Lab 1: Jumping Right In

Bio427 — Biomechanics

The first lecture of the class reviewed basic physical quantities that we will use throughout the course. Distance (position), velocity, acceleration, momentum, force, energy and power were all mentioned in a simple analysis of a jump. In this lab we will combine measurements and predictions in computing the energy humans use in accomplishing a simple standing jump. Our goals are for you to:

- Learn how to use your computer for acquiring kinematic (motion) data

- Learn how to use open source NIH-developed software for image and motion analysis (ImageJ[1])

- Measure aspects of human jumping performance

- Use simple physical equations to predict jumping and test your predictions with measurements

- Contribute to crowd data for jumping humans (and a possible poster topic!)

[1] http://rsbweb.nih.gov/ij/

Conceptual Basis

In a jumping animal, muscles and elastic structures contribute to the forces that propel the animal off the ground. If the animal is starting from rest, these structures allow the animal to exert a force on the ground, accelerating its center of mass away from the ground as the ground exerts an equal and opposite force upon the animal. Once the animal has left the ground, the animal enters a ballistic phase in which the only forces acting upon it are those due to gravity and aerodynamic resistance. Assuming that the animal is reasonably large (e.g. a human), these aerodynamic forces can be safely ignored, and so only gravity acts on the animal while it is in the air.

We can therefore consider a jump as consisting of two phases: a takeoff phase, in which the animal pushes against the ground to accelerate from rest to its takeoff speed, and a ballistic phase in which it follows a parabolic trajectory through the air towards its landing.

If we make the assumption that the muscles and elastic structures of the animal cause the animal to accelerate at a constant rate during its takeoff phase, we may use the (hopefully familiar) standard kinematic equations to describe the takeoff phase:
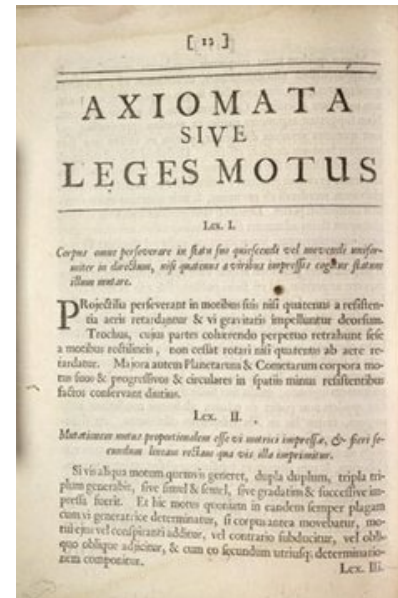
$$d = ut + \frac{at^2}{2} \tag{1}$$

$$v = u + at \tag{2}$$

$$v^2 = u^2 + 2ad \tag{3}$$

where d is the distance the animal's center of mass moves from the bottom of its initial crouch to takeoff, u is the initial velocity of the animal, which is 0 if the animal is starting from rest, v is the takeoff velocity of the animal, t is the time taken for the takeoff phase, and a is the acceleration during the takeoff phase.

Note that, by rearranging these equations, we find that we can estimate a as long as we know any two of v, t, or d. This quantity a is important to us, as we can use it along with a measurement of the animal's mass m to obtain the force exerted by the animal against the ground during its takeoff phase via Newton's second law:

$$F = ma \tag{4}$$

Knowing the force allows us to then calculate the work performed by the animal during the takeoff phase, as well as its power expenditure:

$$W = Fd \tag{5}$$

$$P = \frac{W}{t} \tag{6}$$

Once the animal leaves the ground and enters its ballistic phase, the only forces acting on the animal are those due to the earth's gravitational acceleration ($\mathbf{g}$) and aerodynamic drag, which for large animals we may safely ignore. We may therefore obtain the following equations of motion for the animal in flight:

$$F_x = ma_x = 0 \tag{7}$$

$$F_y = ma_y = mg \tag{8}$$

These equations form a pair of differential equations whose solution is based on the take off velocity ($\mathbf{v} = [v_x, v_y]$) with a takeoff angle α, such that $v_x = |\mathbf{v}| \cos(\alpha)$ and $v_y = |\mathbf{v}| \sin(\alpha)$. Taken together these lead to predictions for the jump height and jump distance:

$$y_{max} = \frac{v_y^2}{2g} = \frac{(|\mathbf{v}| \sin(\alpha))^2}{2g} \tag{9}$$

$$x_{max} = \frac{2|\mathbf{v}|^2 \sin(\alpha) \cos(\alpha)}{g} \tag{10}$$

Methods

Caution: This is not Olympic trials, so you need not unduly stress yourself or place yourself in any situation that might lead to injury. Make sure you jump clear of obstacles and colleagues. If you are wearing high-heels, or shoes with slippery soles, please remove those and jump with either bare feet (nice friction) or socks (less nice friction).

Finding your center of mass

Place one of the markers on the part of your clothing nearest your femoral trochanter (that is the part of the femur sticking out from your hip). This point will serve as an estimate for the location of your center of mass. Working in pairs, enter the basic data in the table below. Estimate (recall) your body mass (1 lb = 0.4536 kg), measure your leg length as the distance from your femoral trochanter to the floor using the tape measures provided.

Recording video

You will be recording video using the webcam built in to the laptop's screen and the video capture program guvcview. Start up guvcview and try to get your subject framed as shown in Figure 3. You don't need to capture the entire jump—just the takeoff—but you need to have the feet in view so that you can identify the frame where the feet leave the ground and the body enters a ballistic phase. You will also need to place an object of known length within the field of view of the camera so that you can calibrate distances: a ruler or two markers separated by some known distance will be sufficient. Hit the "Capture Video" button in the guvcview program, and hit stop after the jump is complete. Your video will be saved as an AVI file in your home directory (it will be named capture-X.avi, where X will be a number). Use a tape measure to measure the total distance jumped by your subject and record this information in the worksheet table Row 4.

Video Analysis

Once you have captured your jump video, you will next import that video into an image analysis program (ImageJ – see Figure 2) and use this program to measure three critical parameters: your takeoff distance (d), takeoff angle (α) and takeoff time (t).

Import your video into ImageJ using the File > Import > AVI command. *Important:* Check the box marked "Use Virtual Stack" when
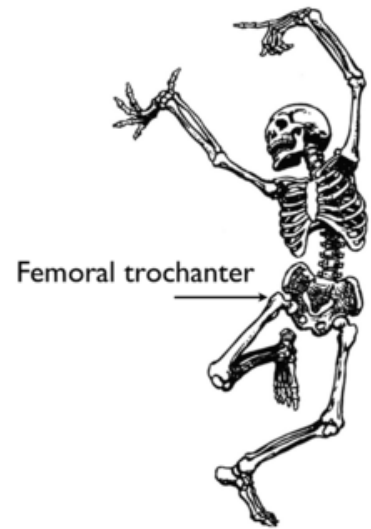

Figure 1: Finding the femoral trochanter

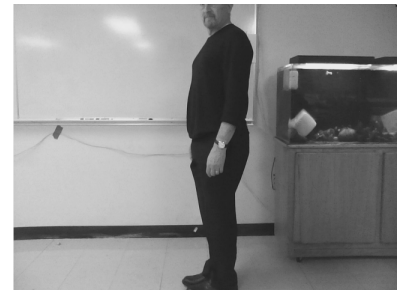Figure 2: Icons for guvcview (top) and ImageJ (bottom)

Figure 3: How to frame your shot

importing your video; otherwise, you may run into memory issues.

Select the line tool in the ImageJ toolbar and draw a line from one end to the other of the distance calibration markers in the frame, and go to Analyze > Set Scale to set the scale of your measurements by associating the length of this line in pixels with the measured length of your calibration object. For example, if you placed two pieces of tape 1 m apart on the floor by your jumper, and the image distance between these two markers is 100 pixels, then you know that 1 pixel distance is equivalent to 0.01 m.

Advance through the video using the slider at the bottom of the video window (or the arrow keys) to the lowest point of the jumper's crouch. Advance through the video, and estimate the number of frames and therefore the time[2] it takes from the initiation of the jump to takeoff and enter those data in the worksheet.

Next, measure the distance moved by the center of mass during the takeoff phase. Using the Line Tool, draw a line originating at the center of mass at the bottom of the crouch, and drag out the end point away to draw a line. Advance the video using the slider at the bottom of the window to the takeoff point, and move the end of the line you just drew to the position of the center of mass in this frame. Using the slider, confirm that the ends of the line you have drawn correspond to the position of the center of mass at the bottom of the crouch and at the point of takeoff. When you are happy with your line placement, select Analyze > Measure, or hit Ctrl+M. ImageJ will now tell you the length of this line (i.e. the distance moved by the center of mass during the takeoff phase) and the angle of the line (i.e. the takeoff angle).

Finally, we want to estimate takeoff velocity as the jumper enters their ballistic phase. By Newton's first law, assuming negligible air resistance, the horizontal component of the jumper's velocity in the air should remain constant. However, due to the action of gravity, the vertical component will not be constant. To estimate takeoff velocity, we need to measure the distance moved by the jumper's center of mass over a sufficiently short period of time that we may safely assume constant velocity. Using the line tool, make a new line that originates at the jumper's center of mass at takeoff, and end that line at the jumper's center of mass three frames later (given the filming rate of 30 fps, this is 0.1 s later). Use the length of this line to arrive at an estimate for the jumper's takeoff speed. You can also try to measure the takeoff velocity using the three frames *prior* to takeoff – is your result different?

You now know the takeoff distance, velocity, time, and angle. Using the above equations, and the data in rows 2–9 you can now fill in the rest of the table.

[2] The webcams should be set to record at 30 frames per second, but you should double check this setting in guvcview.

Estimate the mass you associate with muscles involved in jumping. Use that value to predict the power output per unit mass of jumping muscle (note that this is merely an estimate).

The takeoff angle and velocity can be used to predict the total distance travelled with equations 9 and 10. Enter your predicted values in row 15 and 16 in the worksheet. How do these predicted values compare with your measurements?

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Lab Section: _____

Name 1: _____ Name 2: _____

Data

1	Sex	_____	_____
2	Mass (kg) (1 lb = 0.4536 kg)	_____	_____
3	Leg length (m)	_____	_____
4	Distance travelled (m)	_____	_____
5	Number of frames from crouch to takeoff	_____	_____
6	Time from crouch to takeoff (s)	_____	_____
7	Distance from crouch to takeoff (m)	_____	_____
8	Takeoff angle (radians)	_____	_____
9	Takeoff velocity (m/s)	_____	_____
10	Takeoff acceleration (m/s^2)	_____	_____
11	Takeoff force (N)	_____	_____
12	Takeoff energy (J)	_____	_____
13	Takeoff power (W)	_____	_____
14	Takeoff power per mass of muscle (W/kg)	_____	_____
15	Predicted horizontal distance travelled (m)	_____	_____
16	Predicted jump height (m)	_____	_____

Questions

1. One hypothesis is that we can use measured takeoff angle and takeoff velocity to predict the distance travelled using Equation 10. Your measured and predicted distance may not agree. Explain what factors may contribute to the differences between observed and measured horizontal distance travelled.

2. In estimating the power output of your leg muscles you assumed that all of the jump is powered only by those muscles associated with your legs. How might arm motions contribute? How would you test your hypothesis?

3. You predict energy output (row 12) based on the mass, acceleration and distance travelled by your body as it launches. Speculate on an alternate way to estimate the total energy associated with your jump.