WHY DO YOU JUMP HIGHER WITH A FLEXIBLE VAULTING POLE?

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A computer simulation study revealed why athletes are able to vault higher with a flexible fibreglass pole than with the old-style bamboo poles and steel poles. The crucial feature of the pole vault model was the inclusion of the energy losses associated with the pole plant and takeoff. The simulations showed that a flexible pole reduces the energy dissipated in the vaulter's body when the pole is planted into the takeoff box (as had been suggested previously). Also, a flexible pole lowers the optimum takeoff angle, and so the athlete loses less energy in jumping off the ground. This pole vault model could be combined with previous models to produce a computer simulation program that would allow sports scientists to provide correct biomechanical advice to athletes and coaches.

KEY WORDS: athletics, computer simulation, pole vault, takeoff.

INTRODUCTION: Pole vault performances suddenly improved in the early 1960s when the flexible fibreglass pole replaced the more rigid poles made of bamboo or steel. However, the advantage of the highly flexible pole over the rigid pole has not been adequately explained. It cannot be due to any "catapult" effect because the push heights of the vaulters did not increase much when the fibreglass pole was introduced (Jagodin, 1973; Jeitner, 1967). Rather, the improvement in vaulting performance was accompanied by an increase in grip height.

Arguments for the higher grips that are based on the energy storage capability of the pole, or on a reduction of the rotational inertia of the vaulter-pole system, are incorrect because they violate the principle of conservation of energy (Linthorne, 1989). The most credible explanation for the higher grips is that a flexible pole reduces the shock experienced by the vaulter, and so less energy is dissipated in the vaulter's body during the takeoff (Armbrust, 1993; Linthorne, 1989). The vaulter therefore has a higher takeoff velocity, and is able to take a higher grip on the pole.

This paper presents the results of computer simulations that show that this explanation is only partially correct. There is a second factor that contributes to the vaulter's higher grip on the pole. A flexible pole also lowers the optimum takeoff angle, and so the athlete loses less energy in jumping off the ground.

Two relatively simple models were used to perform the pole vault simulations: a flexible-pole model, and a rigid-pole model. Both models used parameter values that were representative of world-class vaulters. The new and crucial feature of the models was the consideration of the energy losses in the pole plant and takeoff phases of the vault.

FLEXIBLE-POLE MODEL: In the flexible-pole model, the vaulter is a point-mass, M, on the end of a massless elastica with finite stiffness (Hubbard, 1980). The takeoff phase of the vault is essentially a collision of the vaulter and pole with the ground. There is a reduction in velocity when the vaulter plants the takeoff leg and jumps off the ground, and a further reduction when the vaulter plants the pole into the takeoff 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. The vaulter has a takeoff velocity v directed at an angle ϕ to the horizontal. Here, takeoff velocity refers to the velocity as the vaulter jumps up off the ground, just before planting the pole into the takeoff box.

Figure 1 shows the decrease in takeoff velocity with increasing takeoff angle. This curve is for a world-class vaulter, and accounts for the effect of carrying and jumping with the pole (Linthorne 1994).

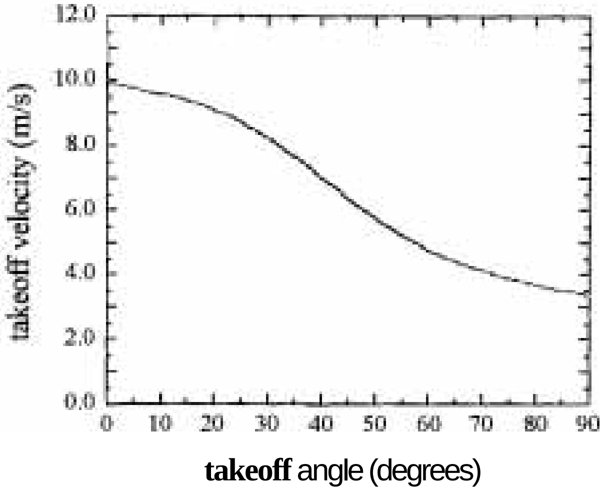

Figure 1 - Takeoff velocity as a function of the takeoff angle for a world-class vaulter.

Considerable energy is also dissipated in the vaulter's body during the pole plant. As the pole is planted into the takeoff 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.

A plausible model is to consider the vaulter's body as a heavily damped linear spring that dissipates all the energy transferred to it. The energy dissipated in the vaulter's body during the pole plant, ΔE, depends on the pole stiffness and takeoff angle according to

$$\Delta E = \frac{F_o^2}{2k} \cos^2(\phi + a) \qquad (1)$$

where F_o is related to the manufacturer's pole stiffness rating, k is a constant, and a is the ground-pole angle at takeoff. Measurements of energy losses at takeoff indicate that k is about 250 N/m for a world-class vaulter (Angulo-Kinzler et al,1994; Gros and Kunkel, 1990).

RIGID-POLE MODEL: A model of vaulting with a rigid pole was derived from the flexible-pole model by replacing the massless elastica with a perfectly rigid rod. However, Equation 1 is not appropriate because it suggests infinite energy loss, whereas the energy loss is, in fact, limited by the kinetic energy of the vaulter.

Just before the pole plant, the takeoff 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 ($v_{//}$). When vaulting with a perfectly rigid pole, the planting of the pole into the takeoff box dissipates the energy associated with $v_{//}$. The energy dissipated due to the pole plant, ΔE, is therefore given by

$$AE = \frac{1}{2} M v^2 \cos^2(\phi + a). \qquad (2)$$

Both the flexible-pole and rigid-pole models underestimate the peak height achieved by the vaulter because the vaulter is passive and so performs no muscular work during the vault. To account for this shortcoming, 80 cm was added to the calculated vault height of each jump (Gros and Kunkel 1990).

RESULTS AND DISCUSSION: Many thousands of vaults were simulated using a wide range of pole and takeoff parameter values. The vaults displayed the expected trends in the location of the peak of the vault to changes in the pole length and pole stiffness. For the optimum vaults in both models, the vault height, grip height, push height, takeoff angle, and takeoff velocity agree with measurements from competition performances by world-class vaulters (Angulo-Kinzler et al., 1994; Ganslen, 1961; Gros and Kunkel, 1990; Jagodin, 1973; Tamura and Kuriyama, 1988)

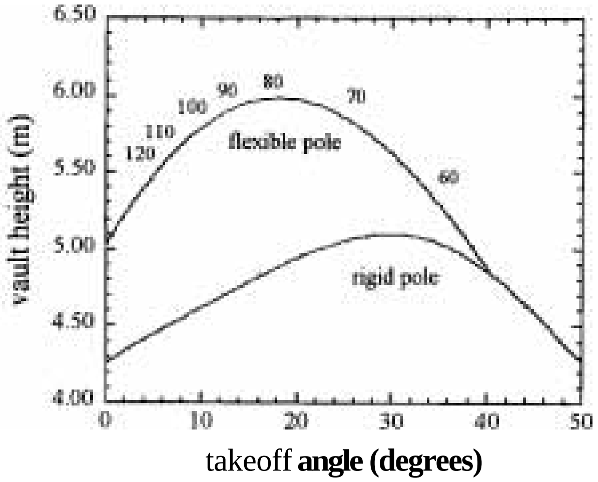

Figure 2 - Maximum vault height as a function of the takeoff angle for the rigid-pole model and for the flexible-pole model. Also shown is the optimum pole stiffness rating (in kilograms).

There is a clear performance advantage to vaulting with a flexible pole (Figure 2). A flexible pole produces a 90 cm higher vault by allowing a 60 cm higher grip and by giving a 30 cm greater push height. The optimum takeoff angle for the flexible-pole model (18 °) is considerably lower than for the rigid-pole model (30 °).

For the rigid-pole model, the optimum takeoff angle occurs when the energy lost due to jumping up at takeoff equals the energy dissipated in the vaulter's body during the pole plant. A similar interplay arises in the ,flexible-pole model. With a flexible pole, however, the energy lost during the pole plant depends on the pole stiffness. A low takeoff 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 takeoff angle does not result in much loss of energy due to jumping, 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 takeoff 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 energy in the jump up off the ground. The optimum takeoff angle is at an intermediate angle that is determined by the balance between the energy lost in jumping up at takeoff, and the energy lost in the vaulter's body during the pole plant because of the stiffness of the pole.

This study confirms that the optimum takeoff angle when vaulting with a flexible pole is lower than when vaulting with a rigid pole. The flexible-pole vaulter jumps up less at takeoff and so retains a greater velocity at takeoff. The vaulter is therefore able to grip higher on the pole and achieve a higher vault. The lower takeoff angle with the fibreglass pole is not commonly recognized, but it is an important effect of using 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; Tamura and Kuriyama, 1988).

Several researchers have investigated the mechanics of pole vaulting using computer simulations. (For example, see Ekevad and Lundberg 1995; Hubbard, 1980). However, they did not consider the energy losses in the pole plant and takeoff phases of the vault, and so were not able to determine the optimum combination of takeoff angle, pole length, and pole stiffness for a world-class vaulter. The model presented here is an important step towards the creation of a useful computer simulation program that will enable the optimum pole and the optimum vault technique for an individual athlete to be calculated. A comprehensive model of pole vaulting should include the following features:

1. 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" (Ekevad and Lundberg, 1995).
2. A multi-segment model of the vaulter that includes internal joint torques and the torque applied by the vaulter to the end of the pole (Ekevad and Lundberg, 1995; Hubbard, 1980). The vaulter model should be based on the anthropometric and strength measures of the athlete.
3. A sequence of movements of the athlete (and their timing) that is selected by the athlete (Ekevad and Lundberg, 1995; Hubbard, 1980).
4. A mechanism of energy loss due to the action of jumping up at takeoff (Figure 1).
5. A mechanism of energy dissipation in the vaulter's body when the pole is planted into the takeoff box (Equation 1). In an advanced model, the energy loss will depend on the pole length, pole stiffness, takeoff angle, and the athlete's movement patterns and body dimensions.

CONCLUSIONS: Simple models were developed that account for many features of pole vaulting. The advantage of a flexible fibreglass pole over the old-style bamboo poles and steel poles is that a flexible pole reduces the energy lost in the takeoff, and so allows a lower takeoff angle.

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