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19:3; 33-42, 2004

A new way of looking at the biomechanics of the pole vault

By Falk Schade, Adamantios Arampatzis, Gert-Peter Brüggemann

ABSTRACT

In recent years there has been a paradigm shift in the study of sport biomechanics, the focus moving from an external description of movements towards an understanding of the internal processes of the movements. On a micro level, these include the interactions between muscle and tendon. On a macro level, studies in track and field include the interactions between the athlete and external implements. Due to the fibreglass pole's elastic nature and large path of deformation, the pole vault is ideal for the study of macro level interaction mechanisms. With the aim of developing individualised technical solutions to help established vaulters improve their results, the authors describe the theoretical background to the approach taken and the evaluation criteria they have developed. Also discussed are the interaction between the vaulter and pole, how energy is transferred to the pole and the differences in the energy considerations between top male and female vaulters gathered during the finals at the 2000 Olympic Games in Sydney. Finally, four movement principles that guide the authors' diagnostic and consultancy work with elite vaulters are outlined. This article is based on a presentation given at the Pole Vault 2004 – Facts and Vision Symposium at the German Sports University in Cologne, 12 –14 March 2004.

AUTHORS

Falk Schade is a biomechanics expert at the Olympic Training Centre Cologne/Bonn/Leverkusen. His responsibilities include providing scientific support to the pole vaulters of Germany's national athletics team. He also coaches pole vault and decathlon at the German Sport University in Cologne and the IAAF Accredited Training Centre in Cologne.

Adamantios Arampatzis is currently an assistant professor at the Institute for Biomechanics and Orthopedics at the German Sport University in Cologne. His major research interest is energy production, storage and utilisation between biological and mechanical systems.

Gert-Peter Brüggemann is the Chair of the Institute for Biomechanics and Orthopedics at the German Sport University in Cologne. His main research interests are the biomechanics of elite and recreational sport, occupational biomechanics and the biomechanics of the spine. He also coaches international level gymnasts.

Introduction

"Vaulting high is what pole vaulting is about."

It is a simple statement, but one that can be difficult to grasp. We know that there are different approaches to training for the pole vault. Nearly every elite vaulter and coach has his/her own philosophy for the event and not all agree. Often these are judged as much on the success of the performer as on how they relate to the fundamental principles of what it takes to vault high. We see developing and even established vaulters sometimes adopting a practice or technical element simply on the basis that someone better is using it. Moreover, we see a tendency towards a generalised model of technique, sometimes known as the Champion's Doctrine, adopted by large numbers of vaulters, regardless of whether the model is appropriate for the individual.

However, in our view, a knowledge-based approach is a better hope for optimising the training process and finding the individual technical solutions that each athlete needs to maximise his/her performance. Developing such an approach calls for a thorough understanding and constantly improving biomechanical knowledge of the event.

The biomechanical analysis (Arampatzis et al., 1997, 1999) of the winning 6.01m vault by the world record holder Sergey Bubka (UKR) at the 1997 IAAF World Championships in Athletics in Athens has shown that had the bar been set as high as 6.30m Bubka would have still cleared it. Such a vault is certainly a level, if not two or three levels, better than the top male pole vaulters currently competing. It is logical therefore that Bubka's way of training and his technique are seen as models. As an orientation for a young vaulter's basic and build-up training, this makes good sense, as Bubka's physical capabilities clearly influenced his technique and performance.

But how should one deal with vaulters who are already at the top level, or are almost there, in order to get them nearer to the level Bubka reached? To what extent is a top-class male vaulter in his mid-twenties able to change fundamental aspects of his technique to bring it closer to Bubka's? And if such a change is possible, will there be an improvement in performance? On the one hand, Bubka demonstrated to perfection how to make use of the elastic qualities of the pole. On the other hand, it must be understood that if, for example, the jumping strength characteristics of an athlete are not similar to those possessed by Bubka, it is unlikely that athlete will be able to use Bubka's specific planting/take-off variation.

In our opinion, performance enhancement at the top levels of pole vaulting can only be achieved through individual movement solutions. Such solutions are best elaborated jointly, with the athlete/coach and the diagnostician working together in the process described in Figure 1.

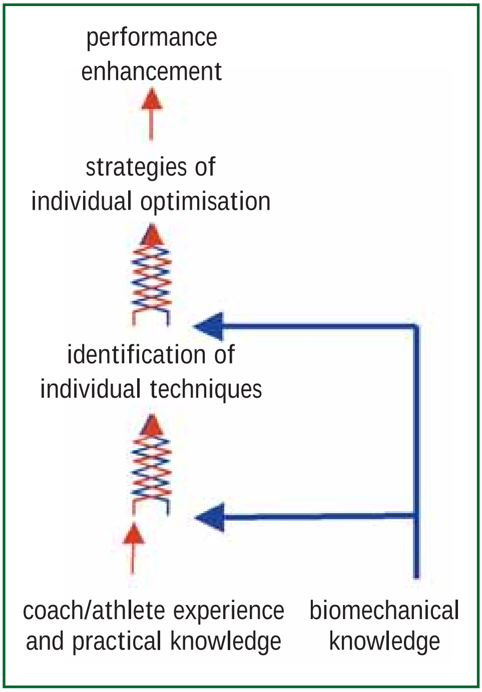

Figure 1: Individualisation of the training process

The main challenge in this context is to determine if and to what extent the technique of an athlete is deficient. It might be possible that the technique in use is already optimal for the complex of performance related characteristics of the athlete! If we can come to a correct conclusion on this matter, the probability of realising a performance enhancement due to something other than simple chance rises significantly.

In order to make such a determination in the pole vault, the technique of the vaulter needs to be measured objectively and understood on the basis of these measurements. It is not enough to simply describe everything that can be seen from the outside. In the past, most applied biomechanical studies of the pole vault looked almost exclusively at the vaulter (ie Gros/Kunkel, 1990; Angulo-Kinzler et al., 1994). Hence, they were paying no attention to the interaction with the pole. However, what is required is an analysis and quantification of the essentials of the event, namely the interaction between the vaulter (active system) and elastic fibreglass pole (passive system). In recent years, there has been a shift in the paradigm of sports biomechanics towards a greater focus on the biomechanical processes, both internal and in relation to external implements, and their measurement. "Movement as interaction" is the hidden understanding in this approach. This, of course, begs the question of how this interaction can be registered and measured.

Energy considerations are an obvious approach. This makes it possible to examine both the movements of the specific athlete and the reaction of the pole, ie to bring both down to a "common denominator". Movement principles can then be derived. These principles explain the exchange of energy between athlete and elastic pole and they can replace the generalised model of technique, the Champions Doctrine, with a model that is both scientifically supported and individualised.

In this article, we outline how we are using energy considerations to develop a new understanding of the pole vault and assist vaulters to improve their performance. We describe the theoretical background to our approach and the evaluation criteria we have developed, including how they are calculated. We then discuss the interaction between the vaulter and pole, how energy is transferred to the pole and the differences in the energy considerations between top male and female vaulters referring to data gathered during the finals at the 2000 Olympic Games in Sydney. Finally, we list four movement principles that guide our diagnostic and consultancy work with elite vaulters.

Theoretical considerations

The following theoretical considerations concerning the energy conversion in the pole vault are based on the earlier work of Arampatzis et al. (2004).

In terms of energy, the pole vault is about the production of energy (the approach run and pole phase) and the transformation of energy (kinetic energy into strain energy into potential energy). These energy transformations occur during the take-off movement (lower extremities), during the pole planting action (upper extremities and trunk) and during the pole phase (athlete-pole-athlete).

It is important to realise that the energy production (by means of muscular work) has to continue during the pole phase. It is also important to know that during the take-off movement the transformation of energy in the lower extremities is similar to the long jump take-off. The take-off direction is similar in the two events and in both, there are parts of the initial energy generated in the approach run which are stored in the elastic structures of the lower extremities throughout the eccentric phase of the take-off. This energy is then passed on in the concentric phase. Hence, we can observe a similar process between muscle and tendon on the micro level to the one we see on the macro level between the vaulter and the elastic pole. This is quite similar in the arm/torso transition throughout the pole planting movement. In this case, we can also find a concentric phase, namely the rockback and stretch/turn, after an eccentric phase. This phase can, however, vary substantially according to the chosen pole plant variation (width of grip, stiffness of the lower arm, giving in of the upper shoulder, pole stiffness, etc.), and the variance has a decisive impact on the following rock-back and stretch/turn.

As a framework for discussing the pole vault and quantifying the energy exchange that takes place, we have chosen a distinct, energy-oriented phase structure of the movement. It consists of two main phases: 1) the approach run, the aims of which are to achieve a high initial energy (approach velocity) at the instant of the final touchdown of the take-off foot and an appropriate take-off and pole planting position; and 2) the pole phase, in which the initial kinetic energy of the athlete is transformed into potential energy and in which the athlete may add further energy to the system.

The pole phase, which starts with the last touchdown of the take-off foot (TD, Figure 2) and ends with the maximum height position of the CM (centre of mass) (HP, Figure 2), can be divided into two additional phases separated by the maximum pole bend position (MPB, Figure 2). Until this position is reached, energy is transferred into the pole and stored as strain energy; from this position onwards, the pole returns its strain energy.

Strain energy: the ability of a body to do work by virtue of its deformation. In the case of elastic bodies it can be called "elastic energy".

Evaluation criteria

Following our selected phase structure, we have developed two criteria to enable us to analyse the quality of interaction with the pole (see Arampatzis et al., 2004). Criterion 1, for measuring the technical quality (specifically the work of the vaulter on the pole within the first pole phase), is the energy gain of the system vaulter/pole up to the maximum pole bend position. This criterion is considered positive if the vaulter adds significant energy; it is considered negative if energy is lost or only a little is added. The value of Criterion 1 is calculated by the difference between the maximum strain energy of the pole (MPB) and the athlete's loss of energy within the first pole phase. If the strain energy of the pole increases from the point of take-off until MPB by more than the vaulter's loss of energy then this "extra increase of pole energy" is the energy gain of the whole system within this phase. Importantly, this gain can only be caused by the muscular work of the vaulter.

The situation is inverted in the second pole phase. If the energy of the vaulter increases from MPB to HP by more than the energy the pole releases, Criterion 2 is considered positive. Again, this energy gain can only be the result of muscular work by the vaulter.

Adding the two criteria gives us the energy balance of the vault, ie the gain of energy between TD and HP. If it is not possible to calculate the energy of the pole (because force measurement equipment in the planting box is not available), the energy balance can also be calculated by the difference between the mechanical energy of the vaulter at the instant of maximum CM height and the instant of touchdown of the take-off foot at take-off. Technical strengths and weaknesses of both pole phases cannot be derived exactly from this data, but the quality of the whole vault, ie what the vaulter makes of the initial energy (the energy generated in the approach run), can be evaluated perfectly.

Calculation of the athlete's mechanical energy

The energy of the athlete is calculated on a kinematic basis. The procedure is free of repercussions and can even be used in championships without any problems. Usually 4 genlocked 50Hz video cameras are used as shown in Figure 2.

The mechanical energy of the vaulter can be calculated either in relation to the CM or as total mechanical energy. In addition, either a two-dimensional or a three-dimensional analysis can be used. The calculation procedure has only very little influence on the calculation of the criteria (Schade et al., 2000).

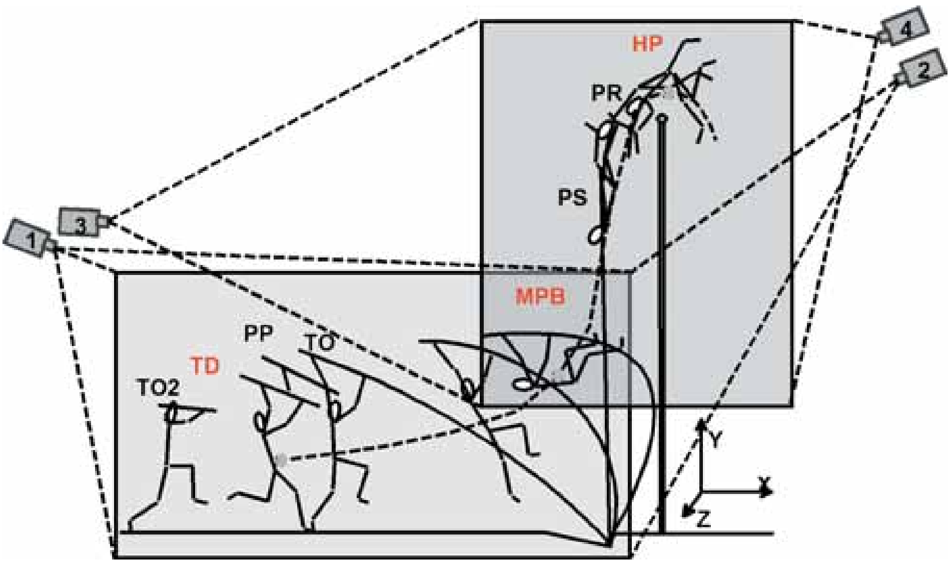

Figure 2: Common camera set-up and calibration for a 3-D kinematic analysis of the pole vault (TO2=take off 2, end of second last ground contact, TD=beginning of last ground contact, PP=pole plant, TO=end of last ground contact, MPB=maximum pole bend, PS=pole straight, PR=pole release, HP=highest point of centre of mass).

The athlete's CM energy can be calculated as follows:

$$E_{CM} = mgH_{CM} + \frac{mv?_{CM}}{2}$$

m : mass of the athlete
H_{CM} : height of the athlete's centre of mass
v_{CM} : velocity of the athlete's centre of mass

The athlete's total body energy can be calculated as follows:

$$E_{tot} = \sum_{i=1}^{12} m_i g h_i + \sum_{i=1}^{12} \frac{m_i v_i ?}{2} + \sum_{i=1}^{12} \frac{\Theta_{iTr} \; ^2{}_{iTr}}{2} + \frac{\Theta_{TLo} \; ^2{}_{TLo}}{2}$$

m_i : mass of the ith segment
g : acceleration of gravity
h_i : height of the centre of mass of the ith segment
v_i : velocity of the centre of mass of the ith segment
$\_{}_{iTr}$: angular velocity of the longitudinal axis of the ith segment
$\_{}_{iTr}$: moment of inertia of the ith segment about its transversal axis
$\_{}_{TLo}$: angular velocity of the trunk about its longitudinal axis
$\_{}_{TLo}$: moment of inertia of the trunk about its longitudinal axis

Calculation of the strain energy of the pole

The strain energy of the pole is the result of the compressive force and bending moment applied to the pole. It can be calculated from the ground reaction forces exerted on the planting box by the lower end of the pole and by the kinematics of the pole bend (Arampatzis et al., 2004). The equation used is as follows:

$$E_{pole} = \int F_p \cdot dr + \int M \cdot d\beta$$

F_p : force in direction of pole deformation
r : pole chord (r = *OP1*)
M : bending moment to the upper end of the pole
_ : angle between top pole tangent and pole chord

Interaction between the vaulter and the elastic pole

Figure 3 shows the vaulter's total mechanical energy and the strain energy of the pole of two elite vaulters in a study conducted during a training session. We can see that the vaulter's energy decreases until the maximum pole bend position (0%) and then increases until approximately the pole straight position. The strain energy of the pole reaches its maximum at the maximum pole bend position. The energy loss in the pole due to friction and deformation ranges between 7% - 10%. The remaining energy is available for use by the vaulter to gain height.

In this study, MK and RS achieve the same velocity prior to take-off, ie the same initial energy, and the same final energy, which is very highly correlated with the maximum CM height. The vaulter's mechanical energy at MPB is also the same for both athletes. But their interaction with the pole is completely different, which can be seen in the difference in maximum strain energy of the poles. In fact, the two vaulters show the same energy decrease in their mechanical energy, but MK reaches higher strain energy of the pole at MPB. This means that he transfers more energy to the pole in the first pole phase. On the other hand, he shows the same increase in his energy in the second pole phase as RS. This means that he adds less energy to the whole system in the second pole phase, because he gets a higher amount of energy out of the pole than RS, but shows the same increase in energy.

It can be concluded that MK performed better in the first pole phase (higher Criterion 1) while RS shows a better second pole phase (higher Criterion 2). But both athletes achieved the same final energy, indicating that different strategies of interacting with the elastic implement pole can lead to similar jump heights.

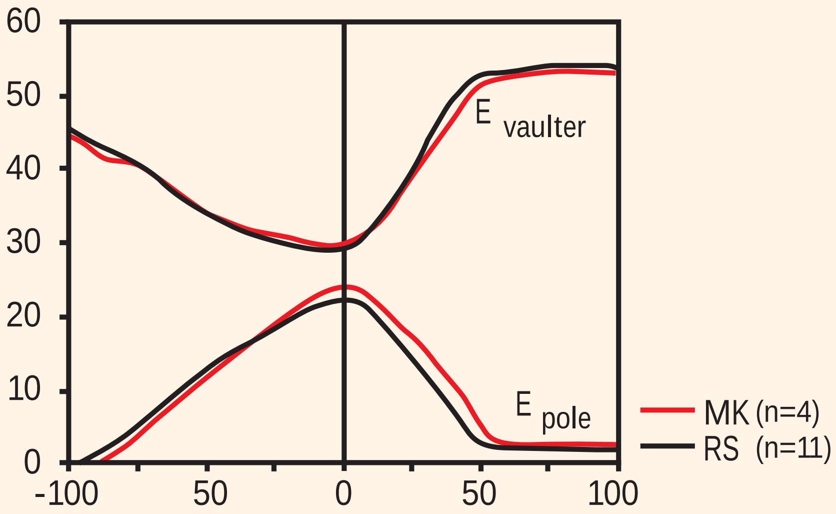

Figure 3: Comparison of the mean total mechanical energy and mean strain energy of the pole of two elite pole vaulters (training session). The x-axis is normalised as follows: -100% up to 0% represent the phase between the beginning of the vault and the maximum pole bend position; 0% up to 100% represent the phase between the maximum pole bend position and the instant of maximum centre of mass height.

The criteria we have developed, therefore, can 1) be used to identify different strategies of interacting with the pole, 2) help to prove the effectiveness of different technical solutions and 3) are highly reproducible (unreleased study), which is an important precondition for using them in elite sports diagnostics.

At the 1997 World Championships, Bubka showed a very high value for Criterion 1 (Arampatzis et al. 1997), indicating an excellent first pole phase. Our studies show the importance of the first pole phase and especially the take-off and pole planting action. The technical solution of this part of the vault seems to be particularly influenced by individual patterns, which makes it very difficult to find an individually optimised technique. Figure 4 shows completely different techniques used by two vaulters of the same performance level. Vaulter 1 is characterised by a high approach velocity and weak jumping abilities. Vaulter 2 has very good jumping abilities.

How is the energy transferred into the pole?

Transferring energy into the pole means bending the pole. The pole can be bent by the vaulter applying a compressive force to the upper end of the pole and by the vaulter applying a bending moment. It is possible to calculate the ratio of both means in relation to the maximum strain energy of the pole (Figure 5). From this we know that the energy that is transferred into the pole due to the compressive force is much higher than the energy transferred by the bending moment - varying between vaulters (but normally consistently reproducible within individuals) from approximately 65% to 85% of the maximum strain energy (unreleased study).

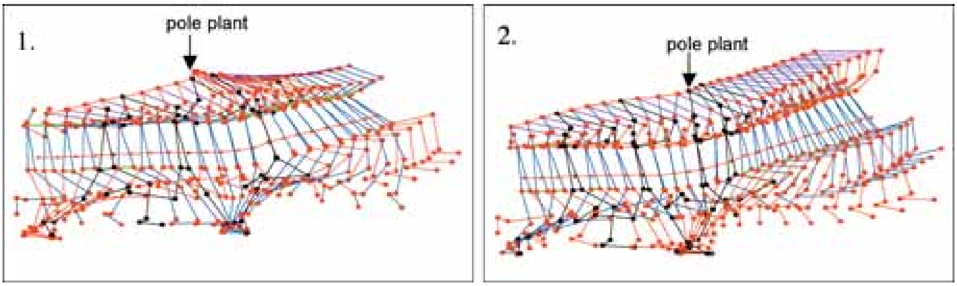

Figure 4: Kinegramme of two different pole plant techniques.

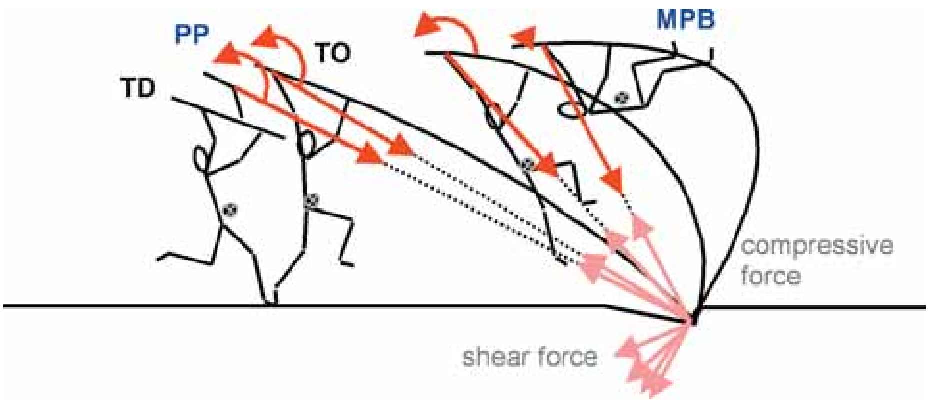

Figure 5: Compressive force and bending moment exerted on the pole

Being passive during the rock back action means increasing the percentage of the bending moment. A dynamic rock back action around the shoulder axis increases the compressive force on the grip hands, leads to a good pole bend and transfers a high amount of energy into the pole. On the other hand, jumping with a stiff lower arm and rotating around the hip axis reduces the percentage of the energy that is transferred into the pole due to compressive force.

Comparison of elite male and female pole vaulters

Figure 6 shows the development of the vaulter's total mechanical energy, the potential energy and the kinetic energy as a mean of the respective best vaults of the first ten placers in men's and women's pole vault finals at the 2000 Olympic Games in Sydney[1].

It is interesting that even though the female vaulters show nearly the same energy gain in the pole phase as the male vaulters their interaction with the pole is different. This can be seen in the decrease and the increase in the total mechanical energy of the vaulter in the first and second pole phases, respectively. The male vaulters show a much higher proportional decrease and increase whereas the female vaulters achieve a relatively high potential energy level earlier in the vault. Additionally, the male vaulters show a significantly greater shortening of the pole chord than the female vaulters, which means that they bent the pole much more.

It can be concluded from the above that the female vaulters have chosen a different strategy of interacting with the elastic pole. They tend to show a passive upward swing instead of an active rock back and pole bending action (Schade et al., 2004).

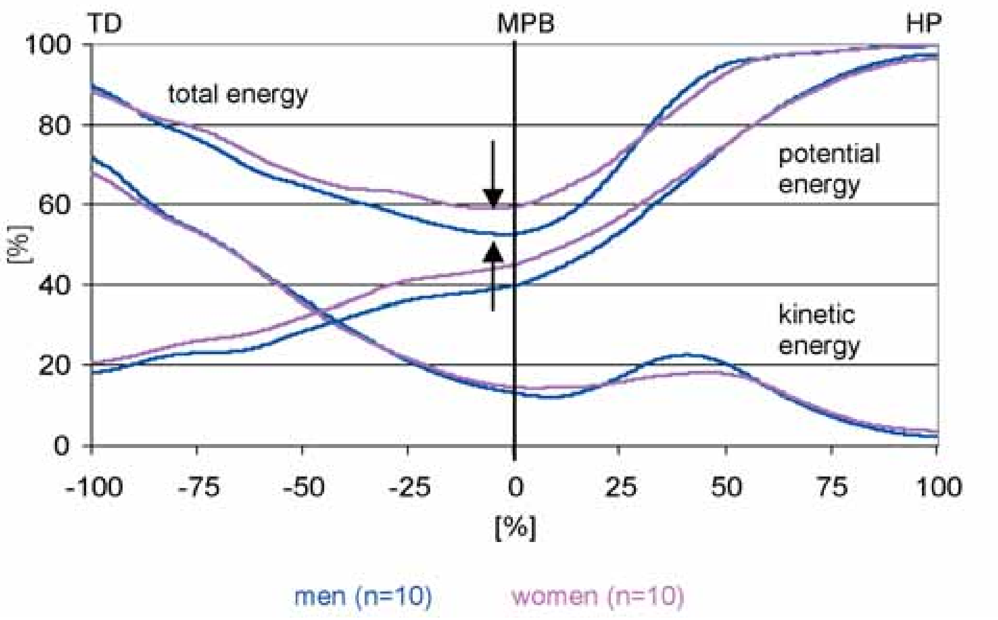

Figure 6: Mean of the vaulter's total mechanical energy, potential energy and kinetic energy of elite male (n=10) and female (n=10) pole vaulters. The x-axis is normalised as follows: -100% up to 0% represent the phase between the beginning of the vault and the maximum pole bend position; 0% up to 100% represent the phase between the maximum pole bend position and the instant of maximum centre of mass height. The y-axis is normalised as follows: the vaulter's energy at the maximum centre of mass height position is set as 100%. TD=last touchdown of the take-off foot, MPB=maximum pole bend position, HP=position of highest point of centre of mass.

Principles of movement in pole vault

By way of a conclusion, we can reiterate that even though it is useful to study the technique of successful athletes, it is also necessary to understand the principles of movement that determine performance. In relation to the pole vault, we have identified the following:

1. Use of swing elements

Using the swing elements, eg the swing leg in the take-off, not only leads to a transfer of momentum it also changes the contraction conditions of the take-off leg. A dynamic lift of the swing leg leads to an increase in resistance that the take-off leg has to overcome. This can have a positive effect on the contraction conditions, as it can lead to a lower speed of contraction. In this case, the muscle can develop more force (comparable to the use of jump weights in the multiple jump of the ancient Olympic Games).

From the practical point of view, swinging the swing leg through is sometimes seen as an indication that the vaulter is avoiding a load increase in the take-off leg. In this case, one has to put forth the question whether this is a techno-motorical problem or whether it is indeed a strength problem in the take-off leg.

2. Energy storage in the body

Similar to the storage of energy in the elastic pole, energy can also be stored in the elastic structures of the human body (eg achilles tendon, patella tendon). This energy is then available in the subsequent course of the vault. This is particularly true for the take-off movement (lower extremities) and the pole planting movement (upper extremities and trunk).

Practically speaking, maximising the storage of elastic energy, usually connected with a stiffening of the contractile components, can have a negative effect on the generation of energy within these components. This is true both for maximising the storage of elastic energy within the elastic structures of the body and for the initial transfer of energy onto the pole at the instant of the plant or immediately after it.

3. Compatibility of take-off and pole planting action

Transformations of energy take place throughout the take-off and during the pole plant. These transformations cannot be optimised in isolation, but they influence each other mutually and are dependent on each other. Pole plant and take-off have to be coordinated and fit together. Individual dispositions are primarily decisive for this compatibility.

From the practical point of view, a “forced” pole planting movement, eg a “free plant”, can have a negative effect on the course of the take-off if the vaulter, because of the limitations to his/her jumping strength capability, is not able to cope with the loads generated in the course of the take-off.

4. Continuous interaction

It is clear that there has to be a continuous interaction in pole vaulting. Passive phases are counter-productive and merely represent short-term strategies to compensate deficits in previous phases of the vault.

The practical implication is that coach and vaulter should be constantly aware of the need for this interaction at all points in a vault.

In our opinion, the success that Bubka achieved with his technique confirms these principles. But rather than say that every vaulter should attempt to emulate Bubka’s technique we think that the identified principles point to key areas that coaches, vaulters and diagnosticians should be addressing in their attempts to optimise individual techniques.

Future investigations

It is our intention to develop the ideas covered in this overview into detailed studies and practical applications and to publish these in the future. Areas of interest currently under consideration include the following:

- Confirmation of the reproducibility of the parameters of interaction between vaulter and pole on an individual level as a basis for technique diagnostics in elite vaulters
- Detailed comparisons of elite vaulter technique based on the parameters of energy interactions
- A description of experiences in the diagnostics of elite vaulter technique, including the degree to which the vaulter/pole interaction can be influenced.

[1] The authors would like to thank the IOC Medical Commission for financing the study during the 2000 Olympic Games in Sydney and the local organisers, SOCOG, for their great support in the Olympic Stadium.

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