

ENERGETICS OF THE POLE VAULT

Work and energy considerations in the pole vault

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Pole vaulting is the most exciting track and field event and many coaches consider it to be the most difficult event to understand as well. The complexity of the pole vault can be simplified by application of basic work and energy principles. This paper uses work and energy principles to build a foundation for the actions used in an effective pole vault.

THE WORK - ENERGY EQUATION

Work and energy principles can be used to explain much of the mechanics of pole vaulting. Mechanical work is most simply defined as force times displacement:

$$\text{Work} = U = F \cdot d$$

where, U = work done

F = average force

d = displacement

If force and displacement are in the same direction, positive work is done by the force. If force and displacement are in opposite directions, negative work is done by the force.

Energy is the capacity to do work. In pole vaulting, three forms of mechanical energy are apparent: kinetic energy, potential energy, and strain energy. Kinetic energy, KE, is the energy an object has due to its motion. Kinetic energy is defined as :

$$KE = \frac{mv^2}{2}$$

where, m = mass

v = velocity

Potential energy is the energy an object has due to its position. Potential energy is defined as:

$$PE = Wh = mgh$$

where, W = weight

h = height

g = 9.81 m/s² = acceleration due to gravity

Strain energy is the energy an object has due to its deformation. Strain energy is defined as:

$$SE = \frac{kx^2}{2}$$

where, k = stiffness

x = deflection or change in length

By definition, work and energy are related. In fact, the work done on an object by non-conservative forces (forces other than gravity) equals the change in energy of the object.

$$\text{Work} = U = \Delta E = E_f - E_i = (KE + PE + SE)_f - (KE + PE + SE)_i = KE_f + PE_f + SE_f - KE_i - PE_i - SE_i$$

This equation forms the basis for our analysis of the pole vault. If we define the initial and final instances during which work is done as the instant of takeoff (the instant when the vaulter's takeoff foot no longer is in contact with the runway) and the instant when the vaulter's center of mass reaches maximum height, then final potential energy becomes the criterion of success in the pole vault, since the maximum height reached by the vaulter's center of mass is directly proportional to

the potential energy of the vaulter at this instant. The work-energy equation can be rewritten as follows to express this final potential energy (PE_f) in terms of work done, initial energies, energy lost, and excess kinetic energy:

$$PE_f = KE_i + PE_i + SE_i + U - E_{lost} - KE_f$$

where KE_i is the vaulter's kinetic energy at takeoff; PE_i is the vaulter's potential energy at takeoff; SE_i is the strain energy in the pole at takeoff; U is the work done by the vaulter from takeoff to release; E_{lost} is the energy lost by friction, inelastic stretching, etc. between takeoff and release; and KE_f is the excess kinetic energy possessed by the vaulter at the instant of maximum height in the form of rotation or horizontal velocity which do not contribute to PE_f .

So, to vault high, a vaulter should maximize the positive elements and minimize the negative elements of the above equation. In other words, a vaulter should maximize energy at takeoff ($KE_i + PE_i + SE_i$), maximize work done from takeoff to release (U), minimize energy lost (E_{lost}), and minimize excess kinetic energy at maximum height (KE_f). Kinetic energy at takeoff, potential energy at takeoff, and work done are the three components which most significantly affect vault height. Figure 1 shows the relative contributions of these three components to a 6 m vault.

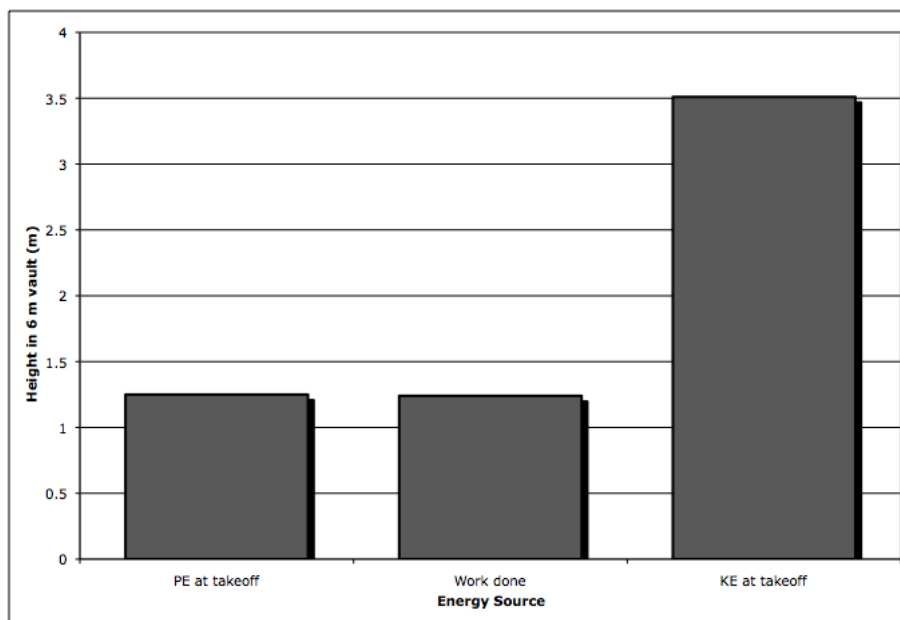


Figure 1. Work and energy component contributions to height in a 6.00 m vault.

What follows are descriptions of what the vaulter should do to maximize these three components and minimize excess kinetic energy and energy lost.

MAXIMIZE KINETIC ENERGY AT TAKEOFF (KE_i)

Kinetic energy at takeoff accounts for about 60% of vault height by an elite vaulter and even more for less skilled vaulters. KE_i is largely determined by the approach run.

FAST RUN.

There is a significant correlation between speed over the last 5 meters of the approach run and crossbar height cleared. This is the most important determinant of success in pole vaulting. Excellent sprinting ability is necessary for success in the pole vault. During the last steps of their approach runs elite male vaulters reach speeds in excess of 9.5 m/s (29.5 ft/s) while elite female vaulters reach speeds in excess of 8.2 m/s (26.9 ft/s). Not all fast vaulters are elite vaulters, but all elite vaulters are fast.

VERTICAL POLE CARRY AND POLE DROP.

Elite vaulters employ a pole drop technique during the run up. This reduces the forces imposed on them by the pole when compared to a more horizontal pole carry. This reduction in load on the arms and shoulders may lead to a faster approach run and takeoff. A possible alternative technique is to push or slide the pole down the runway.

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MID-MARK (COACH'S CHECKMARK).

A coach's checkmark should be used to mark the optimal position of the start of the fourth to last step. Most vaulters have a coach's checkmark at the beginning of their sixth to last step, but research indicates that this checkmark would be more effective at the start of the fourth to last step. The approach run up until the fourth to last step is programmed, i.e., the vaulter tries to make this part of the approach run the same from vault to vault. But, errors occur, and because of these errors, the vaulter must adjust his steps or "steer" at the end of the approach run in order to hit the correct takeoff mark. The adjustments in the step lengths ("steering") don't occur until the last four steps. A checkmark at the start of the fourth to last step would indicate how accurate the programmed part of the vaulter's approach run was. Adjustments in the vaulter's start mark should be based on how far the vaulter is off the coach's checkmark.

ACCELERATE DURING THE LAST THREE STEPS.

Elite vaulters maintain their speed or accelerate into the last steps of the approach run. They also increase their speed from the second to last step to their last step before takeoff. Most developing vaulters slow down during the last three steps. This is easy to do, since this is when the vaulter initiates the pole plant and adjustments in step lengths occur to ensure proper position for takeoff. Many hours of practice are required before a vaulter is able to accelerate during the last steps of the approach run.

A LONGER SECOND TO LAST STEP AND A SHORTER QUICKER LAST STEP.

Most vaulters take a longer penultimate step and a shorter, quicker last step. This sets the vaulter up for a jumping takeoff. The ratio between the last step length and the second to last step length is between 0.90 and 0.95 for most elite vaulters. Step rate is increased during the last step so that speed does not slow as a result of the shorter step. Elite vaulters overcompensate for the shorter step length by increasing step rate such that speed actually increases during the last step.

JUMPING TAKEOFF.

A fast takeoff velocity is necessary for vaulting high. Elite male vaulters have resultant takeoff velocities faster than 8.0 m/s (26.2 ft/s) while elite female vaulters have resultant takeoff velocities faster than 7.0 m/s (23.0 ft/s). The resultant takeoff velocity is composed of a horizontal (forward) velocity and an upward (vertical) velocity. A fast horizontal takeoff velocity is produced by a fast approach run. A fast vertical velocity is produced by an upward jump at takeoff. Elite male vaulters have horizontal takeoff velocities faster than 7.7 m/s (24.9 ft/s) and vertical takeoff velocities faster than 2.2 m/s (6.6 ft/s). Elite vaulters have takeoff angles between 17 and 19 degrees for men and between 18 and 20 degrees for women. Takeoff angles which are too low may lead to pole breakage.

MAXIMIZE POTENTIAL ENERGY AT TAKEOFF (PE_i)

Potential energy at takeoff accounts for about a meter or more of vault height by an elite vaulter. PE_i is largely determined by the vaulter's height and mass distribution, but position during takeoff can greatly affect PE_i as well.

TALL.

Elite vaulters are generally tall. A taller vaulter can produce greater relative PE at takeoff. Taller athletes have an advantage in the pole vault, especially at the pole strike. A taller athlete usually has a higher reach, and an athlete with a higher reach can strike the pole at a higher angle than a shorter athlete with a lower reach. Perhaps this tip should be entitled "Have a high reach height." Most elite male pole vaulters stand more than 6'0" tall. American record holder Jeff Hartwig is 6'3". Olympic champion Tim Mack is 6'2". American record holder Jenn Stuczynski is 6'0". World record holder Yelena Isinbayeva is 5'8½". There are exceptions, of course - Scott Huffman, Greg Duplantis, Svetlana Feofanova for example. Elite vaulters are lean. There are no exceptions to this rule.

UPRIGHT POSTURE.

Elite vaulters stay more upright at the instants of last touchdown, pole strike, and takeoff. An upright vaulter will have a higher center of mass and thus greater PE. Less skilled vaulters tend to lean backward during this phase. This may have an effect on takeoff velocity. It also affects the maximum angle between the pole and the runway.

MAXIMUM ANGLE BETWEEN THE POLE AND THE RUNWAY AT POLE STRIKE.

This reduces the angle the pole must rotate through to get to a vertical position. It also allows for a more efficient transfer of energy to the pole. As grip height increases, this angle decreases, so elite vaulters have smaller pole angles than less skilled vaulter. This angle is also affected by the vaulter's height and reach. A taller vaulter with a higher reach will be able to achieve a higher pole angle. At pole strike, the pole angle for elite vaulters is slightly less than 30°. It increases slightly between the instants of pole strike and takeoff.

HIGH PLANT.

Both hands should be as high overhead as possible. This arms should be extended vertically as much as possible. This position of the arms will increase the height of the center of mass and thus increase relative PE. This position will help achieve a high pole angle at pole strike. Interestingly, the relative vertical extension of the plant arm for some elite

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vaulters is less than that of less skilled vaulters. Perhaps the pretension in the muscles in their shoulders and arms causes these elite vaulters to reduce the relative vertical extension of their plant arm.

TOES OF TAKEOFF FOOT DIRECTLY BENEATH TOP HANDGRIP.

At the instant of pole strike (the instant when the pole butt plug first strikes the back of the box) the top hand should be directly above the toes of the takeoff foot. This position puts the vaulter in the best position for transferring energy to the pole. This also means that at the instant of takeoff the top hand will be in front of the takeoff foot, since the top hand moves forward as the pole begins to bend. Most vaulters plant the pole with their takeoff foot in front of their top hand. Elite vaulters position their takeoff foot more directly below their top hand.

POLE STRIKE OCCURS WHEN THE VAULTER IS UP ON HIS TOES.

Don't plant the pole while you are still on the heel of your takeoff foot. The timing of the pole strike (the instant when the pole first strikes the back of the box) is crucial. The sequence of events occurs like this: the takeoff foot hits the ground (touchdown), the pole hits the back of the box (pole strike), and the takeoff foot leaves the ground (takeoff). These events occur in 0.08-0.12 s (the total time of takeoff foot support) for elite vaulters. For elite vaulters, pole strike occurs in the second half of the support phase, closer to the instant of takeoff. This indicates that they are actively pushing off the ground. They are "on their toes" when pole strike occurs and they actively push the pole upward and forward. If pole strike occurs during the first half of the support phase, closer to the instant of touchdown, then the vaulter will be not be able to actively push the pole upward and forward. The vaulter will be jerked off the ground by the pole. The timing of the pole strike is related to takeoff foot position and the extension of the plant arm.

MAXIMIZE WORK DONE ($U = F \cdot d$)

Work done by the vaulter from takeoff to maximum height is the component of vault height that is determined by the vaulter's actions on the pole. How to maximize this component of the pole vault work-energy equation is the most interesting question. Work done is average force times displacement. There are two constraints on the work done in pole vaulting. The first is the time the vaulter has to do the work (only about 1.3-1.5 seconds). Since time is limited, vaulters should avoid any passive phases and should attempt to add energy by doing work throughout the vault. The second constraint is the displacement the vaulter's center of mass can move through while still in contact with the pole. A crude estimate of this displacement is the sum of the distance between the center of mass of the vaulter and the top handgrip at the instant of takeoff and at the instant of pole release as shown in Figure 2. For most elite vaulters, this distance will be similar (although taller vaulters will have an advantage here). So, the variable which is not constrained is average force, F . How can a vaulter make the average force acting through the handgrips on the pole larger? The vaulter can do this by swing fast and by keeping the body in a position that requires more force to swing it to vertical. The more elongated the body is, the more difficult, i.e., the more force required, to swing it to vertical.



Figure 2. Estimate of displacement component of work.

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SWEEP AND WHIP AN EXTENDED TRAIL LEG.

The centripetal force generated by the sweeping, whipping action of a long and extended trail leg loads the pole and maintains the vaulter's swinging momentum. This force is the force in the work equation. The more extended the leg (or legs) and the faster their swing, the larger the force and thus the more work done. This force accelerates the center of mass towards the top end of the pole.

HANG AND SWING FROM TOP HANDGRIP.

The force exerted by the hands downward toward the butt end of the pole is a compressive force or column load which is primarily responsible for bending the pole. The larger this force is and the further this force is away from the butt end of the pole, the easier it is to bend the pole. Therefore, the vaulter should attempt to swing from his top hand to ensure that this force is exerted on the pole as high as possible. The vaulter should neither pull with this arm nor flex at the elbow, rather the vaulter should think of this arm as a cable and let the pulling force of the pole pull through this cable. Keeping the body swinging in an elongated position will also increase the force which bends the pole. A pulling force will be exerted by the bottom hand after its initial push to start the pole bending. This pulling force assists the vaulter in rotating his body upside down. Vaulters who used a large pushing force with the bottom hand to bend the pole will have to pull with a much larger force in the bottom hand in order to get upside down.

AVOID PASSIVE PERIODS.

The vaulter has less than 1.5 seconds to do work and add energy to the vault. Don't waste it by doing nothing.

ALIGN CENTER OF GRAVITY WITH OR BEHIND THE POLE.

Allowing the center of gravity to pass in front of the pole while the vaulter extends upward produces a moment or torque about the handgrips which causes the vaulter's backward rotation to stop. The legs and trunk then begin to drop and rotate towards the bar. To avoid this, the vaulter should try to stay as close to the pole or behind it as he inverts, extends and turns.

MINIMIZE ENERGY LOST

Energy losses in the pole vault occur due to inelastic stretching of tendons and ligaments, friction between the fibers of the pole, energy not recovered from the pole, etc.

KEEP BODY RIGID AT THE INSTANT OF POLE STRIKE.

The pole strike marks the beginning of the energy transfer from the vaulter to the pole. If the body is "loose", energy which could have been transferred to the pole may be lost through inelastic stretching of the muscles and tendons. Pre-tension in the muscles of the trunk, shoulder girdle, and arms will minimize this energy loss. Some movement will occur at the shoulder joint, but this may be beneficial if it results in a greater contraction of the shoulder extensors due to the stretch reflex response of these muscles.

KEEP TRUNK AND CORE RIGID AT THE INSTANT OF TAKEOFF.

The pole strike marks the beginning of the energy transfer from the vaulter to the pole. If the body is "loose", energy which could have been transferred to the pole may be lost through inelastic stretching of the muscles and tendons. Pre-tension in the muscles of the trunk, shoulder girdle, and arms will minimize this energy loss. Some movement will occur at the shoulder joint, but this may be beneficial if it results in a greater contraction of the shoulder extensors due to the stretch reflex response of these muscles.

INITIATE POLE BEND WITH LOWER HAND.

This lower hand action begins at the pole strike and continues only briefly into the swing, no longer than 0.20 second after takeoff. The force exerted against the pole by the lower hand greatly reduces the column force necessary to bend the pole. Although the pushing action of the lower hand is instrumental in initiating the pole bend, it also slows down the rotation of the vaulter. So, the pushing action only occurs for a brief period of time. Shorter vaulters may have to push more than taller vaulters.

MATCH POLE LENGTH, SIZE, AND PERFORMANCE TO THE ABILITY OF THE VAULTER.

Elite vaulters are able to hold high on long stiff poles because of their superior technique and physical abilities. They match pole size and grip height to their ability so that they can set their standards 60 cm (24 in) or further from the back of the box. Non-elite vaulters should do the same. An incorrect match of pole and vaulter will lead to inefficient transfers of energy to the pole from the vaulter and vice versa.

TIME SWING TO INVERSION TO COINCIDE WITH THE EXTENSION OF THE POLE.

The pole vault is a double pendulum action. To take full advantage of the energy transfers from vaulter to pole and back to vaulter, the periods of the pendulums should match up. The vaulter should strive to "beat the pole" - get into position on top of the pole to take advantage of the energy return from the pole. Pole selection and grip height affect the ability of the vaulter to "beat the pole".