The Physics of the High Jump

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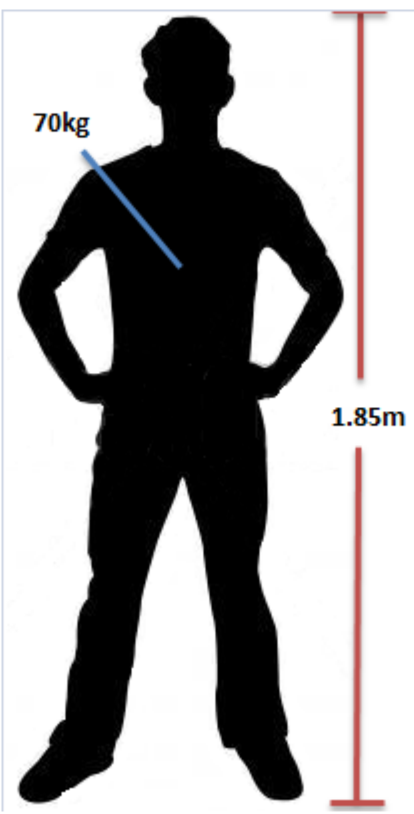
Introduction to the High Jump

The high jump is a track and field event that requires athletes to jump over a heightened horizontal bar by jumping off of only one foot. The high jump can be broken into its two main parts: the approach and the actual jump. The approach can also be broken down into three main parts: traveling along a straight path, the transition, and the curve. The event is highly technical and demands exceptional skill in order for the jump to be completed properly. An accepted, and most popular, method of clearing the high jump bar is known as the “Fosbury Flop” which has the jumper lead with their head and shoulders followed by an arching motion of their back in order to heighten the hips of the jumper over the bar. This paper will examine the physics of the high jump by looking at the jumper’s approach (jumper gradually accelerates towards the bar, changes direction, the different forces applied during each phase, etc) and then the jump itself (redirecting the momentum of the approach into a jump that carries the jumper up and over the bar, different forces applied during the jump, centripetal acceleration, etc).

Given and Gathered Information

In order to examine the physics of the high jump, data was gathered based on a successful jump attempt. The jumper’s results will be examined throughout the paper. The jumper stands at 1.85m tall and weighs 70kg. The jumper applied a force of 400N during the approach and cleared the bar set at a height of 2.00m. It took the jumper a total of 4.50seconds from the moment the jumper began his approach to the moment the jumper landed on the high jump mat after the successful attempt. The total distance the jumper traveled from the jumper’s starting point to the mat was 16.0m. Further analysis of the jump later determined that the coefficient kinetic friction (μ_k) was 0.20, the jumper reached a height of 2.05m at his apex, and had a radius of 0.49m at his apex.



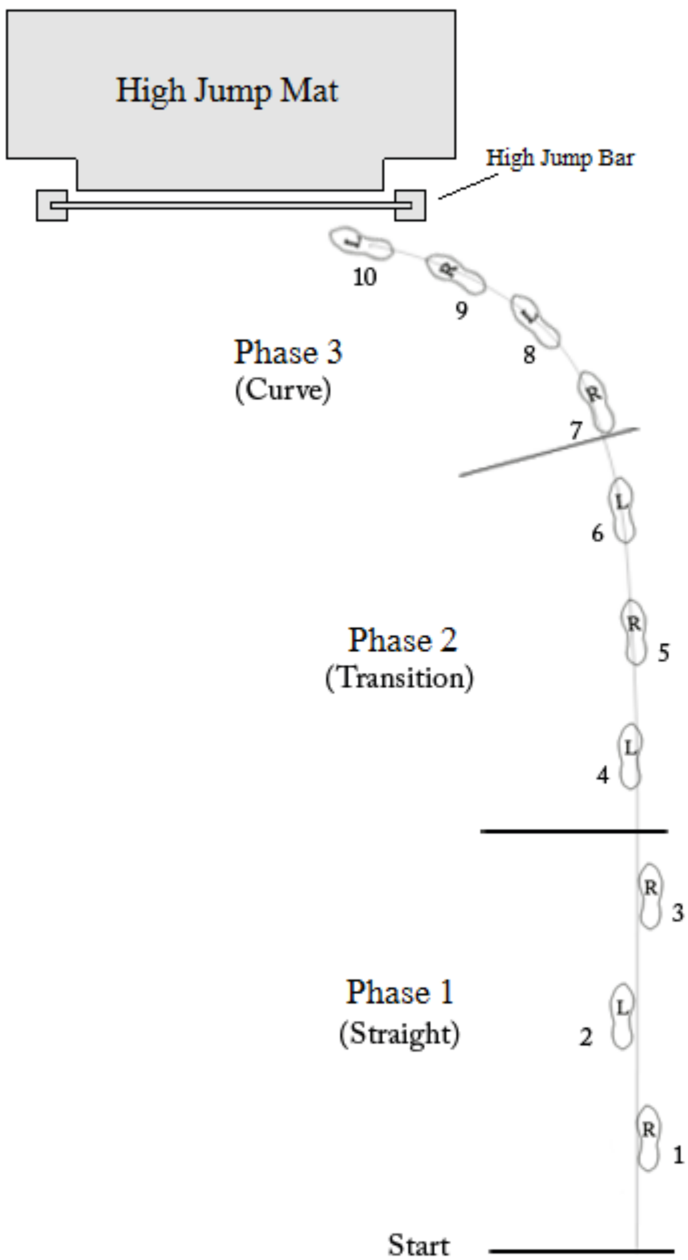
Time it takes to complete Phase 1	1.10s	
Time it takes to complete Phase 2	1.50s	
Time it takes to complete Phase 3	0.90s	
Total time it takes to approach the bar		**3.60s**
Time it takes to jump over the bar	0.90s	
Total time to complete the approach and jump		**4.50s**
Distance to cover (Phase 1)	5.0m	
Distance to cover (Phase 2)	6.0m	
Distance to cover (Phase 3)	4.0m	
Total distance from starting point to bar		**15.0m**
Distance to cover (jump)	1.0m	
Total distance from starting point to mat		**16.0m**
Force applied during approach	400N	
Coefficient of kinetic friction (μ_k)	0.20	
Height of the bar	2.00m	
Height of the jumper at apex	2.05m	
Radius of jumper at apex	0.49m	

Based on the given and gathered data, the velocity of each phase of the approach was determined as follows:

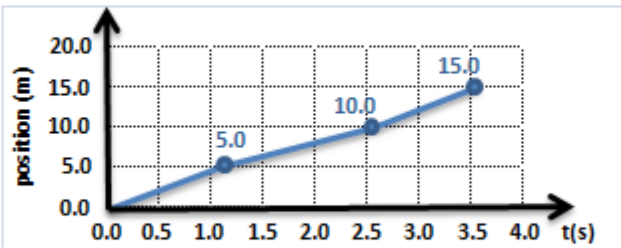
$$\text{Velocity}_{\text{Phase 1}}: 5.0\text{m} \div 1.10\text{s} = 4.55\text{m/s}$$
$$\text{Velocity}_{\text{Phase 2}}: 6.0\text{m} \div 1.50\text{s} = 4.00\text{m/s}$$
$$\text{Velocity}_{\text{Phase 3}}: 4.0\text{m} \div 0.90\text{s} = 4.00\text{m/s}$$

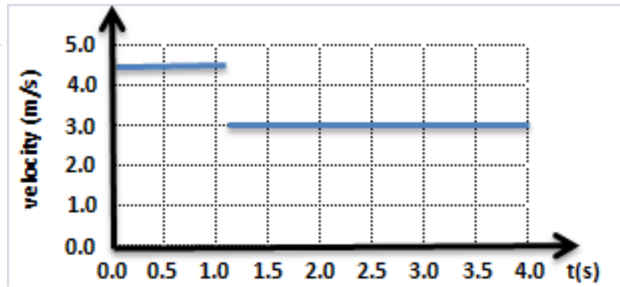
The Approach

The below diagram depicts the typical path a high jumper would take from his starting point to the bar. Phase 1 shows a straight path, Phase 2 shows a transition, and Phase 3 shows the curved path. The final two steps (labeled 9 and 10) are known as the "penultimate step" where the jumper's steps are shortened in order increase the explosiveness of the jump and carry the jumper over the bar.

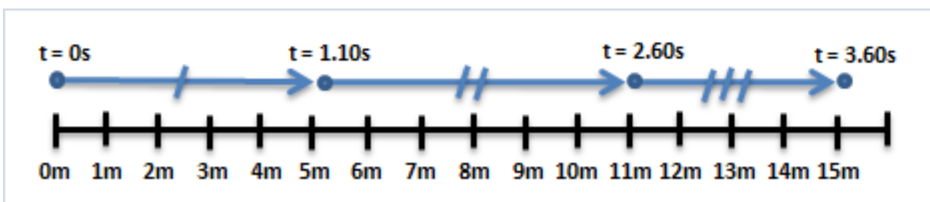


Position-time and velocity-time graphs were created in order to show the progression of the jumper's approach to the bar as the jumper transitions between each of the three phases. The position-time graph shows a strong linear relationship while the velocity-time graph shows the increased velocity during Phase 1 and a decreased, constant velocity from Phase 2 into Phase 3.

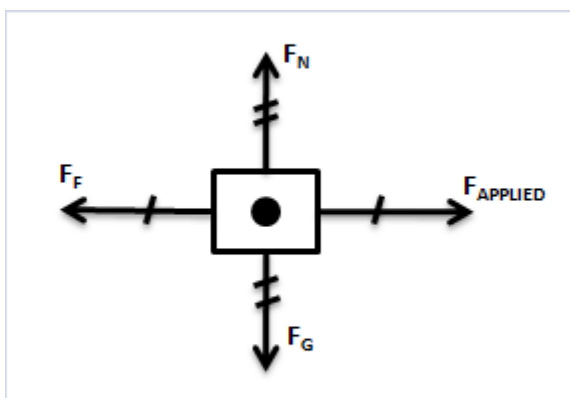




The motion map below also helps to show the progression of the jumper's approach. Although Phase 2 and Phase 3 share an identical velocity, Phase 2 takes the longest amount of time for the jumper to complete while Phase 3 takes the shortest amount of time. This is because a smooth, constant velocity helps the jumper maintain control throughout the approach.

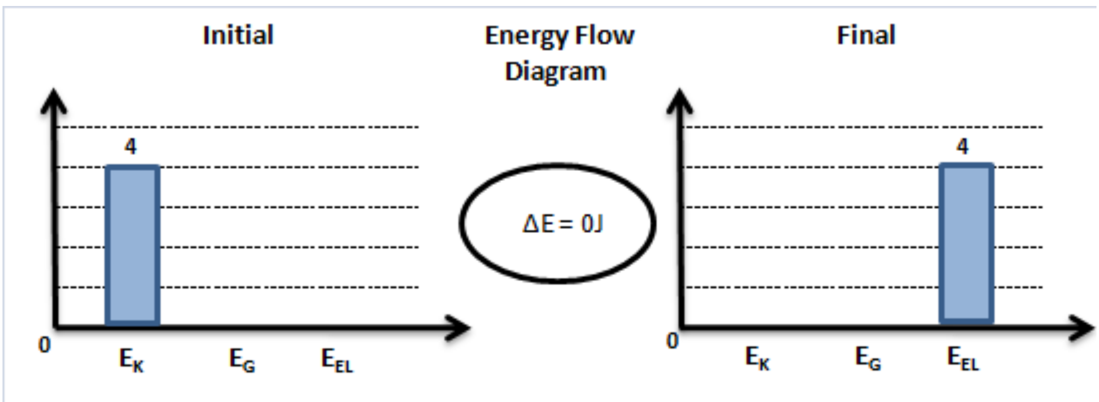


The force diagram created below identifies the forces acting on the jumper as he proceeds through Phases 2 and 3 and prepares for the actual jump. The jumper is traveling at a constant velocity, so the force the jumper applies to run forward equals the force of friction preventing the jumper from running. The jumper is also positioned securely on the surface during the approach, so the force of gravity and the normal force balance each other out.



CV: $F_{NET-X} = \emptyset N = F_{APPLIED} + F_F$
CV: $F_{NET-Y} = \emptyset N = F_N + F_G$

Bar graphs were used to analyze the energy change throughout the approach. When the jumper initially takes off, the jumper only possesses kinetic energy. The value "4" used in the bar graph for kinetic energy was chosen arbitrarily. Since there was no added or subtracted energy to the jumper's approach, the value "4" is transferred from being kinetic energy to elastic energy. This is because all of the energy created during the approach is channeled in the jumper's leg, acting like a spring to propel the jumper up and over the bar during the jumper's penultimate step.

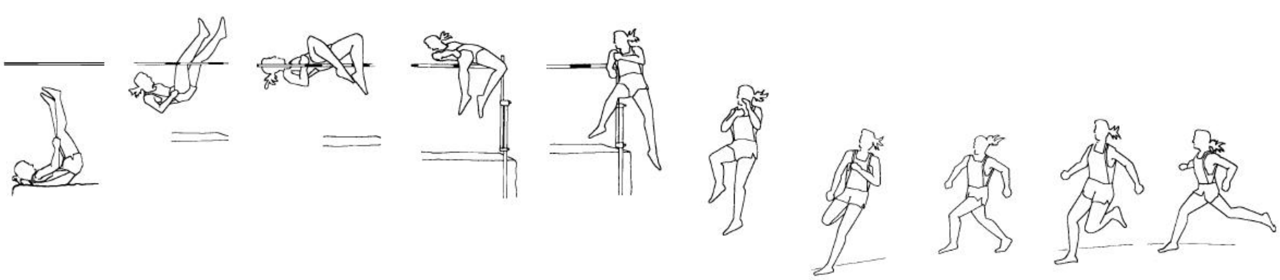


The conservation of energy equation below shows the extent to which the jumper's designated jumping leg bends in order to properly utilize all of the energy created during the approach. The numbers used in the equation were based on the given and gathered information located at the beginning of the paper.

$$\mathrm{E_K} + \emptyset\mathrm{J} = \mathrm{E_{EL}}$$
$$\frac{1}{2}\mathrm{mv}^2 + \emptyset\mathrm{J} = \frac{1}{2}\mathrm{F}\Delta x$$
$$\frac{1}{2}(70\mathrm{kg})(4.00\mathrm{m/s}) + \emptyset\mathrm{J} = \frac{1}{2}(400\mathrm{N})\Delta x$$
$$\Delta x = 0.70\mathrm{m}$$

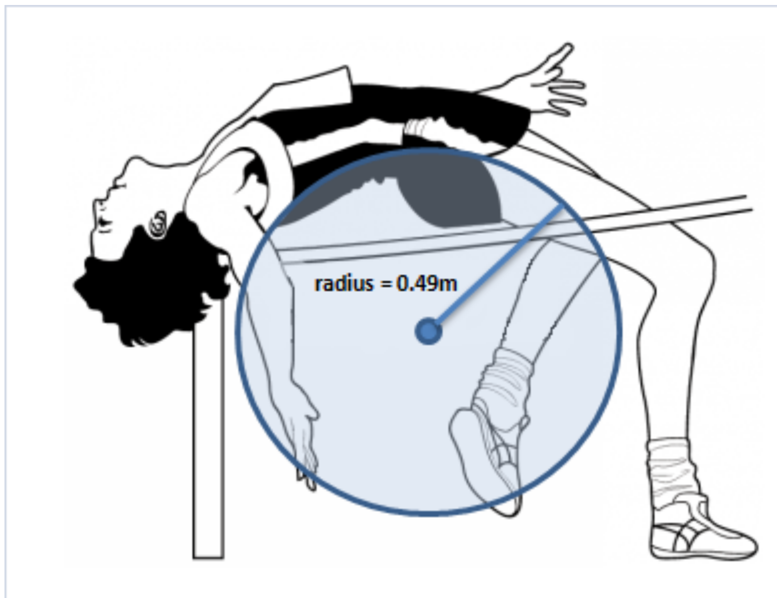
The Jump

The diagram below depicts the path a high jumper would take upon completion of Phase 3 of the approach. Moving from right to left in the diagram, the jumper's penultimate step is shortened and the trail leg of the jumper is driven upward as the jumper's head and shoulders guide the rest of the body up and over the bar. At the apex of the jump, the jumper's back is arched over the bar and the jumper's upper-body has cleared the bar while the jumper's lower-body has not. The momentum created by the approach carries the jumper over the bar and the jumper snaps his legs back to complete the jump.

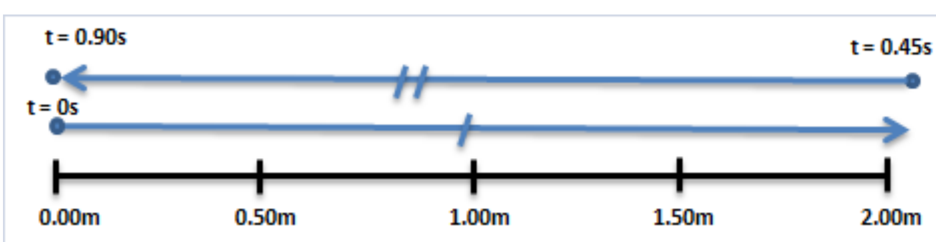


Apex Penultimate Step

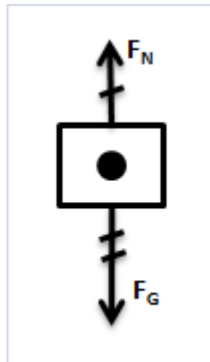
As previously mentioned in the "Given and Gathered Information" section of the paper, the radius of the jumper at the apex is 0.49m. To clarify, this number is a rough estimate and was determined based on pictures of the jumper over the bar after the jumper had already completed the jump. The diagram below shows how the jumper arches his back over the bar and roughly creates a circle with his body. The distance from the jumper to the center of this imaginary circle was determined to be the radius.



A motion map was created to show the path of the jumper as he jumped from the ground (0.00m) and traveled to the apex of his jump (2.05m) and then back down toward the mat on the ground (0.00m). The time it took for the jumper to complete the jump was 0.90seconds, estimated to be 0.45seconds on the way up and another 0.45seconds on the way down.

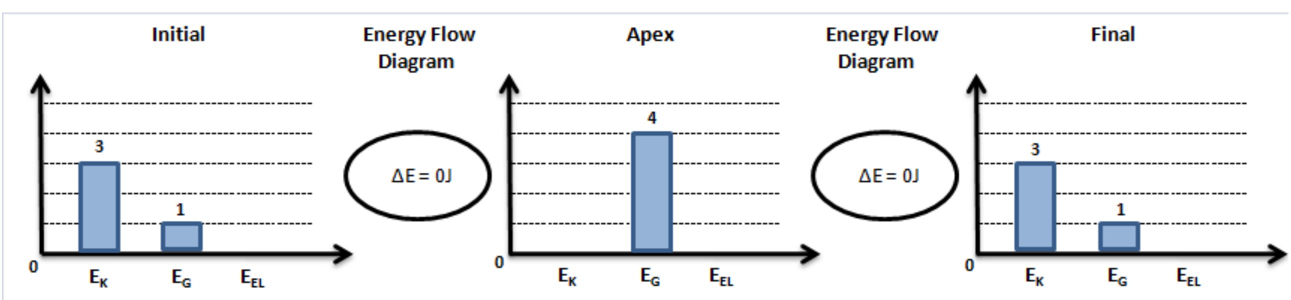


The force diagram created below identifies the forces acting on the jumper as he jumps up, reaches the apex, and then falls back onto the mat. From the moment the jumper leaves the ground, the force of gravity becomes stronger than the normal force, attributing to the jumper's uniform acceleration. The jumper accelerates in a positive direction up to his apex over the bar then accelerates in a negative direction down to the mat.



$$\text{UA: } F_{NET-Y} = \emptyset N = F_N + F_G$$

Bar graphs were used to analyze the energy change throughout the jump. Although the jumper creates elastic energy at the end of his approach, this energy is transferred into kinetic energy. After the jumper explodes into his jump, the jumper possesses kinetic energy and a little gravitational energy. The total value "4" used in the bar graph for kinetic and gravitational energy was chosen arbitrarily. Since there was no added or subtracted energy to the jumper's approach, the total value "4" is transferred from being mostly kinetic energy to all gravitational energy. This is because the position of the jumper is physically higher than he once was. After the jumper reaches the apex of his jump, most gravitational energy is transferred back into kinetic energy as the jumper falls to the mat. Since there was no added or subtracted energy to the jump or fall, the total value "4" is transferred to being kinetic energy and a little gravitational energy.



Considering the velocity of the jumper at the end of the approach was 4.00m/s and the determined radius of the jumper's arched back is 0.49m, the magnitude of the centripetal acceleration of the jumper was determined to be 32.65m/s^2 as the below equation shows.

$$ac = \frac{v^2}{r}$$

$$ac = \frac{(4.00\text{m/s})^2}{0.49\text{m}} = 32.65\text{m/s}^2$$

Since the mass of the jumper is 70kg, the ΣF required to cause the determined centripetal acceleration would be 2,285N.

$$32.65\mathrm{m/s^2}(70\mathrm{kg}) = 2{,}285\mathrm{N}$$

A quantitative force diagram for the jumper can be found below. The gravitational force was determined to be a negative 700N because gravitational force vector in the force diagram points in a downward negative direction. The normal force was then calculated to be 2,985N.

$$\mathrm{F_{NET-C}} = \mathrm{F_G} + \mathrm{F_N}$$
$$2{,}285\mathrm{N} = (-700\mathrm{N}) + 2{,}985\mathrm{N}$$

Using the mass of the jumper, radius of the jumper's arched back, and gravitational force, the velocity at which centripetal force would equal the force of gravity, resulting in the jumper feeling relatively weightless while at the apex over the bar was calculated to be 2.2m/s.

$$\mathrm{F_{NET-C}} = \mathrm{F_G}$$
$$\mathrm{F_{NET-C}} = 700\mathrm{N}$$
$$\mathrm{F_{NET-C}} = 700\mathrm{N} = \frac{\mathrm{mv^2}}{\mathrm{r}}$$
$$700\mathrm{N} = \frac{(70\mathrm{kg})\mathrm{v^2}}{(0.49\mathrm{m})} = 2.2\mathrm{m/s}$$

Conclusion

Despite being shorter than the high jump bar (2.00m), our jumper (1.85m) successfully cleared his attempt and completed the jump. A steady acceleration during Phase 1 and maintaining a constant velocity from Phase 2 into Phase 3 of his approach helped to create enough energy to carry the jumper up and over the bar. This transition of horizontal energy into vertical energy occurs during the penultimate step and continues to carry the jumper higher until the jumper reaches his apex above the bar. Once above the bar, it is necessary for the jumper to arch his back to clear the bar create enough centripetal acceleration for the lower-body of the jumper to also make it over the bar. After a successful jump, the only remaining force and energy present in the system is gravitational force and gravitational energy, pulling the jumper down from his highest point and landing safely on top of the mat. Without proper technique throughout the entirety of the high jump attempt, the high jumper cannot maintain enough control over his body to create the necessary energy to successfully complete the high jump.

Annotated Bibliography

"High Jump Approach." *Jumpers Training Tips And Techniques For Increased Performance*. Web. 1 Dec. 2010. <http://www.track-and-field-jumpers.com/high-jump-approach.html>.

This website discusses the specifics of the high jump approach. It breaks down and analyzes the three different phases of the jump and then ties in the importance of a smooth transition between phases and maintaining a constant velocity into the jump. The website contributed graphs used in the paper and better comprehension of the high jump approach.

Jacoby, Ed, and Bob Fraley. *Complete Book of Jumps*. Champain, IL: Human Kinetics, 1995. Print.

This book gives an in-depth look into the technique of each track and field jumping event. It details the mechanics (approach and jump) as well as the necessary skills of each jump. The book contributed to paper by providing the history of the high jump, a clearer understanding of proper high jump technique, and the terms specific to the jumping event.

Whitehead, Rachel, Kourtney Karleski, and David Young. *The Physics of High Jump*. *Westminster College*. Christopher A. Cline, Ph.D., 10 Dec. 1996. Web. 1 Dec. 2010. <http://people.westminstercollege.edu/faculty/ccline/courses/resources/highjump.pdf>.

This research paper on the physics of the high jump compared different high jump attempts and determined the most ideal setting for the optimal high jump. Among the several discoveries, the most notable drawn conclusion was that the greater velocity a jumper has during the approach produced a higher kinetic energy to carry the jumper up and over the bar during the jump. The paper helped serve as a guide and a means to think deeper about the physics of the high jump.