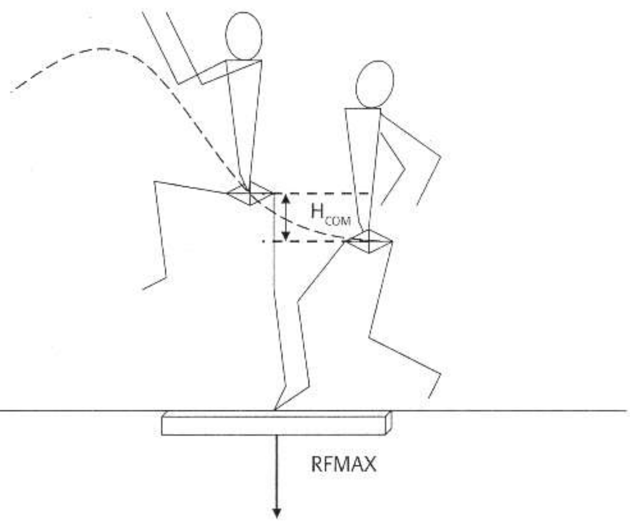

Fig. 1 Trajectory of the center of mass at impulse (between take-off and landing) in a one-leg vertical jump. H_{COM} represents the vertical displacement of the center of mass and RF_{max} the peak vertical force exerted on the ground.

Results

The duration of take-off foot contact was (mean [SD]) 260 ms (36), with a mean time-to-peak force of 143 ms (36). The mean peak force was 3.18 times the body weight (0.4), and the mean power output was 6.85 times the body weight (1.4). The mean value of the rate of force development was 64.3 kN/s (35.4), and the mean displacement of the mass center was 22.5 cm (3). The peak of force development ranged from 15 kN/s to 180 kN/s, and the vertical peak of force ranged from 2.19 to 4.00 times the body weight.

The partial correlation matrix indicates the intercorrelation of many variables, independently of jumping height. TIME was highly and positively correlated with TF_{max} ($r = .81$, $p < .01$) and H_{COM} ($r = .77$, $p < .01$) and negatively correlated with RF_{max} ($r = -.79$, $p < .01$). In other words, the increase in the contact time was prohibitive for the peak of force. RF_{max} was significantly and positively correlated with RP_{max} ($r = .64$, $p < .01$).

The PCA revealed two principal components (Table **2** and Fig. **2**), characterized by a temporal grouping and a force grouping that accounted for 78.3% of the total variance.

The first principal component that was rotated, accounting for 41.1% of the total variance, was associated with the temporal variables. The eigenvalue corresponding to this component was 2.45. This component was highly loaded with the variables H_{COM}, TIME, and TF_{max} (.902, .840, and .808, respectively). All variables from this first principal component were positively loaded, indicating that a large vertical displacement during the take-off phase resulted in a long time-to-peak force and a long contact time.

The second rotated principal component accounted for 37.18% of the variance of the force data. The eigenvalue of this second component was 2.21, and was associated with the force variables. This force component linked together RP_{max}, RF_{max}, and RFD_{max}

Table 2 Results of the PCA showing for each variable factor loadings and commonalities, as well as eigenvalues and percentage of variance for each rotated principal component

Variables	*Factor loadings*		*Commonalities*
	1	*2*	
TIME	.840		.776
TF_{max}	.808		.680
RF_{max}		.746	.667
RP_{max}		.882	.516
RFD_{max}		.744	.367
H_{COM}	.902		.558
Eigenvalue	2.45	2.21	
% of variance	41.1	37.2	

TIME: impulse duration; TF_{max}: time-to-peak force; RF_{max}: peak of vertical force scaled to body weight; RP_{max}: peak of power scaled to body weight; RFD_{max}: rate of force development; H_{COM}: vertical displacement of the center of mass

with loadings of .882, .746, and .744, respectively. The positive loading indicates that a high value of the maximum ground reaction force was associated with a high value of the rate of force development, and were associated with a high power peak. All six force variables were included in the PCA model.

The second goal of this study was to describe the force application strategy differences among different sport group samples using the PCA analysis. Five sport groups were tested and contrasted. Plotting the mean individual scores on the two principal components allowed this comparison (Fig. **3**).

The x-axis of Fig. **2** corresponds to the first principal component, namely the time component. A jumping performance with a large value on this first component would demonstrate higher values for H_{COM}, TIME and TF_{max}. The main strategy employed in these jumps was, therefore, to rely on the temporal component, i.e., on a long contact time and a great vertical displacement of the center of mass. This strategy was more present in the volleyball players of the sample, with component scores ranging from 0.8 to 3.5. Jumps characterized by a negative relationship for the temporal component were likely to be briefer and exhibited a short impulse, a short time-to-peak force, and a small vertical displacement of the COM.

The y-axis of Fig. **2** indicates the 2nd principal component, which was characterized as the force component. A positive high level on this axis indicates a high value of the ground reaction force, a high power output, and a great rate of force development. Fig. **2** reveals that the Fosbury-flop high jumpers (Fosbury-flop) exhibited this characteristic, with high values of RF_{max}, RP_{max}, and RFD_{max} on that axis, averaging a value of 2.6. A large negative value on this axis reveals a low level of power and force, as well as a small rate of force development. The majority of novice jumpers exhibited such an ineffective utilization of the force component. Handball and basketball jumpers exhibited an alternative profile with values of time and force components close to zero.

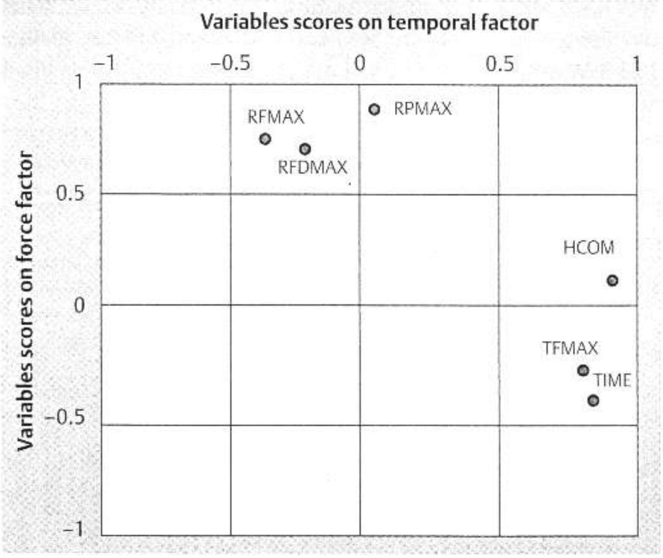

Fig. **2** Variables scores on the two rotated principal components. The *x*-axis represents the first principal component, i.e., the temporal factor, bringing together impulse duration TIME, time-to-peak force TF_{max}, and vertical displacement of the center of mass H_{COM}. The *y*-axis represents the second principal component, i.e., the force factor, and links together peak of force RF_{max}, peak of power RP_{max}, and rate of force development RPD_{max}.

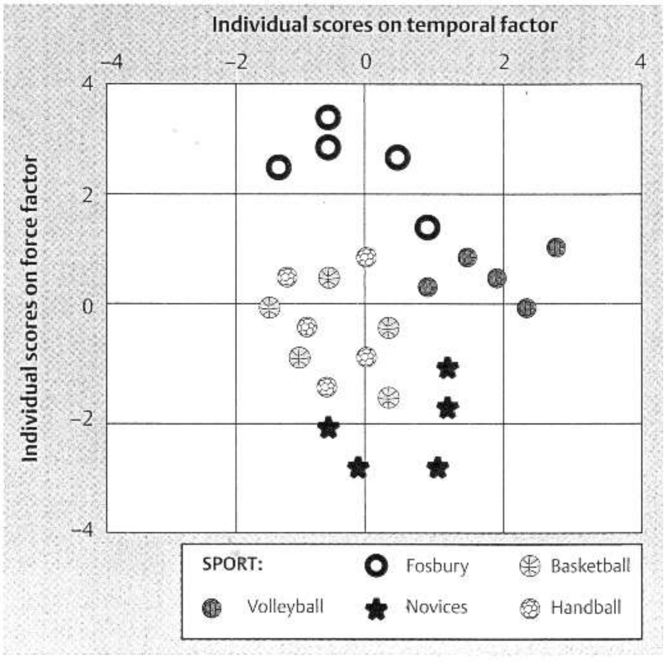

Fig. **3** Individual scores for each subject (mean value of 8 jumps) on the two rotated principal components. The *x*-axis represents the first principal component, i.e., the temporal factor. The *y*-axis represents the second principal component, i.e., the force factor.

Thus, we found a consistent progression in which larger heights (48 ± 5 cm for novices, 55 ± 4 cm for handball players, 50 ± 3 cm for basketball players and 65 ± 4 cm for high jumpers) were achieved by increasing the vertical force but not altering the duration of take-off too much. Novices used small forces (3.01 ± 0.23 BW) during a moderated period of time (233 ± 21 ms); basketball and handball players produced larger forces (respectively, 3.18 ± 0.57 BW and 3.13 ± 0.14 BW) than novices over a slightly longer period of time (respectively, 255 ± 30 ms and 258 ± 4 ms); high jumpers used still larger forces (3.64 ± 0.23 BW) over a similar period of time (238 ± 13 ms). Volleyball players branched off in a different direction in the graph: they produced large jumping height (55 ± 4 cm) mainly by increasing the duration of take-off (288 ± 36 ms) rather than by increasing vertical force (2.89 ± 0.16 BW).

Discussion

The *first* hypothesis was that similarities exist in the structure of the squat jump and the one-leg jump.

In order to validate this hypothesis, a comparative assessment was made between our results and those found in the squat jump [8] and the following similarities were found. First, the two principal components share similar mechanical characteristics in both types of jump. The temporal component linked TIME, TF_{max} and RFD_{max} in the squat jump, and TIME, TF_{max} and H_{COM} in the running jump. The role of H_{COM} thus appears more important in the one-leg jump. This was confirmed by the commonality of this component, which had a very low level in the squat jump, but a higher level in our one-leg jump.

The second principal component involved was a force component in both the squat jump and the one-leg jump. This component includes RF_{max} and RP_{max} in both cases, assuming that an increase of maximum vertical force is obviously linked with an increase of maximum power. In contrast, RFD_{max} appears to be specific to the one-leg jump. Indeed, this variable, present only in the running jump PCA model, reveals that the impact force from heel to ground has a great influence on the change in force value. During the squat jump, there is no impact force because the two feet are already in contact with the ground at the initiation of the jump. This may explain why RFD_{max} is included in the running one-leg jump and not in the squat jump. Hence, our results show the crucial role of the "time" and "force" elements in high jumping, as it has been revealed in the squat jump [8].

Moreover, the comparison between the squat jump and the one-leg jump revealed similarities and differences when considering the plots of individual subjects. First, a difference between the two types of jump exists for volleyball players, because in the squat jump there was not a clear loading of the temporal force, while in the one-leg jump there was. Second, the component scores found for the handball players in squat jumps revealed negative loadings on the force variables, indicating low values in the force peak and the power output. Such a clear profile was not obtained in the one-leg jump: two subjects had positive scores and three subjects had negative scores on the force component.

Lastly, track athletes revealed a high level of scores on the second principal component (force variables) in both types of jump. This similarity suggests that the same spatio-temporal structure occurs in the two types of jump.

Our *second* hypothesis was that participants use a jumping strategy in which variables related to either the magnitude or timing of force production is closely coupled. We found that volleyball players revealed a temporal-prevailing profile (large contact time and eccentric time). Volleyball players were the only athletes to exploit the time component. On the other component, the force-dominant profile, we found a consistent hierarchy between novices, who showed an ineffective utilization of the force component to handball and basketball players, who showed heterogeneous and neutral component profiles to Fosbury-flop athletes, who revealed larger force and power. This result indicates that good performances can be achieved through specificity of each sporting background with different strategies. Volleyball players produced large jumping height (55 ± 4 cm) mainly by increasing the duration of take-off (288 ± 36 ms) rather than by increasing vertical force (2.89 ± 0.16 BW). This strategy of jump is very different for others jumpers, who produced large heights by increasing the vertical force but not altering too much the duration of take-off. Basketball and handball players produced large forces (3.18 ± 0.57 BW and 3.13 ± 0.14 BW, respectively); high jumpers used still larger forces (3.64 ± 0.23 BW) over a short period of time (238 ± 13 ms). So, this shows that participants will use a jumping strategy in which variables related to either the magnitude or timing of force production will be closely coupled. Moreover, this poses the question of the link of the sporting background and the strategy of jump.

Our *last* hypothesis was that athletes from different sporting backgrounds use a jumping strategy that reflects the inherent demands of their sport. Indeed, the PCA model explains that each jumping sport promotes a specific jump adapted to the constraints of the task. Handball and basketball activities involve a high level of constraints by direct confrontation between the opponents, in which the jumps must be highly adaptive. This may explain why these sports do not develop a specific strategy based on one component, but heterogeneous and neutral component profiles. The volleyball task does not involve a direct confrontation (no contact between the opponents), but the optical regulation of the ball's approach and the opponent movement is necessary to achieve an attack, which implies to maintain a long time of contact with the ground before take-off. Our PCA model captures such a behavior. Complementary experiments could be performed to test more specifically this explanation by coupling optical variables and volleyball jumping parameters in different ways (e.g., Lee et al. [12]). Finally, Fosbury-flop does not involve such a regulation. Here, the jumper can focus on the force and power output, which are highly correlated with jumping height [5].

To conclude, the PCA model appears to be a good candidate to understand the specific structure of a one-leg jump. In our study, the one-leg vertical jump could be modeled by only two components: a temporal component (that brings together impulse time, eccentric time and vertical displacement of the center of mass) and a force component (which brings together relative peak of force and power and rate of force development). The PCA model may be used to better circumscribe the jumping profiles of individual athletes, demonstrating the role of sport and practice in shaping jumping components, but also allowing early talent detection.

References

1 Ae M, Sakatani Y, Yokoi T, Hashihara Y, Shibukawa K. Biomechanical analysis of the preparatory motion for take off in the Fosbury flop. J Sport Biomech 1986; 2: 66 – 77

2 Aragon-Vargas LF, Gross M. Kinesiological factors in vertical jump performances: differences among individuals. J Appl Biomech 1997; 13: 24 – 44

3 Chandler RF, Clauser CE, McConvile JT, Reynolds HM, Young JW. Investigation of Inertial Properties of the Human Body. Aerospace Medical Research Laboratories, Aerospace Medical Division. Wright-Patterson AFB, OH, USA: Wright-Patterson Air Force Base, 1975

4 Downling J, Vamos L. Identification of kinetic and temporal factors related to vertical jump performance. J Appl Biomech 1993; 9: 95 – 110

5 Dimitriev V. The Fosbury flop: basic structure of the take off. Soviet Sports Rev 1986; 21: 167 – 171

6 Ginter KD. Trainingsbegleitende Tests beim Flop zur Feststellung von Trainingsschwerpunkten [training test to determine the work training in flop]. Leistungsport 1979; 9: 323 – 330

7 Hay JG, Dapena J, Wilson BD, Andrews J, Woodward G. An analysis of joint contributions to performance of a gross motor skill. In: Asmussen E, Jorgensen K (eds). Biomechanics VI-B. Baltimore: University Park Press, 1978

8 Kollias I, Hatzitaki V, Papaiakovou G, Giatsis G. Using principal components analysis to identify individual differences in vertical jump performance. Res Q Exerc Sport 2001; 72: 63 – 67

9 Komi P, Gollhoffer A. Stretch reflex can have an important role in force enhancement during SSC-exercise. J Appl Biomech 1997; 13: 451 – 460

10 Laffaye G. Le saut en hauteur en Fosbury et les facteurs de performance: une revue de question (Predicting performance in Fosbury high jump: a review). Sciences et Motricité 2001; 42: 3 – 15

11 Laffaye G, Bardy B, Durey A. Leg stiffness and expertise during men jumping. Med Sci Sport Exerc 2005; 37: 536 – 543

12 Lee DN, Young DS, Reddish PE, Lough S, Clayton TMH. Visual timing in hitting an accelerating ball. Q J Exp Psychol 1983; 35: 333 – 346

13 Luhtanen P, Komi P. Segmental contributions to forces in vertical jump. Eur J Appl Physiol 1978; 38: 181 – 188

14 Luhtanen P, Komi P. Mechanical power and segmental contribution to force impulses in long jump take-off. Eur J Appl Physiol 1979; 41: 267 – 274

15 Van Coppenolle H, Boeths W, Goris M, van Cafelghem G. Der diagnostische und pronostische Wert einzelner sportmotorischer Tests für den Fosbury-Flop [diagnostic and prognostic motor evaluation test for Fosbury-flop]. Lehre der Leichtathletik 1983; 58: 179 – 183

16 Vint PF, Hinrich RN. Differences between one foot and two-foot vertical jump performances. J Appl Biomech 1996; 12: 338 – 358