The Pole Vault for Engineers

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Acknowledgements

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www.polevault.com
POLE VAULT 4.90
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Crystal Palace 30 07 2004

POLE VAULT 6.14
Sergey Bubka UKR
Sestriere 31 07 1994
History
History of Pole Vaulting

• Pole-vaulting known to the ancient Greeks?

• The Celts used to pole vault - but for length

• The Dutch used poles to vault over dykes – also for length not height

• Vertical jump – Germany late 18th Century

• 1850’s onwards – competitions in USA and Europe

www.polevault.com
• Rigid poles – ash or hickory - hands moved to ‘climb’ the pole

• 1889 – USA bans movement of hands. New technique – legs reversed ‘rockback’ – feet first, stomach to bar

• 1900 – 1942 lightweight bamboo poles

• Receiving 'box' for the pole introduced early 1900’s
• 1957 Bob Gutowski (USA) - aluminium pole – world record 4.78m

• 1957 Don Bragg (USA) - steel pole - 4.80m

• 1956 – flexible fibre-glass pole

• 1961 - first world record with fibre-glass pole
Pole vaulting – Olympic record heights

<table>
<thead>
<tr>
<th>Year</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900</td>
<td>Solid wood</td>
</tr>
<tr>
<td>1910</td>
<td>Bamboo</td>
</tr>
<tr>
<td>1960</td>
<td>Glass fibre</td>
</tr>
<tr>
<td>1990</td>
<td>Carbon fibre</td>
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</table>
The Rules
Crossbar support

“The crossbar shall rest on pegs so that if it is touched by a competitor or his pole, it will fall easily to the ground.

.....the pegs.....shall not extend more than 55 mm from the supporting members......[from 2003 - previously 75 mm]

..the pegs may not be covered with rubber or with any other material which has the effect of increasing the friction between them and the surface of the bar, nor may they have any kind of springs.”

IAAF Regulations
Vaulting poles

“The pole may be of any material or combination of materials and of any length or diameter, but the basic surface must be smooth.

The pole may have a binding of not more than two layers of adhesive tape of uniform thickness and with a smooth surface.....”

“If in making an attempt, a competitor’s pole is broken, it shall not be counted as a failure and the vaulter shall be awarded a new trial.”

IAAF Regulations
The landing area

“The landing area should measure not less than 5 m ...x 5 m.....

....for competitions....it is recommended that the landing area shall be not smaller than 7 m x 6 m x 0.8 m high....”

IAAF Regulations
Stages of the vault
Run up

Plant

Swing

Rockback

Top
Some sprint speeds

**Donovan Bailey**
27.1 mph (instantaneous speed during 100-meter dash, 1996 Olympics)

**Donovan Bailey**
22.7 mph (Average speed during 100-m dash, 1996 Olympics)

**Sergey Bubka**
22.2 mph (Average sprint speed during pole-vaulting approach)

**Stacy Dragila**
18.7 mph (Average sprint speed during pole-vaulting approach)

**5-minute-mile runner**
12 mph (Average speed)

**10-minute-mile runner**
6 mph (Average speed)
Science of pole vaulting

Simplest approach to ‘how high’ is to carry out an energy balance -

\[
\text{Kinetic energy} = \text{potential energy}
\]

\[
(\text{from running}) \quad (\text{into height})
\]

\[
\frac{1}{2} m v^2 = m g x
\]

\[
x = \left(\frac{1}{2} v^2\right) / g
\]

Hence need to know how fast a pole vaulter runs. Assuming you can cover 100m in 10 seconds gives \(v = 10\) m/s.

This predicts a height \textit{increase} of 5.1 m – but your centre of mass is already about 1 m above the ground so the total height predicted is about 6.1 m (and the current men’s world record is 6.14 m).
Science of pole vaulting

Maths does not allow the human factors:

Moveable centre of mass – athletes can ‘pull’ themselves up the pole and then ‘push’ off the top.

Gradual change from horizontal to vertical motion – effect of the take off angle (e.g. height of athlete) and the fact that athletes can ‘jump’ into the vault.
Fig. 2. 3d calculated total energy and total kinetic energy of an athlete during the pole vault.

Schade et al J Biomech, 33, 1263 (2000)
Run up

**Plant**

Swing

Rockback

Top
Run up
Plant

Swing
Rockback
Top
Simulation of ‘smart’ pole vaulting

Fig. 3. Geometry of vaulter and definition of body segment angles $\theta_j$. 1 = handgrip joint, 2 = elbow joint, 3 = shoulder joint, 4 = hip joint and 5 = knee joint; a = forearm, b = upper arm, c = head, d = trunk, e = thigh and f = shank.
Fig. 6. (a) Pole and vaulter in initial configuration when the last foot of the vaulter leaves the ground. The leg shown is in an intermediate position between the two real legs. CG denotes the centre of gravity of the vaulter and R is the initial constant radius of curvature of the pole. (b) Pole and vaulter at time $t$. 

Ekevad and Lundberg  
*J Biomech, 28, 1079 (1995)*
Fig. 9. Pole-to-ground angle $\phi$ in the reference pole vault by Slusarski.

Run up

Plant

Swing

Rockback

Top
A long pole has low stiffness

- stiffness too low – not enough support
- stiffness too high - may cause ‘bounce back’

A short pole may have sufficient stiffness for support

- but may not be able to achieve height

Performance index $\eta$ is ratio

$$\frac{\text{Increase in potential energy}}{\text{Initial kinetic energy of vaulter plus pole}}$$

Fig. 11. Simulation of pole vaults with different pole lengths: (a) pole length 4.50 m, \( \xi_u = 0.560 \); (b) pole length 4.75 m, \( \xi_u = 0.565 \); (c) pole length 5.00 m, \( \xi_u = 0.580 \).
Fig. 12. Vault height $h$ and performance figure $\eta$ versus pole length $L$. Open squares represent $L = 4.65$ m, $\xi_v = 0.550$ and $L = 4.85$ m, $\xi_v = 0.570$. Filled squares represent the simulations shown in Fig. 11.
Fig. 3. Performance figure $\eta$ versus dimensionless pole stiffness $\kappa_0$ and dimensionless pole length $\lambda$ for elastic pole. The curve on the surface shows where the angle-to-ground at the top position $\phi_W$ is 90°. The dashed curve represents the condition $H_0 = \kappa_{\text{cr}}$ for Euler buckling.

Run up

Plant

Swing

Rockback

Top
Short pole
Low stiffness

Short pole
High stiffness

Fig. 4. Deformed configuration of pole and position of vaulter at different times with time step between two consecutive configurations $\Delta \tau = 0.10$: (a) Short pole with low stiffness, $\lambda = 0.80$ and $\kappa_0 = 3.0$; (b) short pole with high stiffness, $\lambda = 0.80$ and $\kappa_0 = 5.0$. 
Fig. 5. Deformed configuration of pole and position of vaulter at different times. (a) Long pole with low stiffness, $\lambda = 1.21$ and $\kappa_0 = 30$. Time step between two consecutive configurations $\Delta \tau = 0.10$. (b) Long pole with optimal stiffness, $\lambda = 1.21$ and $\kappa_0 = 3.34$. Time step between two consecutive configurations $\Delta \tau = 0.20$. (c) Long pole with high stiffness, $\lambda = 1.21$ and $\kappa_0 = 5.0$. Time between two consecutive config.
Fig. 6. Deformed configuration of pole and position of vaulter at different times with time step between two consecutive configurations $\Delta t = 0.20$. Pole with optimal combination of length and stiffness, $\lambda = 1.1$ and $\kappa_0 = 3.7$. Optimal length and stiffness
Figure 2 Model of the vaulter and pole when vaulting with a rigid pole. The thin solid line shows the trajectory of the vaulter. The vaulter and pole are shown at the instant of take-off, and at the peak of the vault.

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

Figure 3  Take-off velocity as a function of the take-off angle for a world-class pole vaulter. Reprinted by permission from Linthorne (1994).
Figure 5 Peak height of the vault as a function of the take-off angle for the rigid-pole model and for the flexible-pole model. The numbers next to the curve for the flexible-pole model show the change in the optimum pole stiffness ratings (in kg).
Figure 6 Grip height as a function of the take-off angle for the rigid-pole model and for the flexible-pole model. The numbers next to the curve for the flexible-pole model show the change in the optimum pole stiffness ratings (in kg).

Figure 7 Push height as a function of the take-off angle for the flexible-pole model.
Table 2  Comparison of optimum vault parameters for different values of the vaulter’s body stiffness

<table>
<thead>
<tr>
<th>Vaulter’s body stiffness, $k$ (N m$^{-1}$)</th>
<th>Vault height (m)</th>
<th>Take-off angle (degrees)</th>
<th>Grip height (m)</th>
<th>Push height (m)</th>
<th>Pole stiffness rating (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>5.40</td>
<td>24</td>
<td>4.75</td>
<td>0.85</td>
<td>72</td>
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<tr>
<td>250</td>
<td>6.00</td>
<td>18</td>
<td>5.10</td>
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<td>80</td>
</tr>
<tr>
<td>500</td>
<td>6.45</td>
<td>13</td>
<td>5.10</td>
<td>1.55</td>
<td>93</td>
</tr>
</tbody>
</table>

The Pole
Early styles of pole vaulting didn’t allow for bending of the pole.....
Effect of change in 1960 from bamboo to glass fibre composite - the lighter pole enabled a faster run up and take off speed - more kinetic energy.

Glass fibre poles had a much higher failure stress than bamboo, so poles were engineered to bend under the load of the athlete - storing elastic strain energy. The bending allowed athletes to change vaulting technique - to go over the bar with their feet upwards.
Control of vaulting pole properties

Are all poles the same?

Need to optimise for the individual athlete and ensure that they do not fail.
Making vaulting poles

Composite tubing is produced by filament winding. This is the automated process of wrapping resin impregnated filaments (rovings or tows) in a geometric pattern over a rotating male mandrel. The component is then cured under high pressure and temperature.
Modern vaulting poles

The addition of carbon fibre maintains the mechanical properties of the pole, but reduces the weight.

The number and arrangement of the fibres determines the mechanical properties. In particular need to control stiffness.
Pole Manufacturing

The Mandrel – varies in length and diameter like the poles. Fibreglass is wound on to the mandrel. The bigger mandrel diameter the lower the wall thickness to get a given stiffness. As the poles get longer and stiffer (lower flex number or higher weight rating) the larger the mandrel. Most elite vaulters will specify a certain length, flex rating and possibly mandrel size.

Spiral Wraps – narrow spiral-wound strips of fibreglass are applied to the mandrel. The number, type of glass and how they are wrapped all impact pole properties.
Pole Manufacturing

**Full Body Wraps** – typically a rectangular piece that is the full length of the pole and is designed to achieve a certain number of complete wraps around the pole’s circumference when rolled on (with heated rollers). The number of wraps varies with manufacturer.

**The Sail Piece** – a section of fibreglass of varying length – may be up to the full length and shaped like a sail or trapezoid. The location, size and shape of these sail pieces have a major impact on how and where the pole bends when used. This varies between pole models and manufacturers.
Pole Manufacturing

**Curing** – the pole is ‘cooked’ to get the resin to flow and cure. The temperature, steam and pressure all impact the quality of the final product.

**Pre-bend** – once cooled the pole gets a small pre-bend if required.

**Proof-test** – the pole is bent beyond normal vaulting conditions. Further testing performed if needed.

**Flex testing** – loaded centrally in bending and flex recorded.

**Tape** – coloured tape, decals, manufacturers weight-rating applied.
Vaulting Pole Stiffness and Flexibility

• Relative pole stiffness is weight for which the pole is rated

• Flex number …is the deflection of the pole in inches or centimeters when a standard weight, usually 50 pounds, is suspended in the middle of a horizontal pole

• The pole manufacturer determines the flex number for each pole at its factory and then labels the weight rating of the pole according to the range of flex numbers that fall within that weight limit for a given length of pole.

• For a given length and weight rating, the poles having slightly different flex numbers will…respond in a slightly different way.

• A 14' -160 # set of poles may actually correspond to weight ranges of approximately 14' -158 # to 14' -162#, depending on the exact flex number for each pole that makes up that range.

• There is currently no standard for weight rating and flex number and manufacturers differ in their methods.

Roger W. Werne, USA Track And Field Pole Vault Equipment Task Force
Personalised poles …

Need to know which pole to select for you …

Whether a pole breaks depends on the force the athlete puts onto the pole.

\[ F = m a \]

Hence the heavier the athlete, and the faster they run, increases the force on the pole.

Poles are rated by ‘weight’ which allows an athlete to select an appropriate pole. Top performers take poles of higher ‘weight’ as it allows for their better speed and technique.
"I usually take around ten poles to each competition, each of them different. It’s a bit like a golfer with his clubs. The poles are all of a different length and therefore stiffness. Which one I use depends on how much speed I am generating on the runway. I start out with softer, longer poles until I’m fully warmed up and then I’ll keep switching as my speed and confidence increases. The wind conditions will also dictate which pole I use."

Stacy Dragila

www.iaaf.org
What do they say?

“But one of the biggest lessons I learned ...is the importance of communication..........between the brain and body during competition. I try very hard to concentrate during competition- I ‘feel’ and think about every little art of every little phase; from the start of my run-up to the moment I land on the mat.

I have a picture of what I have done. I have to analyze everything, and then to make any adjustments I think are necessary.......When you compete you are on your own. You must learn to think and act fast. To adjust. When I compete my brain becomes a computer.”

Sergei Bubka

www.polevault.com
Materials Properties

Unidirectional composites (vol fraction 66%)
   CFRP Modulus E (approx) = 140 GPa
   GFRP Modulus E (approx) = 35 GPa

Strength of laminae (vol fraction 50%)
   Polyester/glass    700 MPa
   Epoxy/carbon      1000 MPa

Failure strains
   Carbon fibres 0.6 – 1.1 %
   E-glass fibres 2.6 %
Glass or Carbon Fibre Vaulting Poles?

- Most vaulters begin on glass-fibre poles and they are still the most common

- Glass-fibre are easier to begin on, and it becomes difficult to switch to carbon poles

- Carbon-fibre poles store more energy but recoil rapidly. Hard to swing hard and fast enough to get on top of the bend

- Many find that by the time they have rocked all the way back, carbon poles have already unloaded - and the vault is ruined

- A great, fast swing is required in order to use carbon poles effectively.

- BOTTOM LINE: Stay with fiberglass poles, unless your name is Jeff Hartwig or you have a really great swing!

(www.vaultworld.com)
Typical measured parameters for a glass-fibre pole

Pacer FX 14 ft
Outer diameter 32 – 33 mm
Inner diameter 28 mm
Wall thickness 2 mm
Pre-bend approx 22 mm

Modulus $E$ calculated from $EI$ for hollow tube
Approx 55 – 59 GPa
Control of properties

The stiffness of the pole is controlled by its shape (length $L$, outer diameter $d_o$ and inner diameter $d_i$) and the design of the composite.

We can measure the stiffness by looking at the amount of deflection, $D$, generated by applying a given load, $F$, at the mid-point:

\[
D = \frac{FL^3}{48EI}
\]

\[
I = \frac{\pi}{64}(d_o^4 - d_i^4)
\]

The Young’s Modulus, E, of the composite is controlled by the proportion of fibres $f_f$ and the way in which they are arranged in the matrix, i.e. the angles between the fibres and the axis of the pole $\theta$. 
Isinbayeva

Bubka
That’s all folks!