BIOMECHANICAL ANALYSIS OF THE POLE VAULT AT THE VIth WORLD CHAMPIONSHIPS IN ATHLETICS

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INTRODUCTION: From the viewpoint of energetics the main difference between the pole vault and the other jumping disciplines is that the transformation of the approach energy to pole release energy or take off energy can take place without an energy loss and sometimes even with an energy gain (Groß and Terauds 1983; Groß and Kunkel 1990, Arampatzis et al. 1997). A large decrease in the athlete's total energy occurs during this transformation in all the other track and field jump disciplines (Brüggemann and Arampatzis 1997; Müller and Brüggemann 1997).
The reason for this difference is the elasticity of the poles. Several authors (Dillman and Nelson 1968; Braff and Depena 1985; Ekevad and Lundberg 1997) have attempted to determine the influence of the length and stiffness of the poles on jump performance. The results indicate that an optimum pole stiffness and length can be determined which would allow the pole vaulter to jump to his maximum height (Ekevad and Lundberg 1997). During the pole phase the athlete's muscular energy is used to store energy in the pole (Hubbard 1980; Groß and Terauds 1983; Groß and Kunkel 1990). The resultant shoulder joint moments are much higher than the resultant hip and knee moments (McGinnis and Bergman 1986). Using only the amount of muscular energy production during the pole phase (Groß and Terauds 1983; Groß and Kunkel 1990) it is not possible to identify differentiated deficits in the technical components of the athletes (Arampatzis et al.1997).
Arampatzis et al. (1997) outlined 3 criteria which characterize the initial conditions in the pole vault (Criterion 3) as well as the pole vaulter's behavior during the pole phase. During the first part of the pole phase, ending with the maximum pole bend position, energy is transferred into the pole and the total energy of the athlete decreases. The difference between the energy decrease of the athlete and the energy gain of the pole indicates whether this phase of the vault was performed effectively (Criterion 1). During the second part of the pole phase, ending with pole release, energy is transferred back into the athlete and the total energy of the athlete increases. The difference between the returned pole energy and the amount of energy increase of the athlete defines Criterion 2.
The main goals of this study were:

1. To examine the behavior and practical application of 3 criteria concerning energy behavior in the pole vault at the world class level.
2. To determine the amount of influence of the initial conditions, as well as the influence of the athlete's behavior during the pole phase on pole vault performance.

METHODS: The data for this study was collected at the 1997 World Track and Field Championships in Athens, Greece. 25 successful jumps by 11 pole vaulters during the finals were analyzed 2-dimensionally using two video cameras operating at 50 fields per second. A total of 22 frames from each jump were digitized at specific positions. The video data was digitized using the Peak-Motus system. The

calculation of the following parameters was possible using a fast information program developed by the Department of Track and Field and Gymnastics at the German Sport University in Cologne, Germany: CM position, CM velocities and total CM energy.
Using a cluster analysis groups were formed on the basis of similar initial energy (Criterion 3), Criterion 1 and Criterion 2 values. A total of 3 groups were formed (Tab. 2). The differences between the groups were tested using a T-test for an independent sample group.

RESULTS:

Table 1 – Selected analyzed jumps

Name	Jump height (m)	Eff. height (m)	$E_{init.}$ (J/kg)	Criterion 1 (J/kg)	Criterion 2 (J/kg)	End energy (J/kg)	Group
Bubka	6.01	6.50	59.23	4.73	0.27	64.23	3
Bubka	5.91	6.17	57.56	4.08	-0.03	61.61	3
Bubka	5.70	6.27	58.45	3.51	0.48	62.44	3
Tarasov	5.96	6.23	60.85	1.83	-0.71	61.96	1
Tarasov	5.91	6.08	60.99	0.14	-0.35	60.78	1
Tarasov	5.86	6.11	60.78	-1.37	1.38	60.79	1
Tarasov	5.80	6.08	63.17	-3.48	0.91	60.6	1
Starkev	5.91	6.12	55.68	3.70	1.30	60.69	3
Starkev	5.86	6.09	57.51	2.11	0.89	60.51	3
Starkev	5.80	5.95	55.45	2.01	1.62	59.08	2
Starkev	5.70	5.94	55.88	1.97	0.94	58.79	3
Starkev	5.50	5.84	56.10	2.04	0.23	58.37	3
Buckfield	5.70	5.85	55.90	-0.42	2.50	57.98	2
Manson	5.70	5.97	55.78	-1.13	4.58	59.23	2

Table 2 – Analyzed parameters of the starting conditions and the energy exchange phase

Parameter	Group 1 (n=4)	Group 2 (n=9)	Group 3 (n=12)
Initial energy (Joule/kg), Criterion3	61.45 (1.15)	55.89 (0.99) *	57.17 (1.17) * ⊥
End energy (Joule/kg)	61.03 (0.62)	58.25 (0.97) *	60.03 (1.99) ⊥
Muscular work (Joule/kg)	-0.42 (1.55)	2.36 (1.64) *	2.86 (1.70) *
Criterion 1 (Joule/kg)	-0.72 (2.25)	0.29 (1.32)	2.65 (1.11) * ⊥
Criterion 2 (Joule/kg)	0.31 (0.99)	2.07 (1.22) *	0.21 (0.92) ⊥
Effektive height (m)	6.13 (0.07)	5.86 (0.10) *	6.04 (0.21) *
Jump height (m)	5.88 (0.07)	5.60 (0.12) *	5.72 (0.18)

∗ : Statistically significant ($p<0.05$) difference between groups 1 and 2 and between 1 and 3.

⊥ : Statistically significant ($p<0.05$) difference between groups 2 and 3.

DISCUSSION: Individually the athletes at this elite level all demonstrated similar initial conditions and similar characteristics during the energy exchange phase, regardless of their jump height. The various jumps by the same athlete were always in the same group, with one exception. Starkey produced one jump of 5.80 m which had different group characteristics than his other jumps (Tab. 1). Group 1 was composed of only the 4 jumps by Tarasov.

A total of three groups were made in which the athletes demonstrated different initial conditions and energy exchange characteristics. The CM end energy determined both the jump height and the effective jump height. The CM end energy showed a high correlation with both parameters ($r=0.99$, $p<0.05$ with effective height and $r=0.83$, $p<0.05$ with jump height). This indicates that the goal of the pole vaulter should be to attain the highest possible end energy.

Group 1, jumps only by Tarasov, produced the highest initial energy and demonstrated the worst energy exchange characteristics. Tarasov, in all his jumps, could not manage to create additional energy through muscular work. During the first part of the pole phase, where he could take advantage of the pole's elasticity, he showed large deficits.

For an optimum jump the athlete’s CM energy loss must be less than the maximum pole energy (Criterion 1). The amount of pole energy in excess of the decrease in the athlete's CM energy represents muscular work performed by the athlete during the first part of the pole phase which was stored in the pole as elastic energy. If the CM energy loss is higher than the maximum pole energy a net energy loss has occurred. During the second part of the pole phase the elastic energy which was stored in the pole is returned to the athlete. By straightening the body and first pulling then pushing with his arms the athlete can once again add energy to the system through muscular work. If the increase in CM energy is greater than the decrease in pole energy (Criterion 2) the athlete achieves a greater CM end energy. The increase in energy is a result of muscular work performed by the athlete during this phase. If the CM energy increase is less than the maximum pole energy then an energy loss has occurred. Tarasov's technique showed a deficit during this part. He didn’t perform the proper muscular work and therefore achieved no clear energy gain (Tab. 2). The high initial energy he produced was the factor that accounted for his good jump performance.

Groups 2 and 3 showed significant differences in initial energy. Group 3 had the greater value. The energy gain developed by these two groups during the pole phase was the same. This means that the muscular work performed was also the same. In spite of this the behavior of groups 2 and 3 during the pole phase was different. Group 3 achieved a higher value for Criterion 1, and group 2 achieved a higher value for Criterion 2. The athletes in group 3 were able to effectively store energy in the pole through muscular work during the first part of the pole phase. They showed a deficit during the second part.

During the straightening of the pole group 3 showed no clear energy gain. Even Bubka showed a deficit during the second part of the energy exchange phase (Tab. 1), indicating that the best pole vaulter in the world over the past 15 years has room for improvement. He used the pole elasticity most effectively and achieved the highest value for Criterion 1 (Tab. 1). Group 2 achieved a large energy gain in the second part of the energy exchange phase and shows a deficit in the first part. The athletes from this group didn’t effectively use the pole’s elasticity. One possible explanation for this is that perhaps the rock back was too

passive and therefore not enough positive work was performed by the athlete. Criterion 1 and 2 express the performance of the jumpers during the two parts of the pole phase. Both groups 2 and 3 achieved the same energy gain. The deficits of these groups are different. Group 2 had problems during the rock back movement and group 3 had problems during the straightening movement. Based on the observation of total CM energy alone (Groß and Terauds 1983; Groß and Kunkel 1990) it would not be possible to make this diagnosis. Furthermore, the consideration of the two criteria make it clear for both the groups as well as the individual athletes that improvement of individual performance is attainable.
The end energy in groups 1 and 3 showed no significant difference. Group 2 achieved the lowest end energy. The high end energy value of group 1 was achieved through a high initial energy. Group 3, which had a lower initial energy than group 1, attained the same end energy through a more effective pole phase. The initial energy, which is dependent on the horizontal touch-down velocity, shows a significant correlation with the end energy. The co-relations co-efficient is very small ($r=0.47$, $p<0.05$). This observation makes it clear that even in world class level competition the initial energy determines the jump height potential, but that the behavior of the athlete on the pole, from pole plant until pole release, influences the jump performance.

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