4 Energy transformations in the pole vault

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Abstract

This paper describes and explains the changes in kinetic energy, gravitational potential energy, elastic energy, and muscular work during a pole vault. Measurements of a skilled pole vaulter show that the height cleared by the athlete increases linearly with increasing run-up velocity and that this height increase is achieved through a combination of a higher grip on the pole and a greater push height above the pole. The athlete has a net energy gain during the vault. Although the energy lost during the take-off increases with increasing run-up velocity, this loss is not sufficient to negate the increase in run-up kinetic energy and the work done by the athlete during the pole support phase.

1 Pole vaulting

The pole vault is a physically and technically demanding event that requires considerable ability in sprinting, jumping, and gymnastics (Figure 1). In mechanical terms the aim of the athlete is to generate kinetic energy in the run-up and then use a long flexible pole to help convert as much of this energy as possible into the gravitational potential energy of the athlete at the peak of the vault. The best female pole vaulters achieve heights of 4.40-5.05 m, whereas the best male vaulters (who are faster, stronger, and taller) reach 5.60-6.15 m.

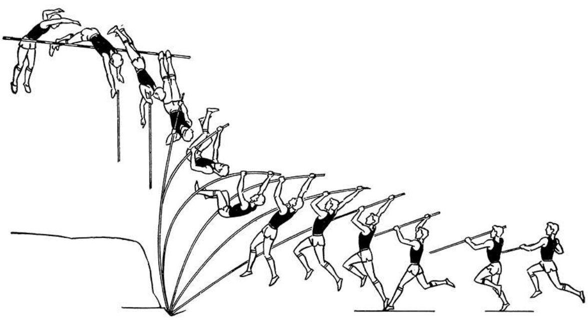

Figure 1: Typical sequence of actions in the pole vault. Reproduced from Ganslen (1979).

2 Energy transformations

In pole vaulting, the conversion of kinetic energy to gravitational potential energy is not a simple process and several additional energy transformations have an important bearing on the height achieved by the athlete. At take-off the athlete plants the pole into the take-off box and executes an upwards running jump. However, planting the pole produces a sharp jarring of the athlete and so some of the athlete's run-up kinetic energy is dissipated due to inelastic stretching of the athlete's body, particularly in the shoulders and back. The upwards jump at take-off is beneficial as it helps smooth the transition from the horizontal motion in the run-up to the vertical motion required to pass over the crossbar. To jump up, the athlete plants their take-off foot ahead of their centre of gravity so as to produce sufficient ground contact time in which to generate vertical velocity. However, this action also produces a horizontal braking impulse and so reduces the athlete's kinetic energy (Linthorne et al., 2011).

After take-off the athlete and pole rotate about the take-off box, transforming some of the athlete's kinetic energy into gravitational potential energy. Also, during the vault the pole bends under the effect of the momentum of the athlete and so elastic strain energy is temporarily stored in the pole. When the pole recoils this elastic strain energy is transformed into the gravitational potential energy of the athlete. Fibreglass and carbon fibre poles are highly elastic and only a small amount of energy is dissipated in the bending and recoiling pole. Another important energy transformation occurs during the pole support phase of the vault. Here, the athlete performs muscular work by lifting his body up against gravity and by exerting a torque on the pole and so adding to the elastic strain energy in the pole. At the peak of the vault the athlete does not access all the available energy. In order to travel forward beyond the crossbar, the athlete must retain a small amount of kinetic energy (equivalent to a horizontal velocity of about 1.0-2.5 m/s) and so the athlete's peak height is reduced by about 5-30 cm.

According to IAAF competition rules, the pole may be any length or diameter and may be constructed from any material or combination of materials. The correct choice of pole stiffness is very important in pole vaulting (Linthorne, 2000). The main advantage of using a flexible pole is that it reduces the jarring action experienced by the athlete when the pole is planted in the take-off box (Linthorne, 2000). Also, the optimum take-off angle with a flexible pole is lower than with a rigid pole and so the athlete retains more run-up kinetic energy because he does not have to jump up as much at take-off. The athlete wants a highly flexible pole so as to minimize the shock on the body during the pole plant and take-off (and hence minimize the loss of kinetic energy), but not so flexible that the pole returns the stored energy to the athlete too late. The athlete must select the pole stiffness so that the pole finishes its recoil at about the time when the pole has rotated to vertical. The optimum pole length and stiffness is different for each athlete and depends on the athlete's run-up velocity, body weight, vertical reach, and vaulting technique.

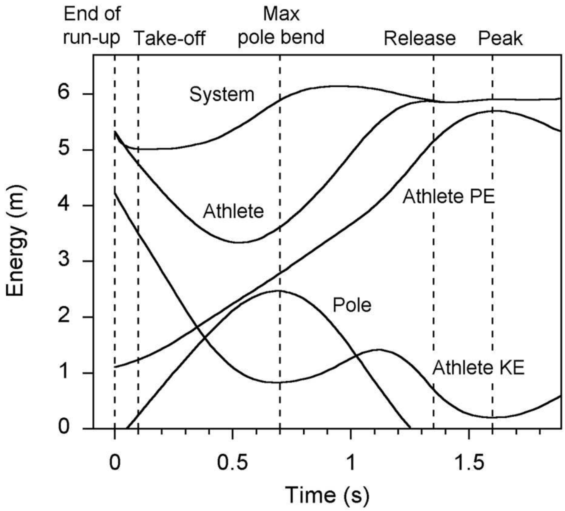

Figure 2: Typical time traces of mechanical energy for an elite male pole vaulter. Here, Athlete KE = kinetic energy of the athlete; Athlete PE = gravitation potential energy of the athlete; Pole = elastic strain energy in the pole; Athlete = total mechanical energy of the athlete (Athlete KE + Athlete PE); System = total mechanical energy of the athlete-pole system (Athlete + Pole). Energy values have been normalized to the athlete's body weight and so are equivalent to a change in the height of the athlete's centre of gravity.

Figure 2 shows the time traces of the athlete energy and pole energy in a performance by a skilled pole vaulter. Despite the energy loss during the take-off, most skilled athletes perform considerable muscular work during the pole support phase and so the athlete has an overall energy gain during the vault. Comparing the total energy of the athlete-pole system at the end of the run-up to the total energy of the system at the peak of the vault gives the following energy balance equation:

$$KE_{\text{run-up}} + PE_{\text{run-up}} = KE_{\text{peak}} + PE_{\text{peak}} + \Delta E_{\text{take-off}} + \Delta E_{\text{pole}} + W_{\text{muscular}} \quad (1)$$

where $KE_{\text{run-up}}$ and $PE_{\text{run-up}}$ are the kinetic energy and gravitational potential energy of the athlete at the end of the run-up, KE_{peak} and PE_{peak} are the kinetic energy and gravitational potential energy of the athlete at the peak of the vault, $\Delta E_{\text{take-off}}$ is the energy change during the pole plant and take-off, ΔE_{pole} is the net change in energy of the pole during its bending and recoiling, and W_{muscular} is the net muscular work done by the athlete during the pole support phase. For an elite male pole vaulter the energy values (normalized by dividing by the athete's body weight) are $KE_{\text{run-up}} = 4.3$ m, $PE_{\text{run-up}} = 1.1$ m, $KE_{\text{peak}} = 0.1$ m, $PE_{\text{peak}} = 5.7$ m, $\Delta E_{\text{take-off}} = -0.9$ m, and $\Delta E_{\text{pole}} = -0.1$ m. The net muscular work done by the athlete during the pole support phase is therefore $W_{\text{muscular}} = 1.4$ m.

3 Effect of run-up velocity on energy transformations

The athlete's run-up velocity is usually seen as the most important factor in pole vaulting. The generally accepted view is that a faster run-up allows the athlete to grip higher on a longer and stiffer pole and hence achieve a higher vault. However, athletes can differ substantially in their ability to achieve a fast run-up velocity. One method of improving our understanding of the effect of run-up velocity is to conduct an intervention study in which a wide range of run-up velocities is obtained by setting the length of the athlete's run-up. Linthorne and Weetman (2012) conducted such a study in which an experienced male pole vaulter with a personal best performance of 4.90 m performed a series of vaults using a run-up length of 2, 4, 6, 8, 12, and 16 steps. At each run-up length the athlete used a self-selected combination of pole length, pole stiffness, and grip height. Video images of the jumps were recorded using a video camera operating at 50 Hz and an Ariel Performance Analysis System was used to manually digitize the motion of the athlete in the video images. The energy variables that were investigated were the kinetic energy, gravitational potential energy, and total mechanical energy of the athlete. In this study the elastic energy stored in the pole was not reported because the ground reaction forces of the athlete and pole were not measured and so an inverse dynamics calculation could not be performed.

In this study the athlete's total mechanical energy (E) was calculated at three key instants: in the last stride of the run-up (E_1), at the instant of take-off (E_2), and at the peak of the vault (E_3). The total change in the athlete's energy between the end of the run-up and the peak of the vault is then $\Delta E_{\text{total}} = E_3 - E_1$. This total energy change was decomposed into the change in energy during the take-off phase ($\Delta E_{\text{take-off}} = E_2 - E_1$) and the change in energy from take-off to the peak of the vault ($\Delta E_{\text{pole-support}} = E_3 - E_2$). That is, $\Delta E_{\text{total}} = \Delta E_{\text{take-off}} + \Delta E_{\text{pole-support}}$. Here, $\Delta E_{\text{take-off}}$ is an indicator of the effectiveness of the athlete's take-off technique, and $\Delta E_{\text{pole-support}}$ is an indicator of the muscular work done by the athlete during the support phase on the pole.

As expected, the athlete's peak height increased as run-up velocity increased and this was achieved through a combination of a greater grip height and a greater push height (Figure 3). (The distance between the lower tip of the pole and the athlete's upper grip on the pole is called the 'grip height'. An athlete 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 peak height and the effective grip height is called the 'push height'.) Note that the relationship between peak height and run-up velocity for this athlete was linear, with a rate of about 0.5 m increase in peak height per 1 m/s increase in run-up velocity.

Figure 4 shows the effect of run-up velocity on the athlete's energy and on the changes in the athlete's energy. As expected, the athlete's run-up energy increased

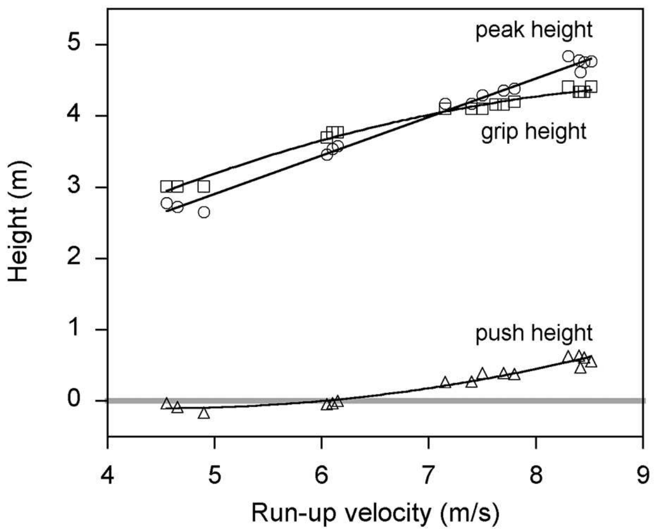

Figure 3: The athlete's peak height, grip height, and push height increased at faster run-up velocities. Adapted from Linthorne and Weetman (2012).

in proportion to the square of the run-up velocity ($KE = 1/2mv^2$). However, the athlete lost energy during the take-off phase and this loss increased as run-up velocity increased (Figure 4b). The energy that was lost during the take-off was due to inelastic stretching of the athlete's body from the jarring action when the pole was planted into the box, and due to the horizontal braking force generated when the athlete jumped upwards at take-off. Both of these mechanisms produced a greater loss of energy as the athlete's run-up velocity increased (Linthorne et al., 2011). Also, when using a faster run-up velocity the athlete's grip height was greater and so the pole angle at take-off was lower, thus increasing the jarring effect of the pole on the athlete.

The amount of energy added by the athlete during the pole support phase increased with increasing run-up velocity (Figure 4b). This might have been because the athlete was able to place himself in a better mechanical position to add muscular energy to the vault. The athlete's total energy at the peak of the vault (E_3) was greater than that at the end of the run-up (E_1) and so the athlete had a net energy gain during the vault. Although the total energy change in the vault between the end of the run-up and the peak of the vault was always positive, the increase in the energy added during the support phase of the vault was less than the increase in the energy that was lost during the take-off and so the overall energy gain tended to decrease slightly with increasing run-up velocity (Figure 4b).

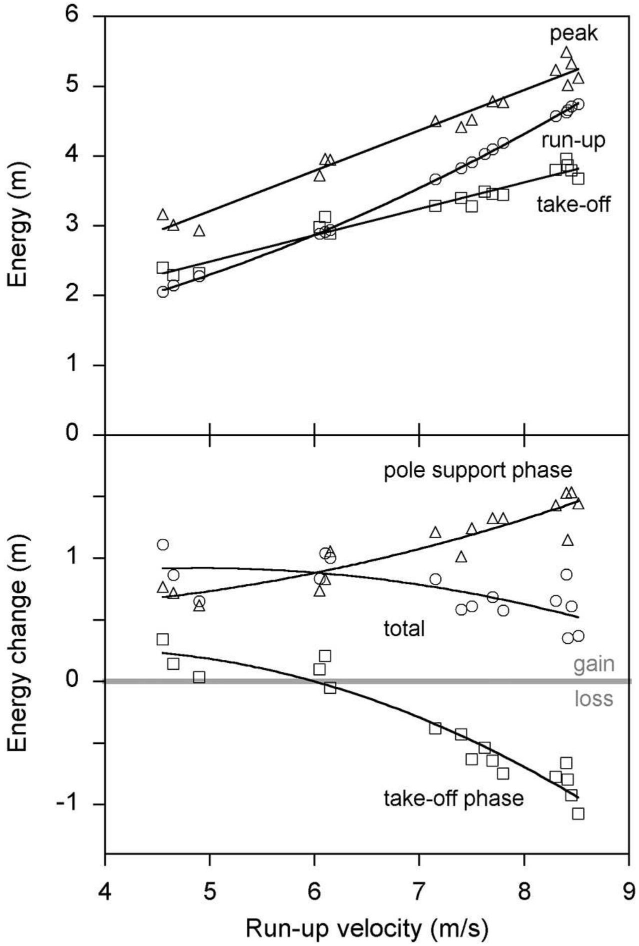

Figure 4: Plot (a) shows the effect of run-up velocity on the athlete's energy in the last stride of the run-up (E_1), at take-off (E_2), and at the peak of the vault (E_3). Plot (b) shows the change in the athlete's energy during the take-off phase ($\Delta E_{\text{take-off}} = E_2 - E_1$), the energy gain of the athlete due to muscular work performed during the pole support phase of the vault ($\Delta E_{\text{pole-support}} = E_3 - E_2$), and the total energy gain of the athlete during the vault ($\Delta E_{\text{total}} = \Delta E_{\text{take-off}} + \Delta E_{\text{pole-support}} = E_3 - E_1$). Adapted from Linthorne and Weetman (2012).

4 Multiple-athlete studies

The results from the study by Linthorne and Weetman (2012) suggest that the vault height for a pole vaulter increases linearly with run-up velocity at a rate of around

0.5 m per 1 m/s increase in run-up velocity. This rate of increase is similar to that indicated by fitting a linear regression curve to data from multiple-athlete studies (Figure 5). McGinnis (2004) reported a rate of 0.6 m per 1 m/s and 0.7 m per 1 m/s for elite male and elite female vaulters, respectively. Although the rate of increase in vault height for the female vaulters is similar to that for male vaulters, a female vaulter has a vault height that is about 0.6 m lower than a male vaulter with the same run-up velocity. This difference probably arises because female vaulters tend to have a lesser relative muscular strength in their upper body and so perform less work during the pole support phase. Also, female vaulters probably suffer a greater loss of energy during the take-off because they tend to be shorter in stature and so have a lower centre of gravity and a lower vertical reach when planting the pole.

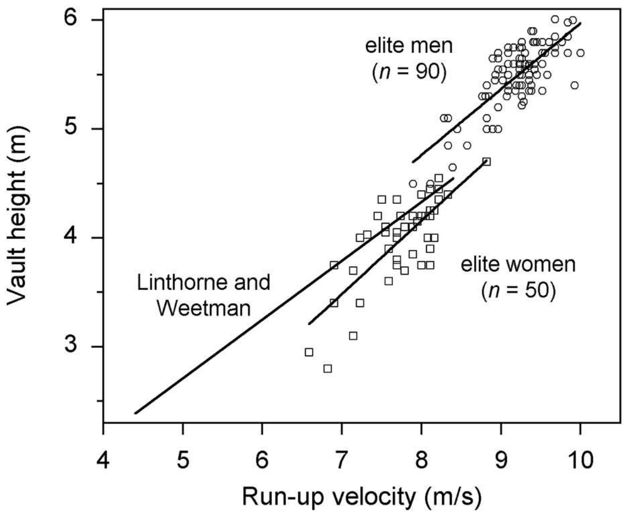

Figure 5: This plot shows the strong correlation between vault height and run-up velocity within groups of elite pole vaulters. Data from McGinnis (2004). Also shown for comparison is the relationship between vault height and run-up velocity for the athlete in the study by Linthorne and Weetman (2012).

5 Modelling studies

A key finding from the study by Linthorne and Weetman (2012) is that the athlete's peak height increases *linearly* with increasing run-up velocity. This result is contrary to that from a well-known simple model of pole vaulting where the athlete generates kinetic energy during the run-up and then uses a long pole to convert nearly all of this kinetic energy into the gravitational potential energy of the athlete's body at the peak of the vault. In this model the athlete's peak height is expected to increase as the *square* of the athlete's run-up velocity. More sophisticated mathematical models of pole vaulting have been developed which include the effects of the flexible pole, the energy losses in the take-off, and the work done by the athlete during the pole support phase (Ekevad and Lundberg, 1997; Hubbard, 1980; Linthorne, 2000; Liu et al., 2011). However, despite the considerable efforts there is not yet a comprehensive model that includes all the essential features of pole vaulting. All of the models presented to date were missing at least one major element and so are not able to give a reliable indication of the relationship between the athlete's run-up velocity and the height achieved by the athlete. A complete model of pole vaulting must be able to account for the effects of run-up velocity on the athlete's energy that are shown in Figure 4.

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