The Physics of High Jump

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Abstract: Our group designed this project to analyze the horizontal and vertical velocities needed for a high jumper to obtain maximum height, and to see if the velocities increase as the height of the bar increases. Knowing the velocities, we could investigate the kinetic and potential energies of the high jump and to determine the work necessary for the jumper to leave the ground. In attempting to explain these physical properties, we were also able to introduce and prove an interesting phenomenon: while the high jumper goes over the bar, his center of mass goes under the bar. In addition we were able to calculate the work that the jumper performed.

Relevant Theory and Equations: Before beginning this investigation, we first needed to understand the principles behind the high jump. The high jump differs from the standing or "Sargent" jump because it is not just a vertical jump, there is also a horizontal motion involved which carries the jumper across the bar. In order for the jumper to achieve maximum height, he must takeoff with the greatest vertical speed possible. The run-up helps the jumper create a more vertical force, which he enhances by swinging his arms and free leg upward before he leaves the ground. High jumpers also try to clear the bar with their centers of mass as low as possible. Many high jumpers roll their bodies horizontally over the bar in an attempt to get their centers of mass as low as possible. In doing this, the jumpers' move their center of mass outside their bodies, and their centers of mass may pass under the bar while their bodies go over the bar.

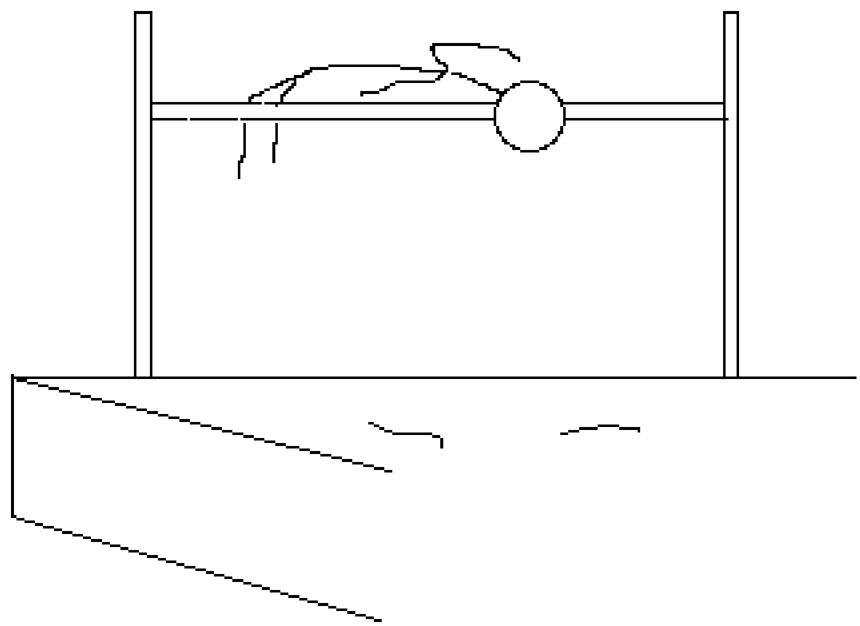

Figure 1. A depiction of a high jumper rolling his back over the bar.

Since we do not know the distance of the run-up, we needed a fixed point to find the horizontal and vertical velocity of the jump. We chose the center of mass because it was one of two points that we knew would move with a constant velocity. We constructed a graph of center of mass versus time, and determined that the slope of the graph was the velocity since

$$\Delta v = \frac{\Delta x}{\Delta t}.$$

Since we knew where the jumper's center of mass was, we could now determine the velocity as well as the kinetic and potential energy of the jumper. During the run-up, the jumper's potential energy was constant and is determined by

$$E_{pot} = y_{CM} \quad ma_g.$$

While the potential energy remains constant, the kinetic energy increased

and is determined by

$$E_{kin} = \frac{1}{2} \ mv^2 .$$

However, the velocity of the entire run is not known. By knowing the x and y components of the run-up and jump, the direction vector is determined:

$$\Delta\vec{d} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

By knowing the direction vector, and the time of each frame, 0.033 seconds, the velocity of the whole run is now determined,

$$V_{1.5} = \frac{\Delta\vec{d}}{0.033}$$

hence we can determine the kinetic energy.

Once the kinetic and potential energies are known, it is possible to show that the energy of this system is not lost. The missing piece of information is the work needed for the initial thrust upward:

$$W = \int \vec{F} \ d\vec{s}$$

However, for this experiment the force is not known. But since we know that the law of conservation of energy holds through out the actual jump, not the backward fall, we can assume the value for W is equal to the total potential energy of the upward motion minus the total energy calculated for the run up[11] :

$$W = E_{pot,u} - (E_{kin,r} + E_{pot,r}) .$$

<u>Procedure:</u> To obtain the data for this experiment, we first viewed recordings from the 1992 Summer Olympics in Barcelona. We chose three

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[11] The law of conservation of energy says that for an isolated system, energy can be transferred from one type to another, but the total energy of the system remains constant.

jumps of different jumpers at heights of 2.24 m, 2.27 m, and 2.34 m. After editing the jumps, we transferred the films to the Videopoint software, and digitized them. However, before we began analyzing the video frame by frame, we established the masses of several parts of the body. By using the Videopoint User's Guide as a reference, we established the mass of eight points on the runners' body:

Number	Item	Percentage
1	left calf	6.00
2	left thigh	9.70
3	right calf	6.00
4	right thigh	9.70
5	left forearm	2.20
6	left upper arm	2.70
7	right forearm	2.20
8	right upper arm	2.70

Using a moving origin and "Center of Mass Tables," we found the position of the high jumper's center of mass in each frame. By graphing the x-position versus time we found the horizontal movement of the center of mass. Similarly, we were able to determine the vertical movement of the jumper's center of mass by graphing the y - position versus time. Finally by using an Excel spreadsheet we calculated the horizontal and vertical velocities for each jump.

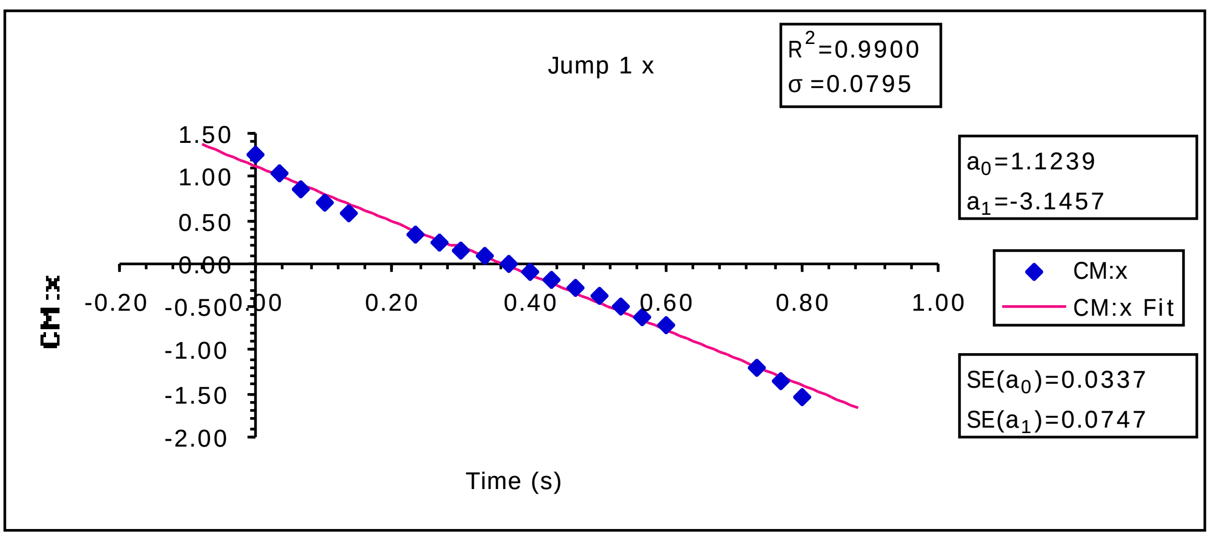
Next we assumed the mass of the high jumper to be 180 pounds. By using the equations stated previously, we calculated the potential energy at the maximum height, and the potential and kinetic energies of the run-up. (We only considered the position points for the run-up, not the whole jump.)

Data:

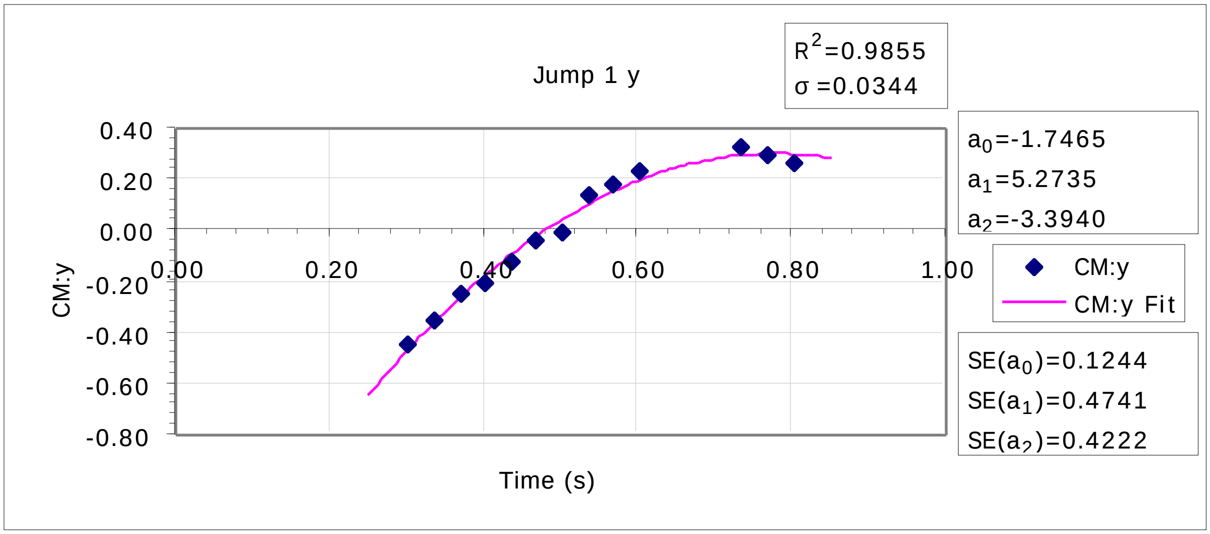
The following data was collected using the above procedures:

Time (s)	CM:x (m)	CM:y (m)
0.000	1.26	-1.47
0.033	1.05	-1.48
0.067	0.86	-1.39
0.100	0.69	-1.32
0.135	0.57	-1.15
0.233	0.32	-0.63
0.270	0.25	-0.50
0.300	0.14	-0.44
0.335	0.10	-0.36
0.370	0.01	-0.25
0.402	-0.08	-0.21
0.435	-0.20	-0.12
0.468	-0.29	-0.04
0.502	-0.37	-0.01
0.535	-0.49	0.14
0.568	-0.61	0.18
0.602	-0.72	0.23
0.735	-1.20	0.33
0.768	-1.35	0.30
0.802	-1.54	0.27

Table 1. The x and y positions of the center of masses and their respective times for jump 1 at 2.24 meters.



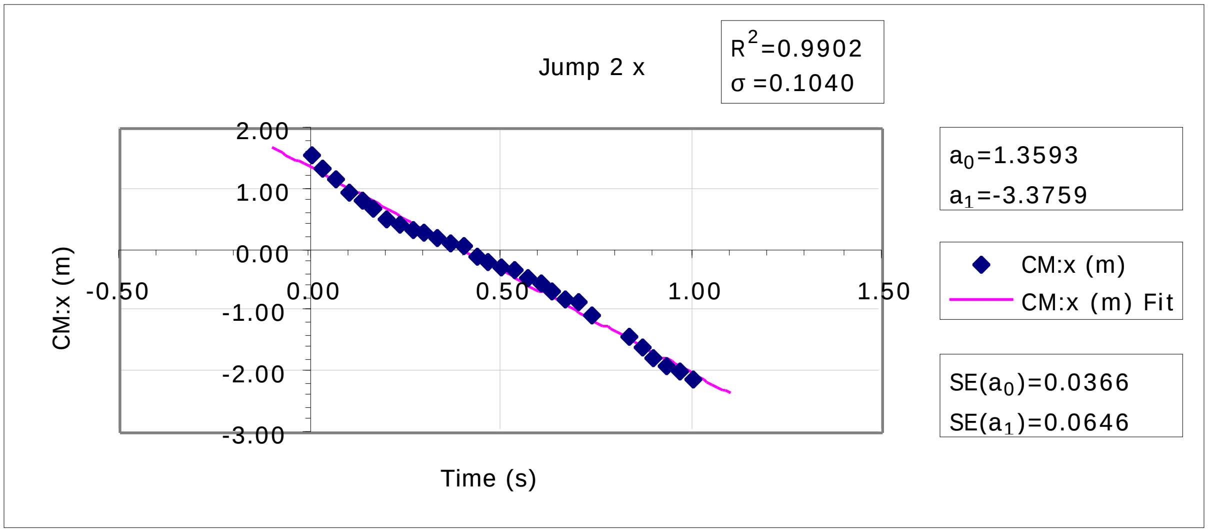
Graph 1. The linear relationship between the horizontal position and time for jump 1.



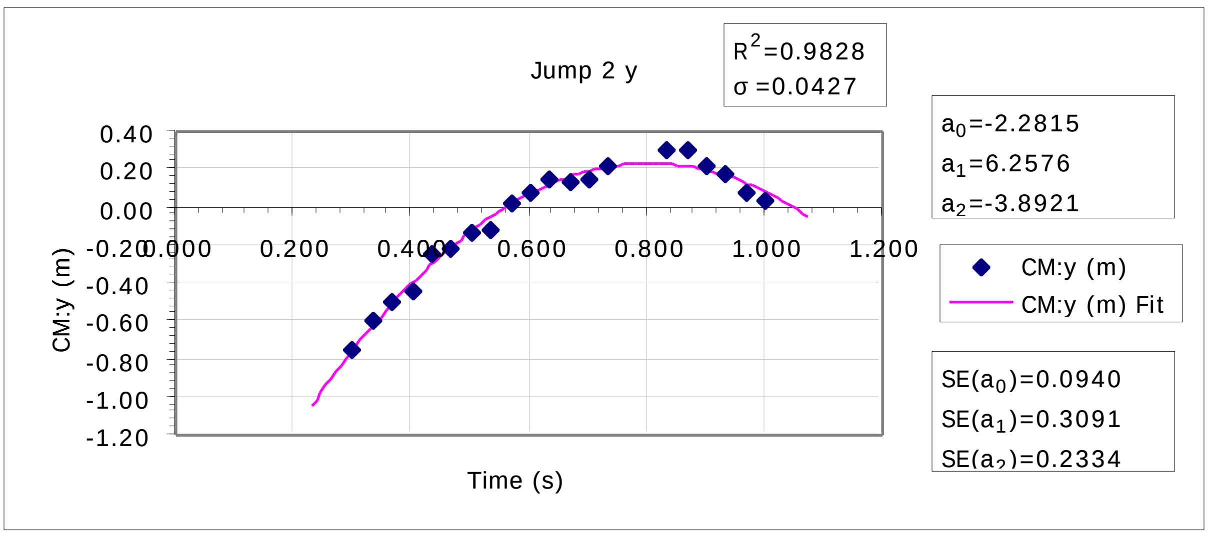
Graph 2. The parabolic relationship between the vertical position and time for jump 1.

time (s)	CM:x (m)	CM:y (m)
0.000	1.55	-1.55
0.033	1.36	-1.53
0.067	1.16	-1.50
0.100	0.96	-1.48
0.133	0.81	-1.44
0.167	0.68	-1.33
0.200	0.52	-1.26
0.233	0.41	-1.09
0.268	0.32	-0.93
0.300	0.28	-0.74
0.368	0.12	-0.50
0.402	0.07	-0.44
0.435	-0.09	-0.25
0.468	-0.21	-0.22
0.502	-0.28	-0.13
0.535	-0.34	-0.12
0.568	-0.48	0.03
0.602	-0.53	0.08
0.635	-0.70	0.15
0.668	-0.81	0.13
0.703	-0.83	0.15
0.735	-1.44	0.30
0.869	-1.60	0.30
0.902	-1.78	0.22
0.935	-1.90	0.17
0.969	-2.00	0.08
1.002	-2.13	0.04

Table 2. The x and y positions of the center of masses and their respective times for jump 2 at 2.28 meters.



Graph 3. The linear relationship between the horizontal position and time for jump 2.

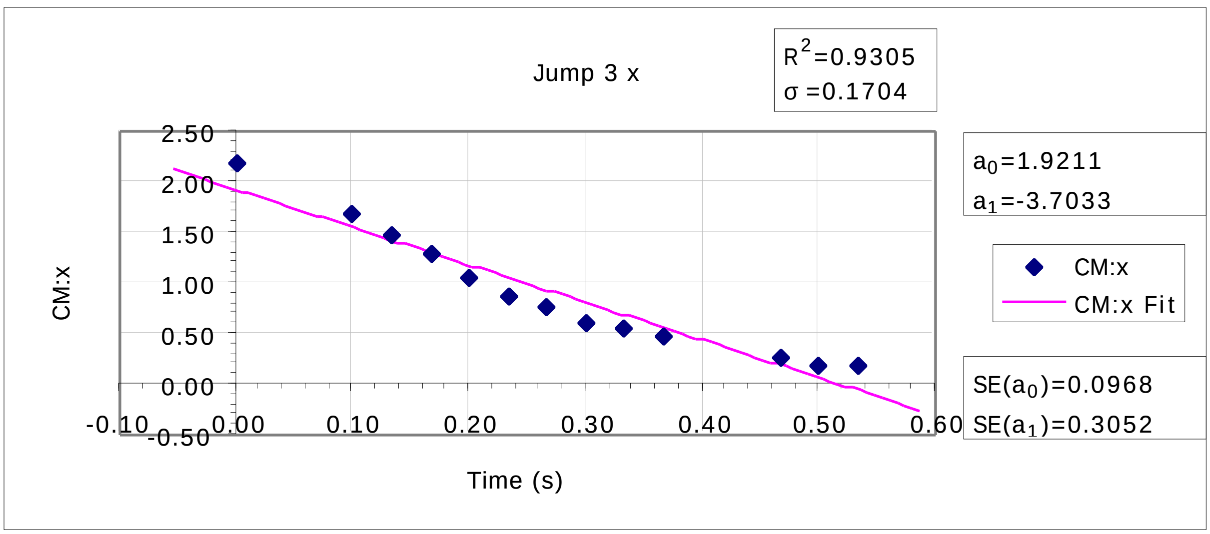


Graph 4. The parabolic relationship between the vertical position and time for jump 2.

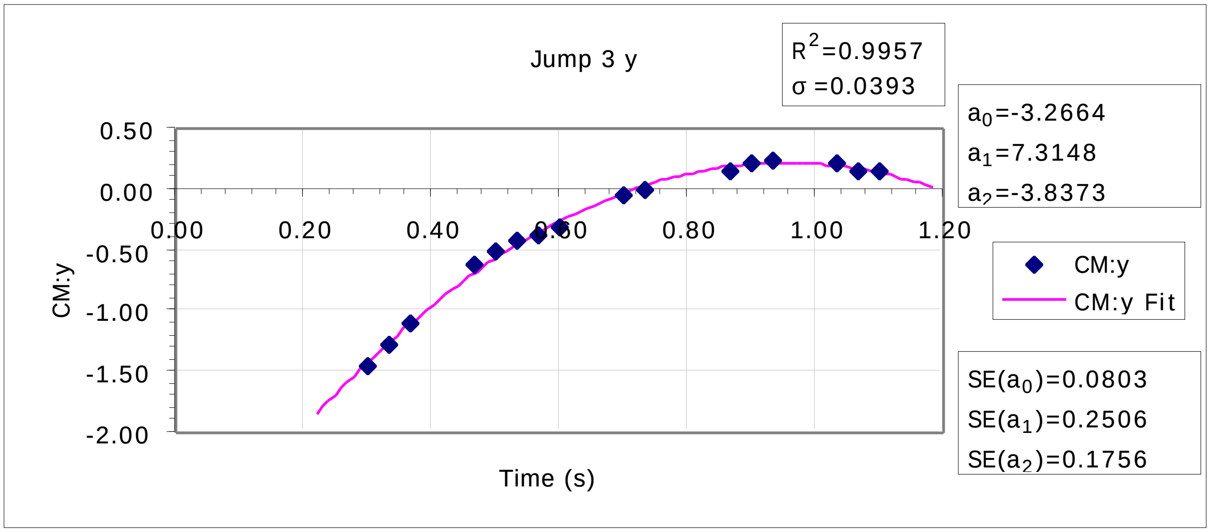
Time (s)	CM:x (m)	CM:y (m)
0.00	2.20	-1.71
0.10	1.70	-1.73
0.13	1.46	-1.71
0.17	1.29	-1.72
0.20	1.06	-1.70
0.23	0.87	-1.65
0.27	0.77	-1.56

0.30	**0.62**	**-1.46**
0.33	**0.55**	**-1.29**
0.37	**0.49**	**-1.09**
0.47	**0.26**	**-0.62**
0.50	**0.20**	**-0.50**
0.53	**0.19**	**-0.41**
0.57	**0.09**	**-0.38**
0.60	**0.04**	**-0.30**
0.70	**-0.27**	**-0.04**
0.73	**-0.35**	**-0.01**
0.87	**-0.72**	**0.16**
0.90	**-0.78**	**0.22**
0.93	**-0.88**	**0.23**
1.04	**-1.20**	**0.21**
1.07	**-1.29**	**0.15**
1.10	**-1.38**	**0.15**

Table 3. The x and y positions of the center of masses and their respective times for jump 3 at 2.34 meters.



Graph 5. The linear relationship between the horizontal position and time for jump 3.



Graph 6. The parabolic relationship between the vertical position and time for jump 3.

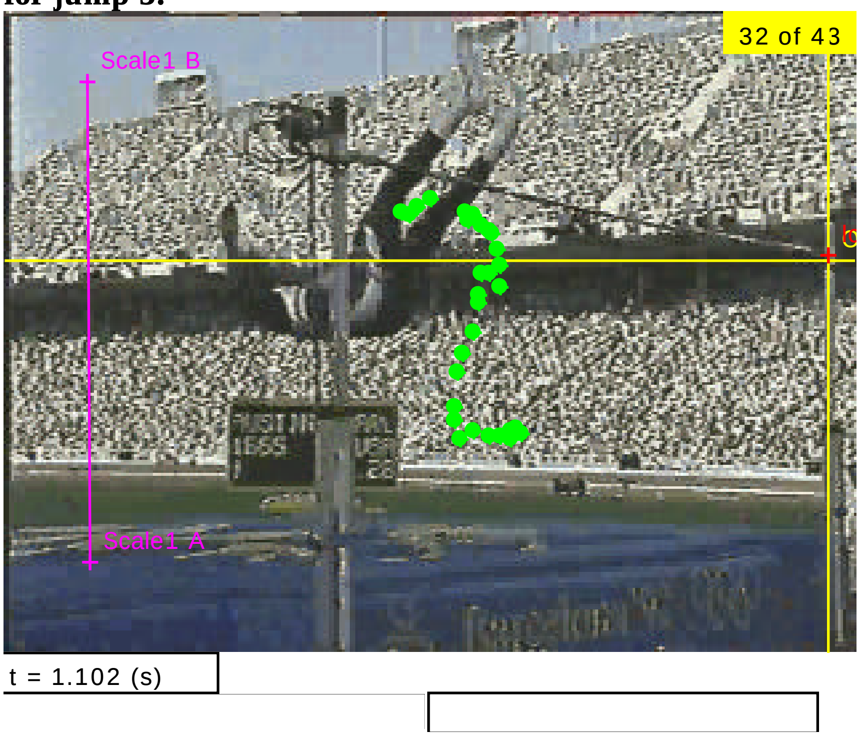


Figure 2. A depiction of the jumper's center of mass going under the bar while he goes over the bar.

Calculations and Data Analysis:

Using the best-fit equation we obtained both the horizontal and vertical velocities for every jump. We have summarized them below:

Jump Height (m)	Horiz. V (m/s)	Vert. V (m/s)
2.24	-3.15	5.27
2.28	-3.38	6.26
2.34	-3.70	7.32

Table 4. The horizontal and vertical velocities for each of the three jumps.

We next calculated the average direction vector for each run-up. Knowing this value, we then calculated the average velocity of the run-up (a sample table of calculations is below):

CM:x	CM:y	d (m)	
2.20	-1.71	0.501	Average d (m)
1.70	-1.73	0.234	0.236
1.46	-1.71	0.167	
1.29	-1.72	0.240	
1.06	-1.70	0.196	Velocity(m/s)
0.87	-1.65	0.133	7.16
0.77	-1.56	0.183	
0.62	-1.46		

Table 5. Values of the average direction vector and velocity for jump 3.

Knowing the velocity, we then calculated the kinetic energy of the run-up. We also calculated the potential energy of maximum height and of the run-up:

Jump Height (m)	**$E_{pot,m}$ (J)**	**$E_{pot,r}$ (J)**	**$E_{kin,r}$ (J)**
2.24	**1.20 E3**	**753**	**691**
2.28	**1.23 E3**	**806**	**866**
2.34	**1.26 E3**	**914**	**1.40 E3**

Table 6. Values of the potential energies and kinetic energy at each height.

With all of this information, we calculated the work needed to leave the ground , knowing that energy is conserved:

Jump Height (m)	**W (J)**
2.24	**-240**
2.28	**-447**
2.34	**-1.06 E3**

Table 7. Values of work needed at each height.

Conclusion

Looking at both the horizontal and vertical velocities, it is seen that as the height of the bar increases both the horizontal velocity and the vertical velocity of the jumper increase. This is what we expected to occur since it would seem unusual for a jumper to have the same horizontal and vertical velocities for different heights.

Figure 2 illustrates how the jumpers' body moves over the bar while his center of mass goes under the bar. This phenomenon occurs because his body is arched and his center of mass is located outside of his body. This is related to the concept of a "U", the approximate shape of the arched jumper. The center of mass of this shape is not on the body itself, but instead in between the two linear sides.

In analyzing the energies, we observed that the greater the height of the bar the greater the kinetic energy of the run-up. We also noticed that the potential energy varied with the different jumps. If it had been the same jumper all three times, then the potential energy would not have changed. However, each of these jumpers has a different height, which in turn affects their potential energies.

We can attribute error in this experiment to possible incorrect analysis of the center of mass, since we based most of our calculations on it. This is due to the difficulty in clicking the same point on the body for each of the eight body parts for every frame. This automatically causes some discrepancy in the results. Also, the motion of the camera and its angle in relation to the bar cause error.