Video Analysis of a Person Landing After a Jump

Apparatus

Tracker software (free; download from http://www.cabrillo.edu/∼dbrown/tracker/)
video: `landing-long.mov` from http://physics.highpoint.edu/∼atitus/videos/
video: `landing-short.mov` from http://physics.highpoint.edu/∼atitus/videos/

Goal

In this experiment, you will measure the force of impact by the floor on a person as he is landing on the floor after he jumps from a table. You will compare the impact force in two different cases: (1) he bends his knees as much as possible and (2) he bends knees a small amount.

Introduction

Newton's second law describes the relationship between the net force on an object (i.e. *system*) and the object's acceleration.

$$\Sigma \vec{F} = m\vec{a} \tag{1}$$

Suppose that a gymnast is landing on a floor during a dismount in the vault or uneven bars events. Or Suppose she is landing on the floor while tumbling during the floor exercise. Or suppose she is landing on the beam during the balance beam exercise. Regardless of the event, when landing there is a large upward force of the floor (or beam) on the gymnast as she slow down during the landing.

Figure 1: Nastia Luikin performs on the balance beam.

A force diagram showing the forces on a gymnast as she is landing on the mat is shown in Figure 2.

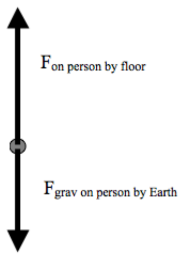

Figure 2: Forces on a gymnast when she is landing.

Applying Newton's second law to the person in the y-direction gives:

$$\begin{aligned}
\Sigma F_y &= ma_y && (2)\\
F_{on\ person\ by\ floor} - F_{grav\ on\ person\ by\ Earth} &= ma_y && (3)\\
F_{on\ person\ by\ floor} - mg &= ma_y && (4)\\
& && (5)
\end{aligned}$$

Let's consider three different parts of her motion:

1. while she is in the air, before she touches the floor.
2. while she is touching the floor and slowing down.
3. after she comes to a stop and she is at rest and remains at rest.

Before the gymnast touches the floor

While she is falling, the floor is NOT touching her. Therefore, the floor exerts no force on her. Then,

$$\begin{aligned}
\Sigma F_y &= ma_y && (6)\\
F_{on\ person\ by\ floor} - F_{grav\ on\ person\ by\ Earth} &= ma_y && (7)\\
0 - mg &= ma_y && (8)\\
-mg &= ma_y && (9)\\
a_y &= -g && (10)
\end{aligned}$$

Her acceleration is equal to $-9.8\ \text{m/s}^2$.

While she is touching the floor and slowing down

When she is landing, she is moving downward and slowing down. Therefore, her y-acceleration is upward (positive). Then,

$$F_{on\ person\ by\ floor} = ma_y + mg \quad (11)$$

shows that the force on the gymnast by the floor is *greater* than her weight (mg). As a result, it is the large upward force of the floor on the gymnast that is causing her to slow down.

While she is remains at rest on the floor

After stops, she is at rest and remains at rest. Therefore, her velocity is constant and her acceleration is zero. Then,

$$\begin{aligned}
\Sigma F_y &= ma_y && (12)\\
F_{on\ person\ by\ floor} - F_{grav\ on\ person\ by\ Earth} &= ma_y && (13)\\
F_{on\ person\ by\ floor} - mg &= 0 && (14)\\
F_{on\ person\ by\ floor} &= mg && (15)
\end{aligned}$$

The force on the gymnast by the floor is *equal to* her weight (mg).

In which case is the force by the floor on her the greatest?

How Time Interval affects the force by the floor on her while landing

As you deduced from Newton's second law, the force of the floor on the gymnast is largest while she is landing. In this case, it is

$$F_{on\ person\ by\ floor} = ma_y + mg \quad (16)$$

By measuring her acceleration, you can calculate the force by the floor on the person. The greater her acceleration, the greater the force by the floor and the more she will "feel" the impact.

The average acceleration of the gymnast while landing is:

$$a_y = \frac{v_{yf} - v_{yi}}{\Delta t} \quad (17)$$

where v_{yi} is her initial velocity when first touching the mat and $v_y f$ is her final velocity when she comes to rest on the mat. Her final y-velocity is zero. Therefore,

$$a_y = \frac{0 - v_{yi}}{\Delta t} \quad (18)$$

$$a_y = \frac{-v_{yi}}{\Delta t} \quad (19)$$

The gymnast's initial velocity when first touching the mat depends on her peak height. The higher she is when she falls, the faster she is moving when she hits the mat and the greater her acceleration and the greater the force on her by the floor during her landing.

The time interval is the duration of time that she is slowing down during her landing. If she bends her knees a lot during her landing, then the time interval will be larger and her acceleration and the force by the floor on her during her landing will be smaller.

If she bends her knees very little during the landing, then the time interval is smaller as she comes to a stop. As a result, her acceleration is greater and the force on her by the floor is greater during the landing.

Procedure

In this experiment, you will analyze the video of a student as he is landing on the floor. You will measure the force by the floor on him during the landing.

1. Download the following files by right-clicking on the link and choosing **Save As...** to save it to your desktop:

   (a) `landing-long.mov`

   (b) `landing-short.mov`

2. Open the *Tracker* software on your computer.

3. Go to the menu **Video→Import...** and import `landing-long.mov` , as shown in Figure 3.

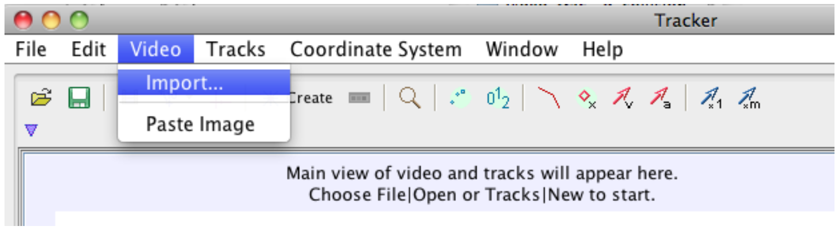

Figure 3: Video→Import menu

4. Play the video and watch the person's motion.
5. There is a 2-m stick in the frame of the video. Use this to set the scale (i.e. calibrate distance) for the video.
6. Set the origin of the coordinate system to be at the base of the meterstick. As you will use, this point is useful for aligning the coordinate system, but in reality the choice of origin isn't important for measuring velocities and accelerations.
7. After setting the origin of the coordinate system, click and drag up or down on the x-axis to rotate the coordinate system so that the y-axis is parallel to the stick. This will compensate for the fact that the camera is not level.

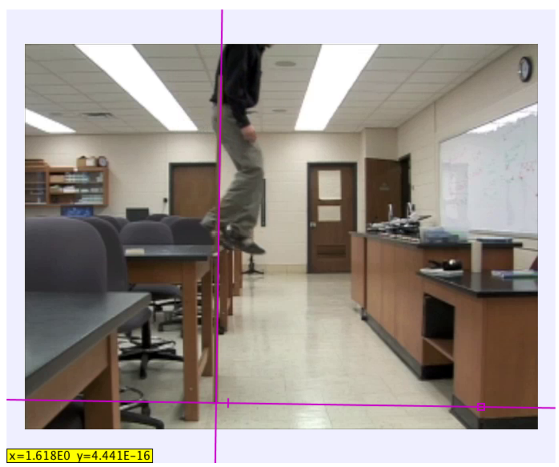

Figure 4: Rotate the coordinate system so that the y-axis is parallel to the 2-m stick.

8. Advance the video to the first frame that his feet are no longer touching the table. Click the "Create" button in the toolbar and select **Point Mass** . Hold the shift key down and start marking his center-of-mass position. Assume that his center of mass is at the center of his belt.
9. View the y vs. t graph. Right-click on the graph and select **Analyze** in order to bring up the Data Tool.
10. Select the portion of the data that represents his motion before his feet hit the floor. You can count the number of dots in the video before his feet hit the floor, and select the same number of data.
11. Fit a curve to this data.

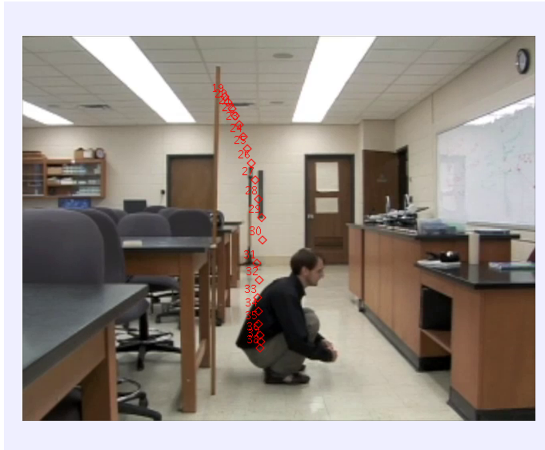

Figure 5: Marks for the person at approximately his center of mass.

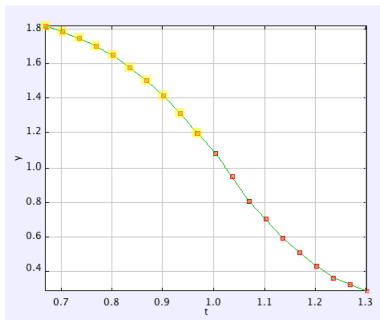

Figure 6: Selected data on the y-t graph for the person while falling

Note: he is in free-fall. What function should fit this portion of the curve? Record the best-fit function and the parameters of the curve fit. From the curve fit, what is his y-acceleration as he is falling?

12. Now, select the portion of the graph where his feet are in contact with the floor and he is slowing down.
13. Fit a curve to this data, *assuming* constant acceleration.

What is his acceleration as he is landing and slowing down?

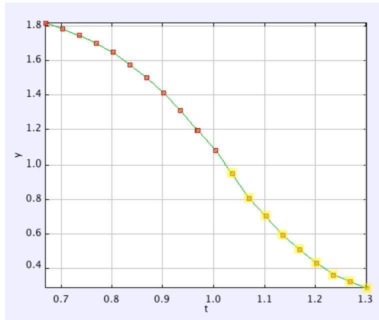

Figure 7: Selected data on the y-t graph for the person while landing

14. View the y-velocity vs. time graph. You will notice the part of the motion where he is accelerating downward and the part where he is accelerating upward.
15. Do a linear fit to each part of the graph.

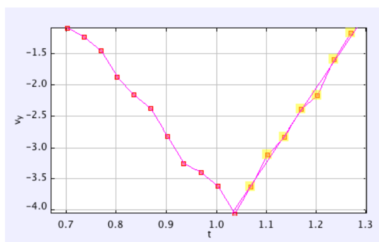

Figure 8: The y-velocity vs. time graph for the person while falling and landing

Using this graph, what is his during each part of his motion? Record your best-fit functions, and record $a_{free\ fall}$ and $a_{landing}$.

Is your determination of the acceleration during each part of the motion consistent with what you measured using the quadratic curve fit on the y vs. t graph?

Now, apply Newton's second law (Eq. 11) to the landing. Calculate the force on the person by the floor as he is landing.

16. Suppose that the person bends his knees less while landing. Will his acceleration be greater or less than in this case? Will the force by the floor on him be greater or less (i.e. will it be a more "jarring" impact or less "jarring" impact)?

Download and analyze the movie `landing-short.mov`. Repeat the analysis that you did for the first video. Record all measurements and calculations below for his motion in the new video. In which case did the floor exert a larger force on the person while he was landing? What caused the force to be larger in this case?