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Research article

Effects of run-up velocity on performance, kinematics, and energy exchanges in the pole vault

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Abstract

This study examined the effect of run-up velocity on the peak height achieved by the athlete in the pole vault and on the corresponding changes in the athlete's kinematics and energy exchanges. Seventeen jumps by an experienced male pole vaulter were video recorded in the sagittal plane and a wide range of run-up velocities (4.5–8.5 m/s) was obtained by setting the length of the athlete's run-up (2–16 steps). A selection of performance variables, kinematic variables, energy variables, and pole variables were calculated from the digitized video data. We found that the athlete's peak height increased linearly at a rate of 0.54 m per 1 m/s increase in run-up velocity and this increase was achieved through a combination of a greater grip height and a greater push height. At the athlete's competition run-up velocity (8.4 m/s) about one third of the rate of increase in peak height arose from an increase in grip height and about two thirds arose from an increase in push height. Across the range of run-up velocities examined here the athlete always performed the basic actions of running, planting, jumping, and inverting on the pole. However, he made minor systematic changes to his jumping kinematics, vaulting kinematics, and selection of pole characteristics as the run-up velocity increased. The increase in run-up velocity and changes in the athlete's vaulting kinematics resulted in substantial changes to the magnitudes of the energy exchanges during the vault. A faster run-up produced a greater loss of energy during the take-off, but this loss was not sufficient to negate the increase in run-up velocity and the increase in work done by the athlete during the pole support phase. The athlete therefore always had a net energy gain during the vault. However, the magnitude of this gain decreased slightly as run-up velocity increased.

Key words: Sports biomechanics, kinematics.

Introduction

The pole vault is a complex athletics event that requires considerable ability in sprinting, jumping, and gymnastics. The event is also characterized by substantial energy exchanges, particularly between the kinetic and gravitational potential energy of the athlete and the strain energy in the pole. However, of all the factors that affect pole vault performance the athlete's run-up velocity is believed to be the most important (Angulo-Kinzler et al., 1994; Linthorne, 2000). The generally accepted view among coaches and sport scientists is that a faster run-up allows the athlete to grip higher on a longer and stiffer pole and hence achieve a higher vault (McGinnis, 1997; Tidow, 1989). Although the basic pole vaulting technique of running with pole, planting the pole, jumping at take-off, inverting on the pole, and arching feet-first over the crossbar is firmly established, athletes can differ substantially in their ability to achieve a fast run-up velocity and in their proficiency in performing the vaulting actions. Variations in run-up velocity and technical proficiency also affect the optimum choice of grip height and pole stiffness for the athlete, which in turn affect the patterns of energy exchange that occur during the vault. Therefore, if coaches are to teach a technique that is appropriate for the individual athlete, they require a detailed understanding of the relationships between the athlete's run-up velocity, the athlete's vaulting kinematics, the characteristics of the pole, the pattern of energy exchanges, and the height achieved by the athlete.

A potentially fruitful method of reaching an understanding of the relationships between performance and technique is to conduct an experimental study on the individual athlete in which the technique variable of interest is deliberately varied. This type of study was conducted by Greig and Yeadon (2000) for the high jump and by Bridgett and Linthorne (2006) for the long jump. Both studies analyzed performances by only one athlete and a wide range of run-up velocities was obtained by setting the length of the athlete's run-up. These studies improved our understanding of the optimum technique of high jumping and long jumping by identifying the optimum run-up velocity and by revealing the magnitude of the change in performance for a given increase in run-up velocity. The long jump study showed that the athlete's optimum technique is to run-up as fast as possible and plant the take-off leg at about 65° to the horizontal. At around the athlete's competition run-up velocity the jump distance increased at a rate of about 0.6 m per 1 m/s increase in run-up velocity. In contrast, the high jump study showed that the athlete has a sub-maximal optimum run-up velocity (about 7 m/s) and that the take-off leg should be planted at about 55° to the horizontal. These studies also showed how technique variables such as the leg plant angle, knee plant angle, take-off velocity, take-off angle, and take-off duration vary in response to changes in the athlete's run-up velocity.

To the best of our knowledge a run-up velocity intervention study similar to those conducted by Greig and Yeadon (2000) and by Bridgett and Linthorne (2006) has not previously been conducted for the pole vault. The pole vault differs from the high jump and long jump in that the athlete is not in free flight after take-off but is still in

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contact with the ground via the pole. The athlete's trajectory after take-off is therefore determined by his choice of pole characteristics and movements in the pole support phase, as well as by his run-up velocity and take-off technique. However, even though the relationships between performance and technique are more complex in the pole vault than in the high jump and long jump, it is still appropriate to conduct a run-up velocity intervention study for the pole vault because of the suspected strong influence of run-up velocity on vault performance.

The study reported here examined jumps by an experienced pole vaulter who used a wide range of run-up lengths so as to produce a wide range of run-up velocities. The aims of the study were (1) to determine the mathematical form and sensitivity of the relationship between run-up velocity and vault height, (2) to determine the changes in the athlete's kinematics and the changes in the pole characteristics that are necessary to make effective use of a faster run-up velocity, and (3) to determine the resulting changes in the patterns of energy exchange that occur during the vault. In this study video analysis was used to obtain kinematic measures of the athlete's technique at key instances during the vault. The performance variables, kinematic variables, energy variables, and pole variables were then plotted against run-up velocity, and the relationships between the variables were determined by fitting curves to the data. We expected that a faster run-up velocity would result in a higher grip height and vault height, but would also require some substantial changes in the kinematics, pole characteristics, and energy exchange patterns so as to achieve the best performance at a given run-up velocity.

Methods

An experienced male pole vaulter (height 1.80 m, weight 70 kg) with a personal best performance of 4.90 m volunteered to participate in the study. The study was approved by the Human Ethics Committee of Brunel University, the participant was informed of the protocol and procedures prior to his involvement, and written consent to participate was obtained. The jumps were conducted in still air conditions in an indoor athletics stadium with a Rekortan running track. The pole vault runway, take-off box, uprights, and landing mats complied with IAAF regulations for pole vault competitions. The participant wore athletic training clothes (tight-fitting lycra shorts and shirt) and spiked athletics shoes.

A wide range of run-up velocities was obtained by setting the length of the participant's run-up. The participant performed 17 jumps for maximum height using a run-up length of 2, 4, 6, 8, 12, and 16 steps (his usual competition run-up length). The order of the run-up lengths was random and an unlimited rest interval was given between jumps to minimize the effects of fatigue on vaulting performance. At each run-up length the participant used a self-selected combination of pole length, pole stiffness, and grip height. The participant in this study was very experienced and regularly performed jumps from short run-ups as part of his normal training program.

Video analysis

A Panasonic NV-D560 video camera operating at 50 Hz was used to record the movement of the athlete during the last two steps of the run-up and during the vault. The video camera was mounted on a rigid tripod at a height of 1.5 m and placed at right angles to the runway about 13 m away from the middle of the runway. The field of view was zoomed to allow the athlete to be visible in the last two steps of the take-off and throughout the vault. The movement space of the video camera was calibrated with three vertical poles that were placed along the midline of the runway and 4 m apart and with a marker on the crossbar. The positive x direction was defined as the forwards direction of the run-up, the positive y direction was defined as vertically upwards, and the origin was the upper edge of the back of the take-off box at the midline of the runway.

An Ariel Performance Analysis System (Ariel Dynamics, Trabuco Canyon, CA, USA) was used to manually digitize the motion of the athlete in the video images. Eighteen body landmarks that defined a 17-segment model of the athlete were digitized in each image, and the two-dimensional coordinates of the body landmarks and the athlete's centre of mass were calculated from the digitized data using the two-dimensional direct linear transform (2D-DLT) algorithm. Coordinate data were smoothed using a second-order Butterworth digital filter with a cut-off frequency of 5 Hz and the velocity of the markers was calculated by direct differentiation of the coordinate data. The choice of cut-off frequency was based on a visual inspection of the power spectra of the coordinate and velocity data.

Data analysis

We measured relevant performance variables, kinematic variables, energy variables, and pole variables similar to those reported in previous biomechanical studies of the pole vault (Angulo-Kinzler et al., 1994; Arampatzis et al., 1999; Gros and Kunkel, 1990; Schade et al., 2004; 2005). The selected performance variables of the athlete were his peak height, grip height, and push height. The kinematic variables that were investigated were the horizontal, vertical, and resultant velocities of the athlete's centre of mass, the direction of travel of the athlete's centre of mass, the height of the athlete's centre of mass, the angle of the leg and knee of the athlete's take-off leg, the pole angle, and the pole chord length. The energy variables that were investigated were the kinetic energy, gravitational potential energy, and total mechanical energy of the athlete. Time traces of these variables were produced and the key instants during the vault at which the variables were noted were the instants of touchdown, pole grounding, take-off, maximum pole bend, and peak of the jump. The characteristic of the pole that was investigated was the effective pole stiffness.

In pole vaulting the peak height reached by the athlete's centre of mass is usually 5–25 cm higher than the vault height (i.e., the height of the crossbar). Pole vaulters are allowed to use a pole of any length and 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 off' or 'push height' (Linthorne, 2000).

In this study the instant of touchdown was defined as the first frame in which the take-off foot was in contact with the ground, and the instant of take-off was the first frame in which the take-off foot broke contact with the ground. The instant of pole grounding was the first frame in which the lower end of the pole made contact with the back of the take-off box as indicated by movement of the athlete's upper arm behind his head due to the reaction force of the pole. In almost all jumps the instant of pole grounding occurs between the instants of touchdown and take-off (Gros and Kunkel, 1990; McGinnis, 1997).

The athlete's velocity and direction of travel (i.e., angle to the horizontal) at any instant were calculated from the horizontal and vertical components of the velocity of the athlete's centre of mass. In this study the run-up velocity was calculated from the change in the horizontal position of the athlete's centre of mass over the duration of the flight phase of the last stride before take-off (Hay and Nohara, 1990). This method produces an accurate measure of run-up velocity as it avoids errors due to excessive filtering of velocity data during the impact between the athlete and the ground at touchdown. The athlete's leg angle was defined as the angle relative to the positive horizontal (i.e., positive x-axis) of a line joining the hip and the ankle joints of the take-off leg, and the knee angle was defined as the angle enclosed by the lines that join the hip, knee, and ankle joints of the take-off leg.

During a vault the pole deforms and recoils. At any instant during the bending of the pole the pole chord length was defined as the distance between the lower tip of the pole and the athlete's upper grip on the pole. The instant of maximum pole bend was defined as the frame at which the pole chord length reached its minimum value. To compare jumps performed with different grip heights the pole chord length at maximum pole bend was also expressed as a percentage of the undeflected pole chord length. The pole angle was defined as the angle of the pole chord to the negative horizontal (i.e., negative x-axis). A pole vaulter may use a pole of any desired length or stiffness. The relationship between the effective stiffness rating of the pole, R_{grip}, and the height of the athlete's grip on the pole, L_{grip}, is given by $R_{grip} = R_{pole}(L_{pole}/L_{grip})^2$, where R_{pole} is the manufacturer's pole stiffness rating and L_{pole} is the manufacturer's specified grip height on the pole.

Energy

Pole vaulting is essentially about generating kinetic energy (i.e., velocity) in the run-up and then using a long pole to convert this energy into gravitational potential energy (i.e., height). However, the conversion of kinetic energy to potential energy is not a direct process and several mechanisms of energy exchange have an important bearing on the height achieved by the athlete. The first of these energy exchanges occurs during the take-off where the athlete experiences a sharp jarring action when the pole is planted into the box and so some of the athlete's run-up kinetic energy is dissipated due to inelastic stretching of the athlete's body. Also, some kinetic energy is lost during the take-off due to the athlete's upwards jumping action (Bridgett and Linthorne, 2006; Linthorne, 2000). Elastic strain energy is temporarily stored in the bending pole during the pole support phase of the vault. Modern poles are highly elastic and so only a small amount of energy (equivalent to a height change of 0.10–0.25 m) is dissipated as heat in the bending and recoiling pole (Arampatzis et al., 2004). Another important energy exchange mechanism occurs during the pole support phase where the athlete performs muscular work, adding energy to the vaulter-pole system and so increasing the peak height achieved by the athlete (Arampatzis et al., 2004; Ekevad and Lundberg, 1997; Hubbard, 1980; Linthorne, 2000).

In the present study the total mechanical energy of the athlete was calculated as the sum of the kinetic energy and gravitational potential energy of the athlete's centre of mass. In calculating the gravitational potential energy of the athlete the zero reference height is arbitrary and in this study was set to ground level so as to be consistent with the choice used by previous investigators (Arampatzis et al., 1999; Gros and Kunkel, 1990; Schade et al., 2004; 2005). In the pole vault the rotational kinetic energies of the athlete's limbs and of the athlete about his centre of mass are relatively small and so were not included in the calculation of the total mechanical energy (Schade et al., 2000).

The athlete's total mechanical energy (E) was noted at four key instants: touchdown (E_1), take-off (E_2), maximum pole bend (E_3), and peak of the vault (E_4). We calculated the total change in the athlete's energy during the vault from touchdown to the peak of the vault ($\Delta E_{total} = E_4 - E_1$). This total energy change was decomposed into the change in energy during the take-off phase ($\Delta E_{take\text{-}off} = E_2 - E_1$), which is an indicator of the effectiveness of the athlete's take-off technique, and the change in energy from take-off to the peak of the vault ($\Delta E_{pole\text{-}support} = E_4 - E_2$), which is an indicator of the muscular work done by the athlete during the support phase on the pole (Armbrust, 1993; Linthorne, 2000). Therefore, we have $\Delta E_{total} = \Delta E_{take\text{-}off} + \Delta E_{pole\text{-}support}$. We also calculated the change in the athlete's energy during the pole bending phase ($\Delta E_{pole\text{-}bend} = E_3 - E_2$) and during the pole recoiling phase ($\Delta E_{pole\text{-}recoil} = E_4 - E_3$). These quantities are indicators of the energy that is stored in the pole and subsequently recovered during the pole recoil. In this study energy values were normalized to body weight and so can be interpreted as an equivalent change in the height of the athlete's centre of mass (Dillman and Nelson, 1968).

Uncertainties

In the present study the greatest source of uncertainty in many of the measured values arose from the sampling frequency of the video camera, and this uncertainty was taken as one half of the difference between the value at the instant of interest and the value at one frame before the instant of interest (Hay and Nohara, 1990). The calculated uncertainties due to the video sampling rate were about 0.1 m/s for take-off velocity, 1.0º for take-off angle, 0.01 m for touchdown height, 0.02 m for take-off height, 2.8º for leg angle at touchdown, 1.3º for knee angle at touchdown, 0.6º for pole angle, 0.07 m for (normalized) energy at touchdown, 0.03 m for energy at take-off, 0.02 m for energy at maximum pole bend, and 0.02 m for energy at the peak of the vault. Repeat digitizing of a trial five times by the same operator indicated that the uncertainties in run-up velocity, pole chord length, and peak height of the athlete were about 0.1 m/s, 0.02 m, and 0.02 m, respectively.

Curve fits

We fitted curves to plots of the data in order to quantify the strength of the relationships between the variables. A wide variety of curves were tested including linear, quadratic, cubic, and exponential curves. In deciding upon the best curve we were guided by a locally weighted regression (loess) fit to the data and by the distribution of the residuals. If two or more fitted curves seemed appropriate for the data a calculation of Akaike's Information Criterion was used to determine which of the curves gave the best fit (Sugiura, 1978).

Fitting curves to the data allowed us to see the trends in the relationships between run-up velocity and the other variables. However, a coach will probably have a particular interest in the rate of change in the athlete's variables when the athlete is using their competition run-up velocity. Therefore, we examined the gradient of the tangent line to the fitted curves at the athlete's competition run-up velocity. The gradient of the tangent line to the fitted curve was obtained by calculating the first derivative (with respect to run-up velocity) of the fitted curve and then calculating the value of this function at the athlete's competition (16 step) run-up velocity.

Data from other athletes

In this study we obtained data from only one male pole vaulter and so our ability to generalize the results to other pole vaulters initially appeared to be limited. However, training data from the log books of pole vault coaches is another source of reliable data that can be used to investigate the relationships between run-up velocity and vaulting performance. Many pole vaulters perform jumps from short run-ups as a part of their normal training program. The coach records the vault height, grip height, and push height for jumps from these short run-ups and looks for changes to indicate the athlete's training progress. The number of run-up steps is recorded rather than run-up velocity because the coach does not usually have a simple method of measuring the athlete's run-up velocity during training. Likewise, the athlete's vault height (i.e., the height of the crossbar) is recorded rather than the athlete's peak height, and in this arrangement the athlete's push height is the difference between the vault height and the effective grip height.

We obtained data for six male pole vaulters of varied ability from the training logs of a pole vault coach (Steve Rippon, personal communication). The relationships between the run-up length and the vault height, grip height, and push height for the athlete in the present study were compared to those for the six other athletes. This comparison allowed us to decide whether the relationships that were observed for the athlete in the present study were individual idiosyncracities or whether they were likely to be similar to those for most other male pole vaulters (Bates, 1996). In the present study the height of the crossbar was not recorded and so we converted the peak height for the athlete in our study to a vault height by subtracting 20 cm, which is typical of the difference between the peak height of the athlete's centre of mass and the height of the crossbar (Angulo-Kinzler et al., 1994; Gros and Kunkel, 1990; Schade et al., 2004; 2005).

Results

The run-up velocity of the athlete in this study increased with increasing run-up length and tended toward an asymptotic maximum value (Figure 1). We observed systematic changes in the athlete's performance variables with increasing run-up velocity. The peak height increased linearly at a rate of 0.54 m per 1 m/s increase in run-up velocity (with a 95% confidence interval of ± 0.03 m per m/s) (Figure 2). The increase in peak height was achieved through a combination of a greater grip height and a greater push height. However, as the athlete's run-up velocity increased the relative contribution of the grip height decreased and that of the push height increased.

Figure 1. This plot shows the effect of run-up length on the run-up velocity of an experienced male pole vaulter. The fitted exponential curve indicates an asymptotic maximum run-up velocity of 8.55 m/s.

We also observed systematic changes in the kinematic variables and pole characteristics with increasing run-up velocity. At the instant of take-off the athlete's resultant velocity is the vector sum of the horizontal and vertical components of the take-off velocity, and the athlete's take-off angle is given by the ratio of the vertical and horizontal components of the take-off velocity. In this study the athlete's resultant take-off velocity increased with increasing run-up velocity (Figure 3). However, the take-off velocity was almost always less than the run-up velocity and the faster the run-up velocity the greater the loss of velocity. In this study the athlete's horizontal take-off velocity increased with increasing run-up velocity whereas the vertical take-off velocity remained almost constant at about 2.5 m/s. Therefore, the change in the athlete's take-off angle was due to the change in his horizontal take-off velocity. As the athlete's run-up velocity increased the horizontal velocity at take-off also increased and so the take-off angle decreased, reaching about 20° at the athlete's competition run-up velocity (about 8.4 m/s).

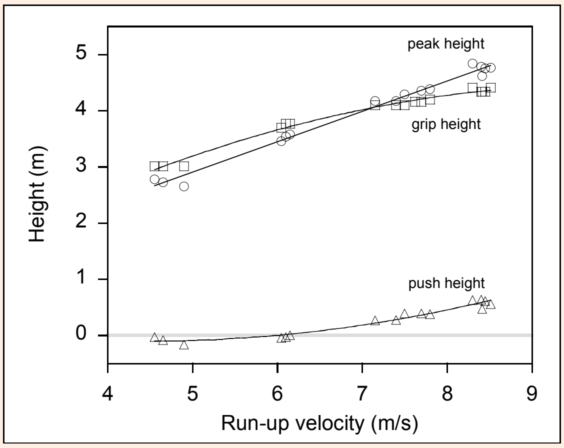

Figure 2. The athlete's peak height, grip height, and push height increased with increasing run-up velocity. The athlete's peak height increased at a rate of 0.54 m per 1 m/s increase in run-up velocity.

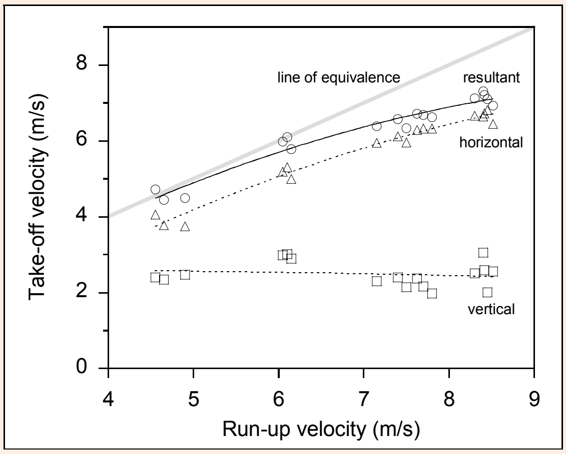

Figure 3. The athlete's take-off velocity increased with increasing run-up velocity (solid line). Also shown are the horizontal and vertical components of the take-off velocity (dashed lines). The grey line is the line of equivalence between run-up velocity and take-off velocity. The athlete's take-off velocity was less than his run-up velocity and the faster the run-up velocity the greater the loss of velocity.

The athlete in this study made small systematic changes to his take-off jumping action as he increased his run-up velocity. He maintained the same leg angle at touchdown (about 70–75º) as run-up velocity increased. The athlete also had a more straightened knee at touchdown when using a faster run-up velocity. His knee angle increased from about 130° at the lowest velocity (about 4.5 m/s in a 2-step run-up) to about 150° at his competetion run-up velocity.

At the instant of pole grounding the athlete's upper arm was always at full extension with his upper handgrip directly above his shoulders. This technique maximized the height of his upper handgrip above the ground (about 2.11 m) and so maximized the angle of the pole to the horizontal at the instant of pole grounding. The pole angle decreased with increasing run-up velocity as a direct result of the increase in his grip height. Because the pole was straight at the instant of pole grounding the geometry of the athlete and pole meant that the pole angle, θ_{pole}, decreased as he used a higher grip according to $\theta_{pole} = \arcsin[(h_{hand}+h_{box})/L_{grip}]$, where h_{hand} is the height of the athlete's hand, h_{box} is the depth of the take-off box, and L_{grip} is athlete's grip height. The pole angle was about 52° at the lowest run-up velocity used in a 2-step run-up and rapidly decreased with increasing run-up velocity, reaching about 31° at the athlete's competition run-up velocity.

The effective stiffness of the pole increased slightly with increasing run-up velocity and reached a stiffness rating of about 81 kg at the athlete's competition run-up velocity. Although the athlete used a higher grip on the pole as the run-up velocity increased (Figure 2), the pole chord length at the instant of maximum pole bend remained almost the same at about 3.0 m. The percentage shortening of the pole chord length at the instant of maximum pole bend initially increased rapidly with increasing run-up velocity, but was almost constant at about 29% for the jumps from 8, 12, and 16 steps.

The time traces of the athlete's kinetic energy, gravitational potential energy, and total mechanical energy followed a consistent pattern in the vaults. The athlete's initial kinetic energy at touchdown showed a sudden decrease during the take-off, followed by a further decrease after take-off as the athlete transferred his initial kinetic energy to strain energy in the bending pole. As the pole recoiled, strain energy was transferred to the gravitational potential energy of the athlete. At the peak of the vault the athlete retained some kinetic energy (equivalent to a horizontal velocity of 2.7 m/s) and so at any given run-up velocity the athlete's peak height was about 0.37 m less than the athlete's normalized total energy at the peak of the vault.

The athlete's total mechanical energy at touchdown (E_1), take-off (E_2), and peak of the vault (E_4) increased with increasing run-up velocity, whereas the athlete's total energy at the instant of maximum pole bend (E_3) increased only slightly at the highest run-up velocities (Figure 4). In all jumps the athlete's total energy at the peak of the vault (E_4) was greater than that at touchdown (E_1) and so the athlete had a net energy gain during the vault.

Except at the slowest run-up velocities, the athlete lost energy during the take-off phase ($\Delta E_{take\text{-}off}$) and this loss increased as his run-up velocity increased (Figure 5a). The amount of energy added by the athlete during the pole support phase ($\Delta E_{pole\text{-}support}$) increased with increasing run-up velocity. Although the total energy change in the vault from touchdown to the peak of the vault ($\Delta E_{total} = \Delta E_{take\text{-}off} + \Delta E_{pole\text{-}support}$) 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 with increasing run-up velocity (Figure 5a). The amount of energy lost by the athlete during the pole bending phase ($\Delta E_{\text{pole-bend}}$) increased with increasing run-up velocity (Figure 5b), as did the amount of energy gained during the pole recoiling phase ($\Delta E_{\text{pole-recoil}}$).

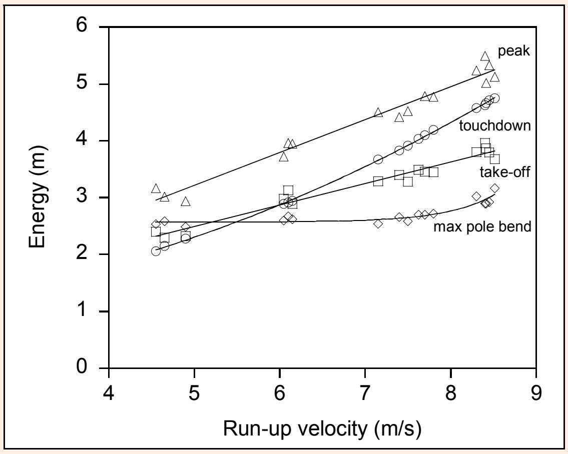

Figure 4. This plot shows the effect of run-up velocity on the athlete's energy at touchdown (E_1), take-off (E_2), maximum pole bend (E_3), and peak of the vault (E_4). Energy values are normalized to body weight and so can be interpreted as an equivalent change in the height of the athlete's centre of mass.

The curves that were fitted to the data provided quantitative measures of the relationships between the athlete's run-up velocity and the performance variables, kinematic variables, energy variables, and pole variables. Selected curves of best fit to the data are listed in Table 1 and shown in Figures 1–5. The rate of change in the variables when the athlete was using his competition run-up velocity was calculated from the gradient of the tangent line to the fitted curves at the athlete's competition run-up velocity (8.4 m/s). For the athlete studied here the rates of change per 1 m/s increase in run-up velocity were: vault height, 0.54 ± 0.03 m; grip height, 0.16 ± 0.07 m; push height, 0.35 ± 0.08 m; take-off velocity, 0.40 ± 0.26 m/s; take-off angle, –3.5 ± 1.0 deg; touchdown knee angle, –0.3 ± 4.6 deg; pole angle, –1.4 ± 0.3 deg; pole chord length, 0.14 ± 0.07 m; effective pole stiffness rating, 1.9 ± 0.9 kg; energy loss during the take-off, –0.50 ± 0.17 m; energy gain during the pole support, 0.20 ± 0.05 m; and total energy gain during the vault, –0.21 ± 0.22 m; (gradient ± 95% confidence interval).

Figure 6 compares the vault height, grip height, and push height for the athlete in the present study with training data for six other male pole vaulters of varied ability. Among the seven athletes the relationships between the run-up length and the performance variables (vault height, grip height, and push height) appeared similar in shape but with different vertical offsets. The order of ability in vault height among the athletes was closely reflected by the order in grip height and push height.

Discussion

The results from the athlete in this study indicate that his optimum technique was to run-up as fast as possible and that his peak height increased linearly at a rate of about 0.54 m per 1 m/s increase in run-up velocity. The increase in peak height was achieved through a combination of a greater grip height and a greater push height. As the athlete increased his run-up velocity he made systematic changes to his take-off velocity, take-off angle, and knee angle at touchdown, and he elected to use a pole with a slightly greater effective stiffness. Although a faster run-up velocity resulted in a greater loss of energy during the take-off, the athlete always had a net gain of energy during the vault because of the muscular work performed during the pole support phase. However, the magnitude of the energy gain during the vault decreased slightly with increasing run-up velocity.

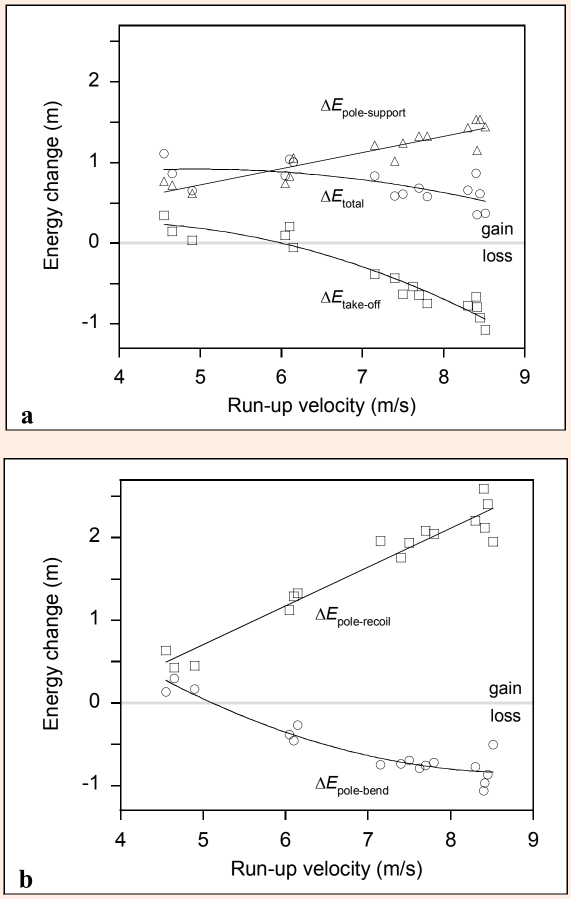

Figure 5. Plot (a) shows the effect of run-up velocity on the energy change of the athlete during the take-off phase ($\Delta E_{\text{take-off}} = E_2 - E_1$), the energy gain of the athlete due to muscular work performed during the pole support phase of the vault ($\Delta E_{\text{pole-support}} = E_4 - E_2$), and the total energy gain of the athlete during the vault ($\Delta E_{\text{total}} = \Delta E_{\text{take-off}} + \Delta E_{\text{pole-support}} = E_4 - E_1$). Plot (b) shows the effect of run-up velocity on the energy loss of the athlete during the pole bending phase ($\Delta E_{\text{pole-bend}} = E_3 - E_2$) and the energy gain of the athlete during the pole recoiling phase ($\Delta E_{\text{pole-recoil}} = E_4 - E_3$).

The finding that the athlete's peak height increased *linearly* with increasing run-up velocity was not an expected result. In a well-known model of pole vaulting the athlete generates kinetic energy ($KE = ½mv^2$) during the run-up and then uses a long pole to convert nearly all

Table 1. Parameter values for selected curves of best fit to the athlete's performance variables, kinematic variables, energy variables, and pole variables. Data are fitted parameter value (± standard error).

Variable	Equation	Fit parameter symbol	Fit parameter units	Value
Run-up velocity	$y = a\ \mathrm{Exp}[-b\ \mathrm{Exp}(-cx)]$	a	m/s	8.55 (.09)
		b	–	1.14 (.06)
		c	1/step	.32 (.02)
		RMSD	m/s	.14
Peak height	$y = mx + c$	m	s	.540 (.017)
		c	m	.21 (.12)
		RMSD	m	.086
Grip height	$y = ax^2 + bx + c$	a	s^2/m	–.052 (.010)
		b	s	1.04 (.13)
		c	m	–.69 (.42)
		RMSD	m	.053
Push height	$y = ax^2 + bx + c$	a	s^2/m	.045 (.011)
		b	s	–.40 (.15)
		c	m	.81 (.47)
		RMSD	m	.058
Take-off velocity	$y = ax^2 + bx + c$	a	s/m	–.070 (.035)
		b	–	1.57 (.46)
		c	m/s	–1.2 (1.5)
		RMSD	m/s	.19
Take-off angle	$y = mx + c$	m	deg·s/m	–3.51 (.51)
		c	deg	48.8 (3.6)
		RMSD	deg	2.6
Energy at touchdown	$y = x^2/(2g) + h_{td}$	g	m/s^2	9.674 (.057)
		h_{td}	m	1.011 (.016)
		RMSD	m	.02
Energy at take-off	$y = mx + c$	m	s	.379 (.021)
		c	m	.59 (.15)
		RMSD	m	.11
Energy at max pole bend	$y = a + \mathrm{Exp}[1 + b(x - \mathrm{c})]$	a	m	2.570 (.032)
		b	s/m	1.80 (.53)
		c	m/s	9.47 (.29)
		RMSD	m	.07
Energy at peak of vault	$y = mx + c$	m	s	.579 (.029)
		c	m	.32 (.21)
		RMSD	m	.15
Energy lost in take-off	$y = ax^2 + bx + c$	a	s^2/m	–.054 (.022)
		b	s	.41 (.29)
		c	m	–.53 (.94)
		RMSD	m	.12
Energy gain in pole support	$y = mx + c$	m	s	.200 (.024)
		c	m	–.28 (.17)
		RMSD	m	.12
Energy gain in vault	$y = ax^2 + bx + c$	a	s^2/m	–.031 (.029)
		b	s	.30 (.99)
		c	m	.17 (1.24)
		RMSD	m	.15

Run-up velocity was plotted against run-up length (steps), all other variables were plotted against run-up velocity (m/s). RMSD = root-mean-square deviation for the regression curve.

of this kinetic energy into the gravitational potential energy ($PE = mgh$) of his body at the peak of the vault (Armbrust, 1993). This model suggests that the athlete's vault height should increase in proportion to the square of the run-up velocity (rather than in proportion to the run-up velocity as found in the present study). 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 (for example; Ekevad and Lundberg, 1997; Hubbard, 1980; Linthorne, 2000; Liu et al., 2011). However, none of the modeling studies cited above reported the form of the relationship between run-up velocity and vault height.

Some investigators have examined competition performances by an athlete in an attempt to gain an insight into the form of the relationship between vault height and run-up velocity. However, McGinnis (1986) and Young and Yeadon (1997) reported an absence of significant correlations in their competition data. Similar negative findings in studies of other athletics events have been attributed to the small range of run-up velocity that is used by an athlete during a competition or to the low number of trials available to analyze from a competition (Greig and Yeadon, 2000). One of the strengths of the present study is that the run-up velocity of the athlete was deliberately manipulated over a wide range and so the form of the relationships between the variables could be clearly identified.

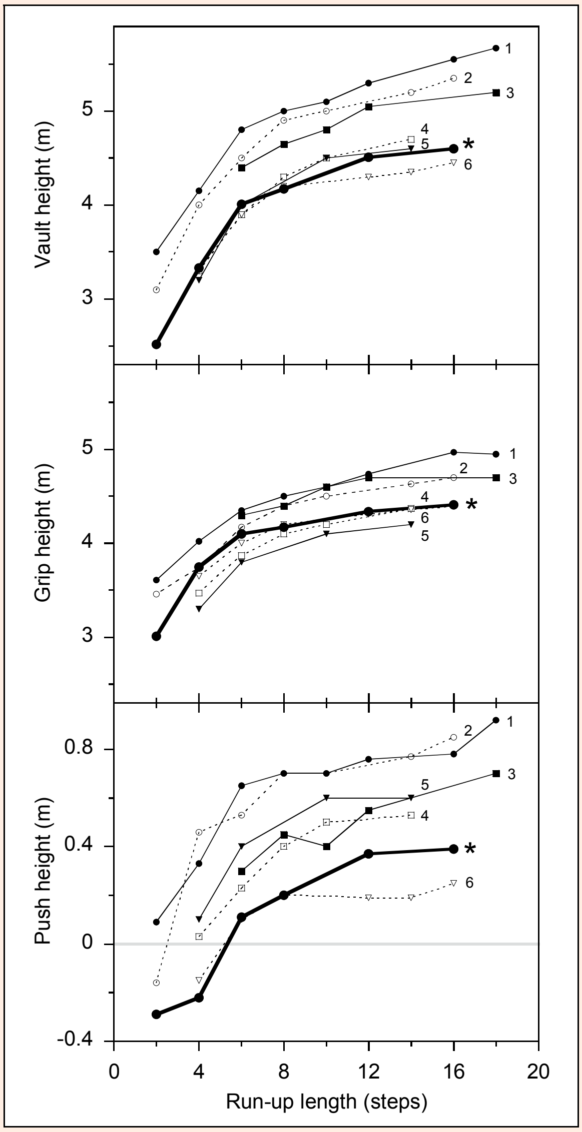

Figure 6. **Data for vault height, grip height, and push height for six male pole vaulters of varied ability (thin lines; labels 1–6). Data for the athlete in the present study is shown for comparison (thick line; label *). The similarity with the six other athletes indicates that the results from the present study are likely to be representative of male pole vaulters.**

Kinematic variables

The effects of run-up velocity on the athlete's take-off technique were similar to those observed in a study of the long jump (Bridgett and Linthorne, 2006). During the pole vault take-off the athlete needs to generate vertical velocity by jumping upwards so as to help smooth the transition from the horizontal motion in the run-up to the vertical motion necessary to pass over the crossbar. However, this take-off jumping action should also minimize any loss of horizontal velocity so as to maximize the athlete's take-off energy (Linthorne, 2000). During the take-off the athlete plants his take-off foot ahead of his centre of mass so as to produce a sufficiently long ground contact time in which to generate vertical velocity (Bridgett and Linthorne, 2006). The jumper's body pivots up and over the take-off foot, during which time the take-off leg rapidly flexes and extends. The leg angle at touchdown used by the athlete in this study was about 10° greater than that used by the elite male athlete in the long jump study by Bridgett and Linthorne (2006). This finding is consistent with the generally accepted view that the pole vault take-off uses a sub-maximal upwards jump that is less vigorous than the long jump take-off and is similar to the take-off in the hop phase of the triple jump (McGinnis, 1997; Plessa et al., 2010; Tidow, 1989). The steeper leg angle at touchdown that is used in the pole vault should result in a lower vertical take-off velocity and a lower loss of horizontal velocity during the take-off.

For the athlete in this study the pole angle during the take-off decreased with increasing run-up velocity as a direct result of the increase in the athlete's grip height. At any given run-up velocity the athlete maximized the height of his upper handgrip above the ground at the instant of pole grounding and this is believed to have helped minimize the energy that was lost during the pole plant and take-off. The interplay between the increase in the pole angle and the resulting decrease in the energy lost during the take-off is believed to be crucial in determining the athlete's grip height at any given run-up velocity (Johnson et al., 1975; Linthorne, 1994; 2000). When using a faster run-up velocity the grip height is greater and so the pole angle is lower, and this should lead to an increase in the energy that is lost during the take-off (Figure 5a).

Energy exchanges

For the athlete in this study the pattern of the time traces of the athlete's kinetic energy, gravitational potential energy, and total mechanical energy were similar to those seen for other skilled pole vaulters when using a flexible pole (Dillman and Nelson, 1968; Gros and Kunkel, 1990; Schade et al., 2004; 2005). As run-up velocity increased the athlete in this study maintained a constant centre of mass height (i.e., gravitational potential energy) at touchdown and so his (normalized) total mechanical energy at touchdown increased according to $E_1 = v^2/(2g) + h_{td}$, where v and h_{td} are the horizontal velocity and height of the athlete's centre of mass at touchdown and g is the acceleration due to gravity (Armbrust, 1993). That is, the athlete's energy at touchdown increased in proportion to the square of run-up velocity (Figure 4; Table 1). The athlete's energy at take-off and at the peak of the vault both increased linearly with run-up velocity (Figure 4), but the reason for this relationship is unclear. Likewise, it is also unclear why the athlete's energy at maximum pole bend remained almost constant across all run-up velocities (Figure 4).

For the athlete in this study the energy lost during the take-off increased as the athlete's run-up velocity increased (Figure 5a). The energy lost during the take-off is believed to be due to inelastic stretching of the athlete's body from the jarring action when the pole is planted into the box and due to the horizontal braking force generated when the athlete jumps upwards at take-off (Bridgett and Linthorne, 2006; Linthorne, 2000). Both of these mechanisms are expected to produce a greater loss of energy as the athlete's run-up velocity increases. Firstly, the jumping action in the pole vault take-off is likely to be similar to the long jump in that a faster run-up produces a greater loss of energy in the take-off because of the increase in horizontal braking impulse (Linthorne et al., 2011). Secondly, a faster run-up velocity allows the athlete to use a higher grip height and so the pole angle is reduced. A lower pole angle is expected to increase the energy that is lost due to the jarring action when the pole is planted into the box (Johnson et al., 1975; Linthorne, 1994; 2000).

Previous studies of performances by skilled pole vaulters have shown that the total change in the athlete's energy during the vault (ΔE_{total}) is almost always positive (Angulo-Kinzler et al., 1994; Arampatzis et al., 1999; Dillman and Nelson, 1968; Gros and Kunkel, 1990; Schade et al., 2004; 2005). That is, the energy added through muscular work performed during the pole support phase is usually greater than the loss of energy during the take-off phase (and other losses such as frictional heating in the bending pole and aerodynamic drag on the athlete during the pole support phase). An interesting finding from the present study is that the total energy gain during the vault decreased slightly with increasing run-up velocity (Figure 5a). This decrease was primarily the result of the sharp increase in the energy that was lost during the take-off at the higher run-up velocities.

The magnitude of the energy lost by the athlete during the pole bending phase ($\Delta E_{pole\text{-}bend}$) increased with increasing run-up velocity (Figure 5b), presumably because the athlete produced a greater deformation in a stiffer pole and so more energy was transferred to strain energy in the pole (Arampatzis et al., 2004; Dillman and Nelson, 1968). The energy change of the athlete during the pole recoil phase ($\Delta E_{pole\text{-}recoil}$) was greater than the energy loss during the pole bending phase (Figure 5b), but this was mainly because the pole recoil energy was augmented by the work done by the athlete. A more complete study of energy exchanges in the pole vault would include a calculation of the energy stored in the bending pole. However, in the present study we were not able to calculate the energy stored in the pole because we did not measure the ground reaction forces of the athlete and pole with force platforms (Arampatzis et al., 2004).

Curve fits

In this study we calculated the rate of change in the athlete's performance variables, kinematic variables, energy variables, and pole variables when the athlete was using his competition run-up velocity (8.4 m/s). Such knowledge might aid the coach in deciding upon the most fruitful areas to address when attempting to improve the athlete's competition performance. Such knowledge would also indicate the changes in kinematics and pole characteristics that are necessary in order to effectively use a faster run-up velocity. For the athlete studied here the rate of increase in take-off velocity at the athlete's competition run-up velocity was 0.40 m/s per 1 m/s increase in run-up velocity (Figure 3). That is, at the athlete's competition run-up velocity only about 40% of an increase in run-up velocity was transferred to an increase in take-off velocity. For the athlete studied here the rate of increase in vault height was 0.54 m per 1 m/s increase in run-up velocity, whereas the rate was 0.16 m for grip height and 0.35 m for push height. These values indicate that at the athlete's competition run-up velocity about one third of the rate of increase in vault height arose from the increase in grip height and about two thirds arose from the increase in push height.

Comparison to data from other athletes

A comparison of the vault height, grip height, and push height for the athlete in the present study with training data for six other male pole vaulters showed that the athletes had relationships of similar shape but with different vertical offsets (Figure 6). At any given run-up length a superior vault height by an athlete tended to be achieved through both a greater grip height and a greater push height. The similarities in the shape of the relationships shown in Figure 6 indicates that the relationships observed in the present study are not individual idiosyncracities and are likely to be similar to those for most other male pole vaulters (Bates, 1996). The relationships observed in the present study could also be similar to those for skilled female pole vaulters because the performances and techniques of skilled female vaulters are similar to those of skilled male vaulters of shorter stature and lesser muscular strength (McGinnis, 2004; Schade et al., 2004).

Conclusion

This study confirmed that run-up velocity has a very strong influence on performance in the pole vault and that the optimum technique is to run-up as fast as possible. The peak height of an experienced male pole vaulter increased at a rate of about 0.54 m per 1 m/s increase in run-up velocity, and this increase was achieved through a combination of a greater grip height and a greater push height. The athlete always performed the basic pole vaulting actions, but he made minor systematic changes to his jumping kinematics, vaulting kinematic, and selection of pole characteristics as the run-up velocity increased. Although a faster run-up velocity resulted in a greater loss of energy during the take-off the athlete always had a net gain of energy during the vault because of the muscular work performed during the pole support phase. However, the magnitude of the energy gain during the vault decreased slightly with increasing run-up velocity. Training data from other male pole vaulters suggests that the results from the athlete in the present study are representative of skilled vaulters.

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Key points

- In the pole vault the optimum technique is to run-up as fast as possible.
- The athlete's vault height increases at a rate of about 0.5 m per 1 m/s increase in run-up velocity.
- The increase in vault height is achieved through a greater grip height and a greater push height. At the athlete's competition run-up velocity about one third of the rate of increase in vault height arises from an increase in grip height and two thirds arises from an increase in push height.
- The athlete has a net energy gain during the vault. A faster run-up velocity produces a greater loss of energy during the take-off but this loss of energy is not sufficient to negate the increase in run-up velocity and the increase in the work done by the athlete during the pole support phase.

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