

Energy loss in the pole vault take-off and the advantage of the flexible pole

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Abstract

A model of pole vaulting with a flexible pole was developed with the aim of predicting the optimum take-off technique and pole characteristics for a typical world-class pole vaulter. The key features of the model are that it includes the interdependence of the take-off angle and the take-off velocity, and that it accounts for the energy losses in the pole plant and take-off phases of the vault. A computer simulation program was used to systematically investigate the effect of different combinations of take-off velocity, take-off angle, grip height and pole stiffness on the performance of a world-class male vaulter. For the highest vault with this model, the vault height and the optimum combination of take-off velocity, take-off angle, grip height and pole stiffness were in good agreement with measured values for world-class vaulters using fibreglass poles.

The results from the model were compared with those from a model of vaulting with a rigid pole. There was a clear performance advantage to vaulting with a flexible pole. The flexible pole produced a 90 cm higher vault by allowing a 60 cm higher grip and by giving a 30 cm greater push height. There are two main advantages of a flexible fibreglass pole over a rigid pole made of steel or bamboo. A flexible pole reduces the energy dissipated in the vaulter's body during the pole plant, and it also lowers the optimum take-off angle so that the athlete loses less kinetic energy when jumping up at take-off.

Keywords: athletics, computer simulation, pole vault, sports biomechanics, take-off

Introduction

The pole vault is an exciting athletic event that requires high levels of sprinting, jumping and gymnastic ability. Figure 1 shows the sequence of actions of a world-class pole vaulter. The main aim of the run-up is to arrive at the take-off with the maximum amount of controlled speed. At take-off, the vaulter plants the pole into the take-off box and executes an upwards running jump.

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The pole begins to bend under the effect of the momentum of the vaulter, and the vaulter and pole system rotates about the take-off box with the initial kinetic energy of the run-up being transformed into potential energy of the vaulter above the ground. As the pole bends and recoils, the vaulter rotates about the shoulders, and then pulls up on the pole so as to pass over the crossbar feetfirst. The peak height achieved by the vaulter is determined mostly by the kinetic energy at the end of the run-up, but there are also considerable energy losses in the pole plant and take-off phases, and there is a significant positive contribution from the work done by the vaulter during the pole support phase (Stepp 1977; Armbrust 1993; Linthorne 1994).

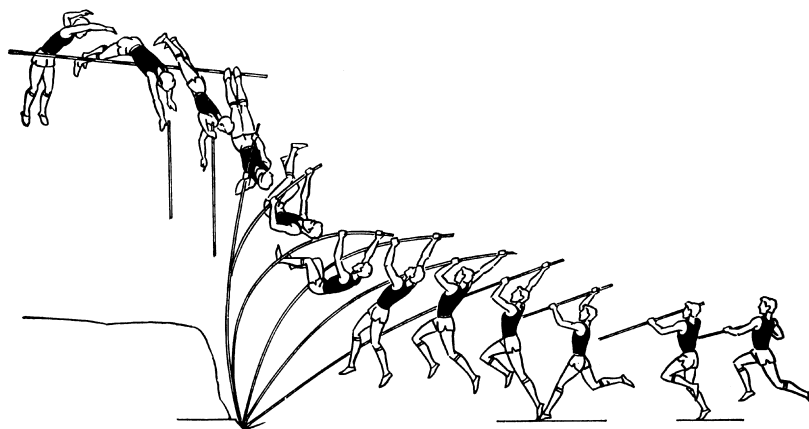


Figure 1 Sequence of movements by a world-class male pole vaulter. Reproduced from Ganslen (1979).

The physical characteristics of the pole are important in pole vaulting. International Amateur Athletic Federation rules do not place any restriction on the length of the pole, the materials from which it is constructed, or the energy storage capacity of the pole (IAAF 2000). Most world-class male pole vaulters use fibreglass or carbon fibre poles that are 5.00–5.20 m long. These poles may be bent by over 120° without breaking, and are able to store an amount of elastic strain energy that is equivalent to about one half of the vaulter's run-up kinetic energy (Arampatzis *et al.* 1999; Gros & Kunkel 1988, 1990). Most world-class vaulters have the top of their upper grip at between 4.90 and 5.15 m from the lower tip of the pole. This distance is called the vaulter's 'grip height'. A vaulter also has what is termed an 'effective grip height', which is 20 cm less than the grip height because of the depth of the take-off box below the level of the runway. The difference between the vaulter's effective grip height and the height of the crossbar is commonly called the 'push height'. World-class male pole vaulters are able to clear a crossbar set at 5.80–6.15 m above the ground, and have a push height of about 1.00 m.

Rationale for the study

Computer simulation studies have advanced our understanding of the mechanics of pole vaulting. Researchers have produced models that account for most of the major aspects of the event, and the

resulting simulations appear realistic in that they agree with the experiences of athletes and coaches, especially concerning the effects of pole selection and changes in movement patterns on vault performance (Walker & Kirmser 1973, 1982; Vernon 1974a, 1974b; Hubbard 1980; Braff & Dapena 1985; Durey & Journeaux 1995; Ekevad & Lundberg 1995). Despite considerable work, the relations between the size, speed and strength of the athlete, the characteristics of the pole, and the technique employed by the athlete, are not fully understood. One of the goals of sports biomechanics researchers is to develop a computer simulation program that enables the optimum pole and optimum technique for an athlete to be predicted from the individual's anthropometric and strength measures.

An outstanding task in progressing towards this goal is to produce a model that accounts for the energy losses associated with the pole plant and jumping actions in the take-off phase. An adequate consideration of the take-off phase has been conspicuously absent from simulation studies of pole vaulting. The present paper proposes a mathematical model of pole vaulting that includes the relation between the take-off angle and the take-off velocity, and accounts for the energy losses in the pole plant and take-off phases of the vault. The aim was to produce a model that accurately predicts the optimum combination of take-off velocity, take-off angle, pole stiffness, and grip height for a typical world-class pole vaulter. Computer

simulations were performed using a body mass, body height and run-up velocity that are representative of a world-class male vaulter, and the effects of the take-off angle, the pole stiffness, and the grip height on the vault performance were systematically investigated.

The simulations from the pole vault model were compared to those from a model of pole vaulting with a rigid pole. A comparison of the optimum vault height, grip height and take-off angle for the two models was expected to shed light on the question of why athletes are able to vault higher with a flexible fibreglass pole than with the old-style bamboo pole or steel pole.

The following sections provide additional background on the need to consider energy losses in the take-off phase of the vault, and on previous explanations of the advantage of the flexible pole. A model of vaulting with a rigid pole is presented, which is then extended to produce a model of vaulting with a flexible pole. For both models, the optimum grip height and the optimum take-off angle and take-off velocity are identified. The results are then compared to reveal the biomechanical advantage of the flexible fibreglass pole over the relatively rigid bamboo pole or steel pole.

Shortcomings of previous simulation studies

Vernon (1974a, 1974b) and Walker & Kirmser (1973, 1982) used a flexible-pole model with a one-segment pendulum model of the vaulter to show that successful vaulting is highly sensitive to changes in grip height, pole stiffness and take-off velocity. They also showed that success depends strongly on the timing of the movement patterns during the vault. Later studies improved the realism of the simulations by including the torque applied by the vaulter to the end of the pole, and by using multisegment vaulter models controlled by internal joint torques (Hubbard 1980; Braff & Dapena 1985; Durey & Journeaux 1995; Ekevad & Lundberg 1995).

Because these computer simulation studies did not account for the energy losses associated with the pole plant and jumping actions in the take-off

phase of the vault, they were not able to predict the optimum combination of take-off and pole parameter values for a world-class athlete. For illustration, Ekevad & Lundberg (1995) assigned the vaulter a constant take-off velocity and take-off angle (the vaulter's 'initial conditions') and then examined the effect of the vaulter's actions during the support phase on the grip height and pole stiffness required for a successful vault. The authors did not explain *why* the vaulter would choose that particular take-off angle, and they did not consider how the choice of take-off angle would affect the vaulter's take-off velocity, optimum grip height and optimum pole stiffness.

The choice of take-off angle by the vaulter is important to successful vaulting. In essence, the aim of pole vaulting is to convert the kinetic energy generated in the run-up into the gravitational potential energy of the vaulter at the peak of the vault. However, the action of jumping up at take-off dissipates some of the vaulter's kinetic energy (Linthorne 1994). Pole vaulters have found by trial-and-error that the height of the vault is greatest when they jump up to produce a take-off angle of 15–20° (McGinnis 1987, *Performance Limiting Factors in the Pole Vault*. Unpublished report to the United States Olympic Committee Sports Medicine Council; Gros & Kunkel 1988, 1990; Angulo-Kinzler *et al.* 1994). Linthorne (1994) used a mathematical model to show that the optimum take-off angle is a compromise that results in the greatest take-off energy. The vaulter retains more of their kinetic energy as the take-off angle is directed closer to a right-angle through the pole, but the vaulter suffers a reduction in kinetic energy as the vaulter jumps up to increase the take-off angle. Unfortunately, Linthorne's model applies only to vaulting with a rigid pole. Its predictions are in good agreement with measurements of vaulters using the old-style bamboo poles or steel poles, but its predictions do not agree with measurements of vaulters using fibreglass poles.

Ekevad & Lundberg (1997) produced a simple model of pole vaulting with a flexible pole, which considered the vaulter as a passive point mass on the end of the pole. They examined the influence of

pole length and pole stiffness on the energy losses in the take-off. An optimum combination of pole length and pole stiffness is reported, but only for a single specific combination of take-off velocity and take-off angle.

A new model of pole vaulting is therefore required if the optimum combination of take-off velocity, take-off angle, grip height and pole stiffness is to be determined. The model must account for: (1) the interdependence of the take-off angle and the take-off velocity; (2) the energy losses in the pole plant and take-off phases of the vault; and (3) the effects of a flexible pole.

Why do vaulters jump higher with a flexible pole?

Pole vault performances suddenly improved when the flexible fibreglass pole was adopted in the early 1960s, and some observers decried their use, believing that the pole was 'catapulting' the vaulter up over the bar (Cramer 1970). However, this catapult notion is dispelled by the fact that the vaulters' push heights did not increase much when the fibreglass pole was introduced (Jeitner 1967; Jagodin 1973). A notable feature of the adoption of the fibreglass pole was the large increase in grip height. At the end of the steel pole era the grip heights of world-class vaulters were at about 4.10 m, whereas those of early fibreglass vaulters were 60 cm higher at about 4.70 m (Jagodin 1973). The higher grip height is commonly considered to be the main advantage of the flexible pole.

Many articles have appeared in coaching journals attempting to explain the higher grips used when vaulting with a flexible pole. For example, Attig (1979) and Geese (1987) argue that a flexible pole bends to some shorter effective length, reducing the moment of inertia of the vaulter on the pole, and so enabling the pole to rotate to vertical more easily. Unfortunately, this argument violates the principle of conservation of energy (Linthorne 1989). A vaulter's grip height is actually determined primarily by the kinetic energy at take-off. The higher the kinetic energy at take-off, the longer the pole the vaulter is able to rotate to vertical.

The most credible explanation for the higher grips when using a flexible pole is that the pole reduces the shock experienced by the vaulter, and so less energy is dissipated in the vaulter's body during the take-off (Stepp 1977; Linthorne 1989; Armbrust 1993). The vaulter therefore has a higher take-off velocity, and is able to rotate a longer pole to vertical.

There is a lesser known difference between vaulting with a flexible pole and vaulting with a rigid pole which may also be important. Linthorne (1994) noted that the take-off angles for vaulters using fibreglass poles are lower than for vaulters using bamboo or steel poles (Angulo-Kinzler *et al.* 1994; Ganslen 1961). He suggested that part of the contribution to the advantage of a flexible pole may be that the optimum take-off angle is lower, and so the vaulter does not lose as much kinetic energy when jumping up at take-off. As regards the present study, it was therefore expected that a successful model of pole vaulting must produce two key results: (1) the vault height and grip height are considerably higher with a flexible pole than with a rigid pole; and (2) the take-off angle is lower with a flexible pole than with a rigid pole.

Rigid-pole model

The model of vaulting with a rigid pole presented here is similar to an earlier mathematical model (Linthorne 1994). The previous rigid-pole model was simplified slightly so that its predictions could be directly compared with those of the flexible-pole model, which is described in the next section. In both the rigid-pole and flexible-pole models, the vaulter has a body height of 1.85 m, a body mass of 80 kg, and is capable of attaining a horizontal velocity of 10.0 m s^{-1} in the last stride before take-off. These values are representative of world-class male vaulters (McGinnis 1987, *Performance Limiting Factors in the Pole Vault*. Unpublished report to the United States Olympic Committee Sports Medicine Council; Gros & Kunkel 1988, 1990; Angulo-Kinzler *et al.* 1994). Female vaulters are not considered in this study. The pole vault has only recently been adopted seriously by female

athletes, and so the event is considered to still be in the 'development' stage.

Both the rigid-pole model and the flexible-pole model consider the athlete as a passive point-mass on the end of the pole. It is recognized that the vaulter adds to the height of the vault by performing muscular work during the vault, and that a successful vault is highly sensitive to the timing of the control actions of the vaulter. Nevertheless, the control actions of the vaulter were deliberately omitted so as to produce a tractable model which would not require an extremely large number of simulations to reveal the broad effects of the energy loss mechanisms in the take-off and pole plant phases.

Take-off phase

Figure 2 shows a schematic diagram for an athlete vaulting with a rigid pole. The vaulter is a point-mass, M , on the end of a massless and perfectly rigid rod of length L_0 . The pole length is the height of the vaulter's upper grip on the pole, and the height of the vaulter at take-off, h , is taken as the vaulter's body height.

The take-off phase of the vault is essentially a collision of the vaulter and pole with the ground.

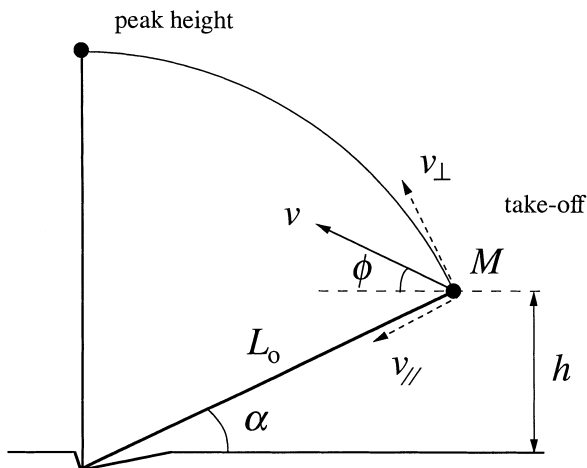


Figure 2 Model of the vaulter and pole when vaulting with a rigid pole. The thin solid line shows the trajectory of the vaulter. The vaulter and pole are shown at the instant of take-off, and at the peak of the vault.

There is a reduction in velocity when the vaulter plants the take-off leg and jumps up off the ground, and a further reduction when the vaulter plants the pole into the take-off box. In this model, the energy loss associated with the vaulter's jump is separated from that of the pole plant, even though in practice these two events usually occur simultaneously. Here, *take-off velocity* refers to the velocity as the vaulter jumps up off the ground, just before planting the pole into the take-off box. The vaulter has a take-off velocity, v , directed at an angle, ϕ , to the horizontal, as shown in Fig. 2. Figure 3 shows the decrease in the vaulter's take-off velocity with increasing take-off angle. This curve corresponds to a world-class vaulter, and accounts for the effects of carrying and jumping with the pole (Linthorne 1994).

Pole plant phase

Just before the pole plant, the take-off kinetic energy of the vaulter may be divided into the kinetic energy associated with the component of the velocity that is perpendicular to the pole (v_{\perp}), and the kinetic energy associated with the component of the velocity that is parallel to the pole (v_{\parallel}) (see Fig. 2). When vaulting with a perfectly rigid

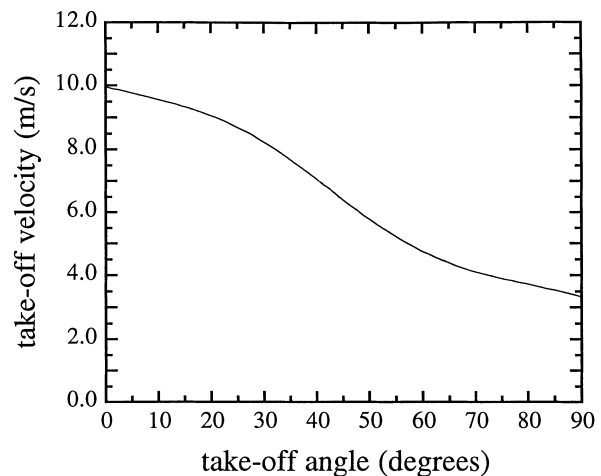


Figure 3 Take-off velocity as a function of the take-off angle for a world-class pole vaulter. Reprinted by permission from Linthorne (1994).

pole, the planting of the pole into the take-off box dissipates the energy associated with $v_{//}$. The energy dissipated due to the pole plant, ΔE , is given by:

$$\Delta E = 1/2 M v^2 \cos^2(\phi + \alpha) \quad (1)$$

where α is the ground-pole angle at take-off. In this model, no energy will be lost if the vaulter has a take-off that is perpendicular to the pole, and all of the vaulter's take-off kinetic energy will be dissipated if the take-off is parallel to pole. In an actual vault with a bamboo pole or steel pole, the lost energy is probably dissipated in the vaulter's body, rather than in the pole or in the take-off box.

After the take-off and pole plant, the vaulter stays on the end of the pole and rotates about the take-off box at constant radius. The only force on the vaulter is gravity, and so the initial kinetic energy of the vaulter is gradually converted to gravitational potential energy.

In a pole vault competition, the vaulter is allowed to position the crossbar anywhere from 40 cm in front to 80 cm beyond the back of the take-off box (IAAF 2000). In this model, the crossbar is vertically aligned with the lower tip of the pole when the pole is placed in the take-off box. That is, the crossbar is vertically aligned with the lowest point of the take-off box (see Fig. 2). The height with which the vaulter is credited is the vaulter's height as the pole rotates through the plane of the crossbar. Because the vaulter is passive, and so performs no muscular work during the vault, the model underestimates the vault height. To account for this shortcoming, 80 cm was added to the calculated vault height of each jump (Gros & Kunkel 1990).

Flexible-pole model

A model of vaulting with a flexible pole was derived from the rigid-pole model by replacing the perfectly rigid rod with one of finite stiffness. The important elements in the mathematical description of the flexible pole were identified from the results of other investigators. Hubbard (1980) modelled the pole as a long slender rod (i.e. an

elastica), and used large deflection theory to calculate the deformation of the pole as a function of the force and moment applied by the vaulter to the end of the pole. Hubbard's calculations show that in the absence of an applied moment, the behaviour of a flexible pole is similar to that of a perfectly elastic one-dimensional spring which shortens along its chord in response to an applied compressive force. The longitudinal reaction force of the pole, F , is then given by:

$$F \approx F_0 + 0.6 F_0 \frac{L_0 - L}{L_0} \quad (2)$$

where L_0 is the undeflected pole length, L is the deflected pole length, and F_0 is the Euler buckling load of the pole (see Fig. 4). As in the rigid-pole model, the vaulter's grip height is equal to the (undeflected) pole length. Measurements by Fuchimoto *et al.* (1991) show that for fibreglass and carbon fibre poles, the manufacturer's pole stiffness rating is approximately equal to the Euler buckling load of the pole. For example, a pole rated at 80 kg has a Euler buckling load of $F_0 \approx 800$ N.

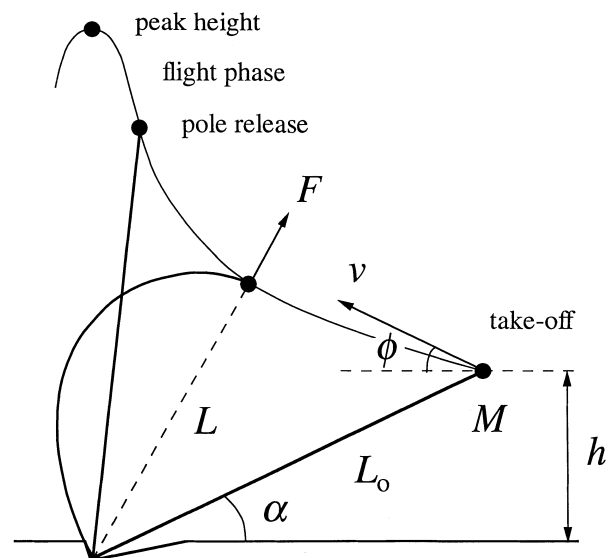


Figure 4 Model of the vaulter and pole when vaulting with a flexible pole. The thin solid line shows the trajectory of the vaulter. The vaulter and pole are shown at the instant of take-off, maximum pole bend, pole release and at the peak of the vault.

The flexible-pole model does not include the moment applied by the vaulter to the end of the pole because this has a relatively minor effect on the flexural characteristics of the pole (Hubbard 1980). Likewise, the non-uniform stiffness of the pole along its length and the deviation of the pole from perfectly straight have also been neglected (Ekevad & Lundberg 1995). Burgess (1996) examined the optimum pole material and geometry to minimize the mass of the pole. However, such considerations are 'fine details' in comparison to the broad scope of the present investigation, and so have been neglected.

Take-off and pole plant phases

The dependence of the vaulter's take-off velocity on the take-off angle is given by the curve in Fig. 3, as for the rigid-pole model (Linthorne 1994). Special consideration was required to account for the energy losses in the pole plant phase. The act of replacing the perfectly rigid rod with an elastica produced a flexible-pole model which did not generate realistic results. This was because there was no longer a mechanism for energy dissipation during the pole plant phase. In this model, no energy was dissipated when the pole was planted into the take-off box, and all of the kinetic energy associated with $v_{//}$ was retained. A maximum vault height of 7.70 m was produced with an optimum take-off angle of 0° . This is not consistent with actual vaulting, and so the description of the pole plant phase of the vault was revised to include a mechanism for dissipation of energy in the vaulter's body.

Consider the actions of a vaulter during the take-off and pole plant (see Fig. 1). Just before the pole is planted into the take-off box, the vaulter is driving forward and upward, the vaulter's body is upright, and the upper arm is extended directly above the vaulter's head. As the pole is planted into the take-off box, the vaulter attempts to maintain the orientation of the arms and torso through muscular activation, but the force exerted by the pole is too great, and so the vaulter's arms are deflected backward relative to the shoulders, and the vaulter's torso is deflected backward relative to

the hips. Work is done by the pole in reorienting the vaulter's body against its muscular forces. Some of the vaulter's kinetic energy is therefore dissipated as heat in the vaulter's muscles. Energy may also be dissipated by inelastic stretching of the tendons and ligaments as the body is hyperextended.

For the various energy loss mechanisms in the vaulter's body, the relations between the amount of energy lost and the vaulter's take-off parameters and pole parameters are not known. A plausible model is to consider the vaulter's body as a heavily damped linear spring which dissipates all the energy transferred to it. The total energy dissipated in the vaulter's body, ΔE , depends on the pole stiffness and take-off angle according to:

$$\Delta E = \frac{F_0^2}{2k} \cos^2(\phi + \alpha) \quad (3)$$

where k is a constant.

During the take-off, the relative deflection of the pole is usually less than a few percent, and so the force exerted by the pole on the vaulter is approximately equal to the Euler buckling load, F_0 . The F_0^2 factor in Equation 3 means that the energy dissipated in the vaulter's body increases greatly if the vaulter decides to use a stiff pole. When vaulting with a pole of low stiffness, the force exerted on the vaulter and the deflection of the vaulter's body are relatively small, and so the energy dissipated is also small. When vaulting with a pole of high stiffness, the force exerted by the pole on the vaulter is larger, resulting in a more extreme deflection of the vaulter's body, and hence a greater dissipation of energy.

The parameter k in Equation 3 characterizes the 'stiffness' of the vaulter's body in the pole plant phase of the vault. The value of k reflects the level of resistance of the vaulter's arms and torso to being deflected backward relative to the hips by the pole. Measurements of energy losses at take-off indicate that k is about 250 N m^{-1} for a world-class vaulter (Gros & Kunkel 1988, 1990; Angulo-Kinzler *et al.* 1994).

The $\cos(\phi + \alpha)$ factor in Equation 3 accounts for the vaulter's take-off angle. No energy will be lost if the vaulter has a take-off that is perpendicular to the

pole, and the energy lost will be greatest if the take-off is parallel to pole. In this model, it is assumed that the total energy dissipated in the vaulter's body does not exceed the energy associated with the component of the take-off velocity that is parallel to the pole. That is, for any given take-off angle, the energy lost due to the pole plant does not exceed that lost when vaulting with a rigid pole.

After the take-off and pole plant, the vaulter stays on the end of the pole as it rotates about the take-off box. In this model, the vaulter releases the pole when it has recoiled to its initial length, and then continues in free flight under the influence of gravity (see Fig. 4). The height with which the vaulter is credited is the vaulter's height when passing through the plane of the crossbar after releasing the pole. To account for the omission of the work done by the vaulter during the support phase, 80 cm was added to the calculated vault height of each jump (Gros & Kunkel 1990).

Results

Computer programs were written in Microsoft QuickBASIC for the rigid-pole model and for the flexible-pole model. In both programs, the vault simulation commenced just prior to take-off with a selected pole length and take-off angle (and a selected pole stiffness in the flexible-pole model). The corresponding take-off velocity was determined from Fig. 3, and the energy dissipation due to the pole plant was calculated using Equations 1 or 3, as appropriate. The vault trajectory after the take-off and pole plant phases was calculated by numerical integration. A constant integration step size of 0.01 s was used and found to be adequate. The position of the vaulter at the end of each time interval was calculated from the previous position and velocity, and from the forces acting on the vaulter. A trace of the entire vault trajectory was generated, and the vault height was recorded.

Rigid-pole model

Thirteen take-off angles in the range 0° to 50° were selected. For each take-off angle, a series of vaults

was simulated with pole length increments of 1 cm over a range of 3.00–6.00 m. The resulting vault heights were plotted as a function of the pole length, and the maximum vault height and its corresponding pole length were determined.

The vaults simulated using the rigid-pole model displayed the expected pattern of vaulting. For example, with a short pole the vaulter was able to rotate through the plane of the crossbar with ease, but if the vaulter selected a pole that was beyond a certain length, the vaulter did not have sufficient momentum to rotate the pole to vertical. With this model, the vaulter does not achieve a flight phase (where the vaulter rises above the height of the pole) because the model does not include the work done by the vaulter during the support phase of the vault. At any given take-off angle, the highest vault was that for which the vaulter was just able to rotate the pole to the vertical position. That is, the maximum vault height was always equal to the maximum effective grip height (i.e. the maximum pole length minus the depth of the take-off box), plus 80 cm to account for the work done by the vaulter during the support phase. The maximum vault height and its corresponding pole length (i.e. grip height) are shown as a function of the take-off angle in Figs 5 and 6, respectively.

The optimum vault in the rigid-pole model compares favourably with competition performances. World-class vaulters from the end of the rigid-pole era had grip heights of about 4.10 m, and cleared heights of around 4.70 m (Ganslen 1961; Jagodin 1973; Tamura & Kuriyama 1988) (see Table 1). However, it is expected that rigid-pole performances would have increased by about 30 cm since then due to increases in the physical capacity of vaulters, and due to minor technique refinements. That is, had the fibreglass pole not been introduced, the best pole vaulters would probably now be gripping at around 4.40 m on the pole, and be vaulting about 5.00 m. For the optimum vault in the rigid-pole model, the vault height (5.10 m), grip height (4.50 m), push height (0.80 m) and take-off angle (30°) are similar to those expected if present-day vaulters were to use bamboo poles or steel poles.

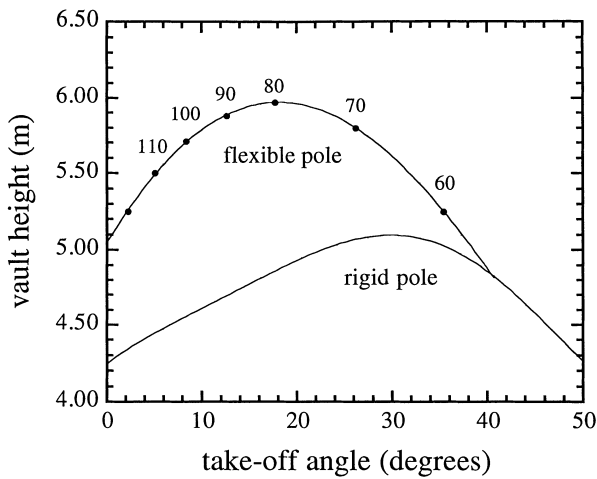


Figure 5 Peak height of the vault as a function of the take-off angle for the rigid-pole model and for the flexible-pole model. The numbers next to the curve for the flexible-pole model show the change in the optimum pole stiffness ratings (in kg).

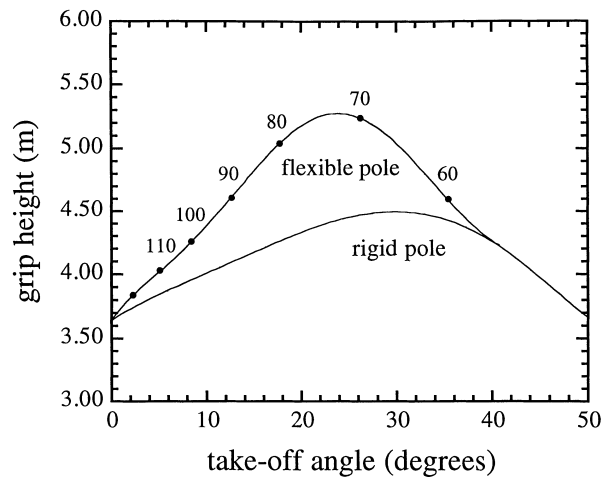


Figure 6 Grip height as a function of the take-off angle for the rigid-pole model and for the flexible-pole model. The numbers next to the curve for the flexible-pole model show the change in the optimum pole stiffness ratings (in kg).

Flexible-pole model

For the simulations with the flexible-pole model, 13 take-off angles in the range 0° to 50° were selected. For each take-off angle, a series of vaults were simulated with pole length increments of 1 cm over a range of 3.00–6.50 m, and with pole stiffness rating increments of 1 kg over a range of 55–140 kg. The resulting vault heights were plotted as a function of the pole length and pole stiffness, and the maximum vault height and its corresponding pole length and pole stiffness were determined. This process was performed for $k = 125, 250$ and 500 N m^{-1} in Equation 3.

The vaults simulated using the flexible-pole model displayed the expected pattern of vaulting, and followed the expected trends in the location of the peak of the vault to changes in the pole length and pole stiffness. For example, at any given take-off angle, increasing the pole length caused the horizontal position of the peak of the vault to shift closer toward the take-off point. A similar effect was produced by increasing the pole stiffness. The highest vaults were always achieved when the vaulter selected the pole length and pole stiffness so that the peak of the vault coincided with the plane of the crossbar.

On viewing the general pattern of vaulting, it was evident that a restriction had to be placed on the

Table 1 Comparison of model results with data for world-class pole vaulters

Variable	Rigid-pole model	Steel or bamboo poles†	Flexible-pole model	Fibreglass or carbonfibre poles‡
Vault height (m)	5.10	4.40–4.80	6.00	5.80–6.15
Grip height (m)	4.50	3.90–4.25	5.10	4.90–5.15
Push height (m)	0.80	0.70–0.90	1.10	0.80–1.20
Take-off angle (°)	30	20–26	18	15–20
Take-off velocity (m s^{-1})	7.0	No reliable data	8.0	7.5–8.5
Pole stiffness rating (kg)	–	–	80	75–100

†Ganslen (1961), Jagodin (1973), Tamura & Kuriyama (1988).

‡Angulo-Kinzler *et al.* (1994), Gros & Kunkel (1988, 1990), McGinnis (1987, *Performance Limiting Factors in the Pole Vault*. Unpublished report to the United States Olympic Committee Sports Medicine Council).

risk to the vaulter when executing a vault. The reason for this restriction is as follows: at low take-off angles the highest vaults were always obtained with a pole of low stiffness. In these vaults the vaulter travelled low to the ground toward the take-off box, and then rose sharply to a peak. It is unlikely that a vaulter would use such a pole because the success of the vault is highly sensitive to changes in the pole length. If the vaulter chooses a pole length just slightly longer than the optimum length, the peak of the vault shifts to well in front of the plane of the crossbar, and so the vaulter is at risk of injury by not landing safely in the pit.

Greater realism in the flexible-pole model was achieved by requiring that the vaulter would not select a pole such that the horizontal position of the peak of the vault shifted by more than 10 cm per 1 cm change in the pole length. This is equivalent to preventing a vaulter from risking injury through a small error in selecting the correct pole length.

The 'excessive risk' criterion had the added effect of restricting the maximum deflection of the pole. Vaults for which there was a high sensitivity of the position of the peak to the pole length were always produced with a very large pole deflection. In the unrestricted model, a successful vault could be achieved with the pole shortening to less than 10% of its undeflected length. By contrast, a fibreglass pole usually breaks when bent to less than about 60% of its undeflected length. Coincidentally, the value of the 'excessive risk' criterion used here restricted the maximum pole deflection to about that observed in a present-day fibreglass pole.

For the restricted flexible-pole model, the maximum vault height and its corresponding pole length (i.e. grip height) are shown as a function of the take-off angle in Figs 5 and 6 (for $k = 250 \text{ N m}^{-1}$). Also shown with these curves is the corresponding optimum pole stiffness rating. The dependence of the push height on the take-off angle is shown in Fig. 7. This figure compares the vault height with the effective grip height; the difference between the two curves is the vaulter's push height.

For the optimum vault in the flexible-pole model, the vault height (6.00 m), grip height

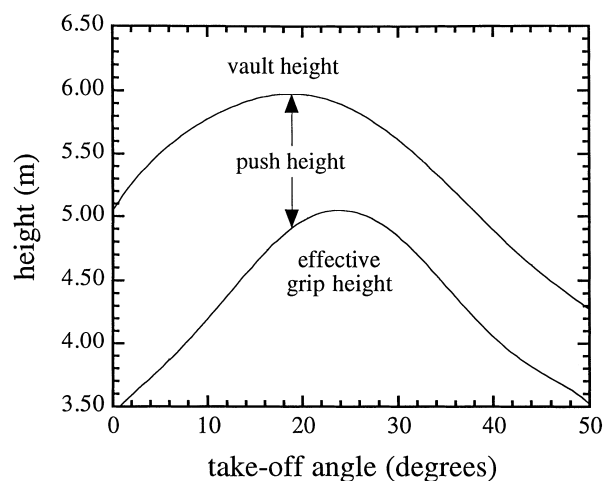


Figure 7 Push height as a function of the take-off angle for the flexible-pole model.

(5.10 m), push height (1.10 m), take-off angle (18°), take-off velocity (8.0 m s^{-1}) and pole stiffness rating (80 kg) are similar to measured values for present-day world-class vaulters (McGinnis 1987, *Performance Limiting Factors in the Pole Vault*. Unpublished report to the United States Olympic Committee Sports Medicine Council; Gros & Kunkel 1988, 1990; Angulo-Kinzler *et al.* 1994) (see Table 1). For the optimum vault in this model, the history of the pole bend and the maximum degree of pole flexion are also similar to those observed for world-class fibreglass vaulters.

The advantage of the flexible pole

There was a clear performance advantage to vaulting with a flexible pole (see Figs 5 and 6). The flexible pole produced a 90 cm higher vault by allowing a 60 cm higher grip and by giving a 30 cm greater push height. The optimum take-off angle for the flexible-pole model (18°) was considerably lower than for the rigid-pole model (30°).

For the rigid-pole model, the optimum take-off angle occurs when the kinetic energy lost due to jumping up at take-off equals the energy dissipated in the vaulter's body during the pole plant. A similar interplay arises in the flexible-pole model. However, with a flexible pole, the energy lost

during the pole plant depends on the pole stiffness. A low take-off angle requires the vaulter to use a stiff pole so as to reduce the vaulter's forward momentum and cause the peak of the vault to coincide with the plane of the crossbar. Although a low take-off angle does not result in much loss of kinetic energy due to jumping up, the stiff pole results in a very high energy loss in the vaulter's body during the pole plant, and so the overall energy loss is high. At the other extreme, a high take-off angle allows a pole of low stiffness to be used, and so little energy is lost in the pole plant, but the vaulter loses a lot of kinetic energy in the jump up off the ground. The optimum take-off angle is at an intermediate angle that is determined by the balance between the kinetic energy lost in jumping up at take-off, and the energy lost in the vaulter's body during the pole plant because of the stiffness of the pole.

The models used in this simulation study satisfied the criterion that the take-off angle when vaulting with a flexible pole is lower than when vaulting with a rigid pole. Interestingly, at the optimum take-off angle for each type of pole, about the same amount of energy is dissipated in the vaulter's body when the pole is planted into the take-off box. However, the flexible-pole vaulter jumps up less at take-off, and so retains a greater velocity at take-off (see Fig. 3). The vaulter is therefore able to grip higher on the pole, and hence achieve a higher vault. The lower take-off angle of the fibreglass vaulter is not commonly recognized, but it is an important effect of the use of a flexible pole, as is the higher grip height.

This investigation suggests that not all of the improvement in performance when vaulting with a flexible pole is reflected as an increase in the grip height; there is also a moderate increase in the push height. Measurements of competition vaults by world-class vaulters support this finding. Jagodin (1973) noticed that the push heights of early fibreglass vaulters were about 8 cm higher than those of vaulters from the end of the rigid-pole era. Similarly, Tamura & Kuriyama (1988) report push heights for present-day fibreglass vaulters that are about 20 cm higher than for vaulters from the

bamboo pole and steel pole eras. However, some of this difference may be due to an improvement in the physical capacity of the vaulters since the introduction of the fibreglass pole. Also, the fibreglass-pole vaulter may be able to perform more work during the support phase by being placed in a mechanically more favourable position.

Sensitivity of the models

The geometry of the rigid-pole model used here is slightly different from that in Linthorne (1994). In the earlier model, the vaulter was a point-mass located at the vaulter's centre of mass, halfway between the feet and the vaulter's upper grip. The ground-pole angle (α) in the model was determined by the vaulter's vertical reach. Unfortunately, this geometry was difficult to incorporate into a flexible-pole model, and so the model was simplified slightly by representing the vaulter as a mass on the end of the pole. In the simplified rigid-pole model, the height of the vaulter at take-off, b , was adjusted so that the maximum grip height predicted in the vault simulations agreed with that of the previous model. Good agreement was obtained for $b = 1.85$ m, which conveniently coincides with the average body height of world-class vaulters. Therefore, in both the rigid-pole and flexible-pole models presented here, the height of the vaulter's mass at take-off was set as the vaulter's body height.

For the rigid-pole model, increasing the body height of the vaulter by 10 cm increased the vault height and the grip height by about 16 cm, but there was no change in the optimum take-off angle (Linthorne 1994). Also, increasing the vaulter's maximum running speed by 1.0 m s^{-1} increased the vault height and grip height by about 30 cm, but again there was no change in the optimum take-off angle. Similar effects for increases in body height and maximum running speed were observed with the flexible-pole model.

A limitation of the pole vault models presented here is the representation of the vaulter as a passive point-mass. The model does not include the effects of the control actions and muscular work performed by the athlete during the support phase of

the vault. To account for this omission, 80 cm was added to the height of each vault. As stated before, the control actions of the vaulter were deliberately omitted so as to produce a tractable model which would not require an extremely large number of simulations to reveal the broad effects of the energy loss mechanisms in the take-off phase. The good agreement between the model calculations and measurements of world-class vaulters suggests that the model is not overly simplistic, and that the essential mechanics of pole vaulting have been included.

The curves shown in Figs 5–7 for the flexible-pole model are for $k = 250 \text{ N m}^{-1}$. This value of k was deliberately chosen to give good agreement between the calculated optimum vault height and the performances of a world-class vaulter. There was no independent estimate of its value. However, the selection of $k = 250 \text{ N m}^{-1}$ produced remarkably accurate values for the optimum take-off angle, take-off velocity, pole stiffness and the maximum degree of pole flexion, again suggesting that the model accounts for the essential mechanics of the take-off. Greater values of k gave a higher maximum vault height and push height, and a slightly lower optimum take-off angle (see Table 2).

For the flexible-pole model, the inclusion of the ‘excessive risk’ criterion was necessary to produce realistic vaults. Relaxing the criterion lowered the optimum take-off angle and increased the maximum vault height and grip height. Further investigation of the energy dissipation mechanisms during the pole plant may produce a model that does not require the imposition of an ‘excessive risk’ criterion.

Table 2 Comparison of optimum vault parameters for different values of the vaulter’s body stiffness

Vaulter’s body stiffness, k (N m^{-1})	Vault height (m)	Take-off angle (degrees)	Grip height (m)	Push height (m)	Pole stiffness rating (kg)
125	5.40	24	4.75	0.85	72
250	6.00	18	5.10	1.10	80
500	6.45	13	5.10	1.55	93

The expression for the energy dissipated in the pole plant (Equation 3) is simple, and only considers a crude approximation of the effects of the athlete’s take-off technique. The expression must involve a strong dependence of energy loss with increasing pole stiffness. A model in which the energy loss was only a linear function of the pole stiffness, as opposed to F_0^2 , was not realistic in that the optimum take-off angle was always close to horizontal. Many coaches consider the actions and body position of the athlete during the take-off to be important determinants of successful vaulting. An advanced model of the pole plant and take-off would consider how the energy losses depend on the orientation of the arms and trunk, and the position of the take-off foot relative to the upper grip (Young & Yeadon 1998).

Future simulation studies of pole vaulting

The model presented here is an important step towards creating a useful model that can predict the effects of changes in technique and equipment selection on an individual athlete’s performance. A comprehensive model of pole vaulting should include the following features:

- A flexible pole that is represented by an elastica. The pole length, pole stiffness and grip height is selected by the athlete. An advanced model would include the non-uniform stiffness of the pole along its length, and the pole ‘pre-bend’ (Hubbard 1980; Ekevad & Lundberg 1995).
- A multi-segment model of the vaulter, which includes internal joint torques and the torque applied by the vaulter to the end of the pole (Hubbard 1980; Braff & Dapena 1985; Durey & Journeaux 1995; Ekevad & Lundberg 1995). The vaulter model should be based on the anthropometric and strength measures of the athlete.
- A sequence of movements of the athlete (and their timing) during the vault that is selected by the athlete (Hubbard 1980; Braff & Dapena 1985; Durey & Journeaux 1995; Ekevad & Lundberg 1995).

- A mechanism of energy loss due to the action of jumping up at take-off (Fig. 3).
- A mechanism of energy dissipation in the vaulter's body when the pole is planted into the take-off box (Equation 3). In an advanced model, the energy loss will depend on the grip height, pole stiffness, take-off angle and the athlete's movement patterns and body dimensions.

Investigating the influences of all of these parameters is a major task requiring a large number of simulations.

Concluding remarks

This study highlighted the importance of considering the energy losses during the pole plant and take-off phases of the vault. A consideration of the pole plant and take-off phases was necessary to determine the optimum combination of take-off velocity, take-off angle, grip height and pole stiffness for a world-class vaulter.

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