# 4. Analysis of Standing Vertical Jumps Using a Force Platform

OBJECTIVES

- To examine a standing vertical jump from the viewpoints of force-time, velocity-time, position-time, and force-position.

- To develop a greater understanding of the relations between force, acceleration, velocity, and displacement.

- To calculate the flight height of a jump from the time of flight and by using the impulse-momentum relation.

INTRODUCTION

In this session you will use the output of a force platform to analyse a standing vertical jump. A physically active male participant performed two maximum-effort jumps while standing on a force platform. The jumps were a countermovement jump (CMJ) and a jump with no countermovement (i.e. a squat jump, SJ) starting from about the same height as the low-point of the countermovement jump. The participant performed both jumps with the hands placed firmly on the hips.
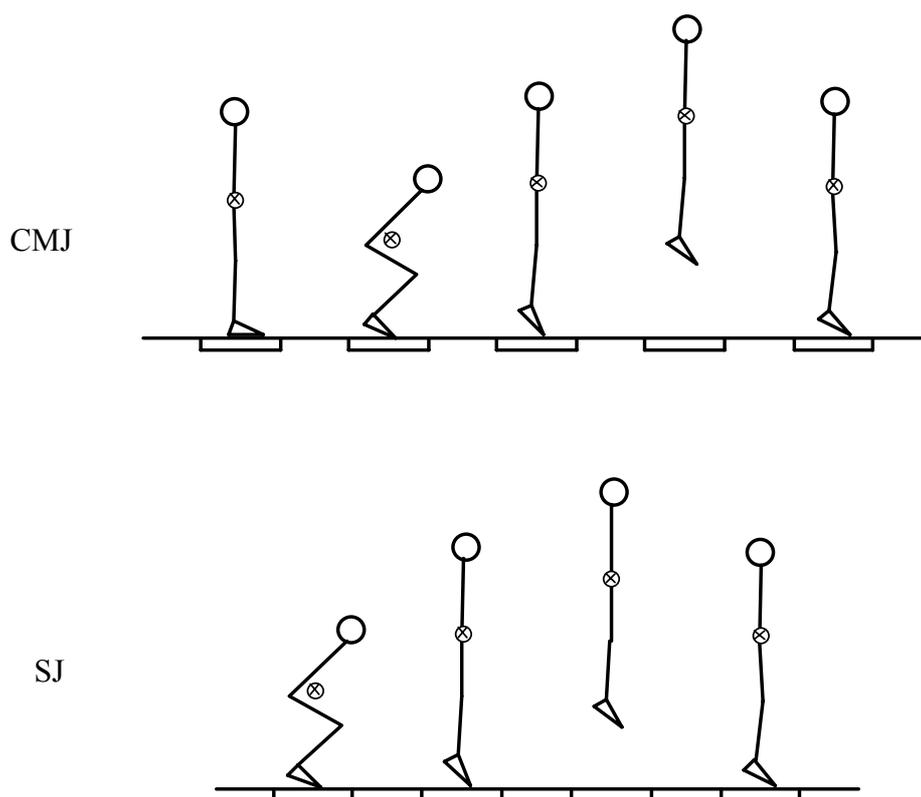

(Linthorne, 2001)

PROCEDURE

Go to one of the University computers and log on to the computer in the usual way.

Open a web browser (*Netscape* or *Internet Explorer*) and go to the "Laboratory Items" page on the *Biomechanics of Sport and Exercise* Blackboard site. **Vertical Jump.exe** is a stand-alone application for analysing vertical jumping, and it has two associated data files, **Countermovement Jump.dat** and **Squat Jump.dat**. Copy these 3 files from the Blackboard site to your computer hard disk. (I suggest you place the files in the **My Documents** folder.)

Start the application program by double-clicking on the **Vertical Jump.exe** icon. After a few seconds the **Vertical Jump** window will appear, but without any traces in the graph windows.
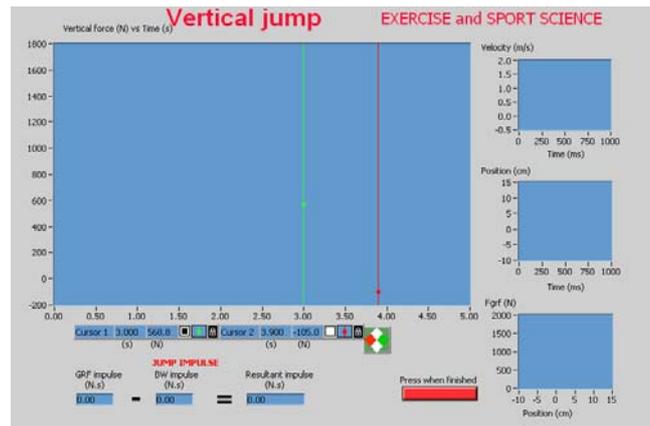
1. COUNTERMOVEMENT JUMP

From the **Operate** menu, select **Run**. The **Choose File to Read** window will appear. Select the countermovement jump data file (**Countermovement Jump.dat**) and click **Open**. The traces for a countermovement jump will appear.
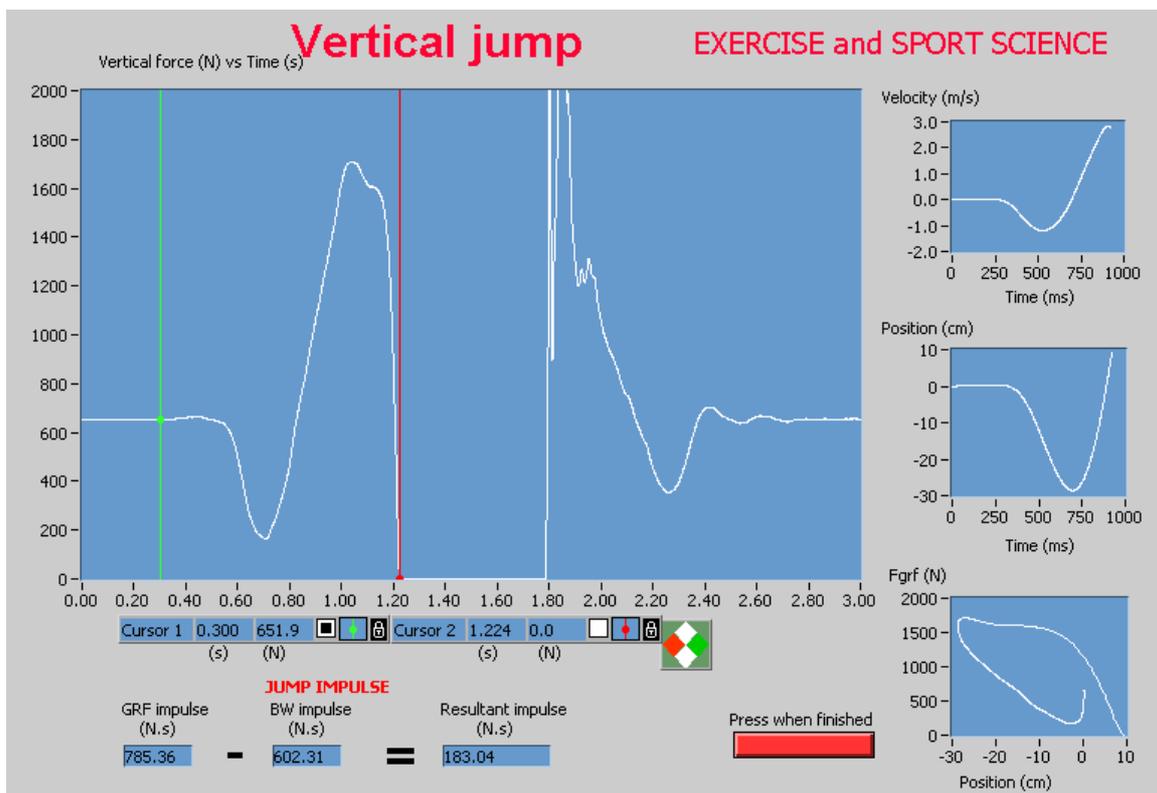
Force-Time Curve

The main graph shows vertical ground reaction force (in newtons) on the vertical axis, and time (in seconds) on the horizontal axis. Identify the following regions on the force-time curve:

- initial stationary position ($F_{GRF} = BW$)

- unweighting phase ($F_{GRF} < BW$)

- propulsion phase ($F_{GRF} > BW$)

- instant of take-off ($F_{GRF} = 0$ N)

- flight phase ($F_{GRF} = 0$ N)

- instant of landing

- the landing 'impact' force peak

- final stationary position ($F_{GRF} = BW$).

You might wish to enlarge the graph by changing the ranges of the time and force axes. Suggested ranges are 0.00 to 3.00 seconds, and 0 to 2000 N. Select the end value of the time axis (should be 5.00) by clicking with the mouse. Type in the new end value (3.00), then press the **Enter** key. Repeat for the force axis.

There are two coloured vertical lines (cursors) on the force-time graph. Click on one of the cursors with the mouse. Hold down the left-hand mouse button and drag the cursor to the left and right. The time (in seconds) and force (in newtons) corresponding to the positions of the cursor are displayed in the **Cursor 1** and **Cursor 2** boxes below the graph.

Trouble-Shooting (if you have problems)

When rescaling the time axis, make sure that the cursors are within the selected time interval, otherwise you will lose the cursors. If you find that you have lost a cursor, rescale the time axis to the original settings (0.00 to 5.00 seconds).

Minor software bug #1: Changing the time axis scale will reset the force axis scale to the original setting (0 to 4000 N).

Minor software bug #2: When the cursors are moved to the far left or right of the graph, the curve might scroll out of view. Reset the curve into view by typing the appropriate start and finish times (or forces) into the graph axes. (Don't forget to press the **Enter** key after inserting the values.)

Fixing Difficult Software Problems: If all else fails, click on the **Press when Finished** button, then select **Exit** from the **File** menu. Start the application program as before.

Vertical Velocity and Vertical Position Curves

There are three graphs to the right of the main force-time graph. These are graphs of:

- vertical velocity (in m/s) versus time (in milliseconds)

- vertical position (in cm) versus time (in milliseconds)

- vertical ground reaction force (in newtons) versus vertical position (in cm).

Consider only the first two graphs (velocity-time and position-time). These curves are obtained from calculations using the force-time data between the green (start) and red (finish) cursors.

Place the green cursor in a region of constant force ($F_{GRF} = BW$) just before the start of the jump. Place the red cursor slightly to the right of the green cursor. Slowly move the red cursor along the time axis and watch the curves of velocity-time and position-time. Stop when you reach the instant of landing.

Move the red cursor about, and accurately identify the following points:

- vertical velocity is greatest downwards (negative) during the countermovement
- vertical velocity is greatest upwards (positive)
- lowest point in the countermovement (vertical position is a minimum, and vertical velocity is zero)
- peak of the jump (vertical position is a maximum, and vertical velocity is zero).

Mark these points on the graph of the force-time curve below.
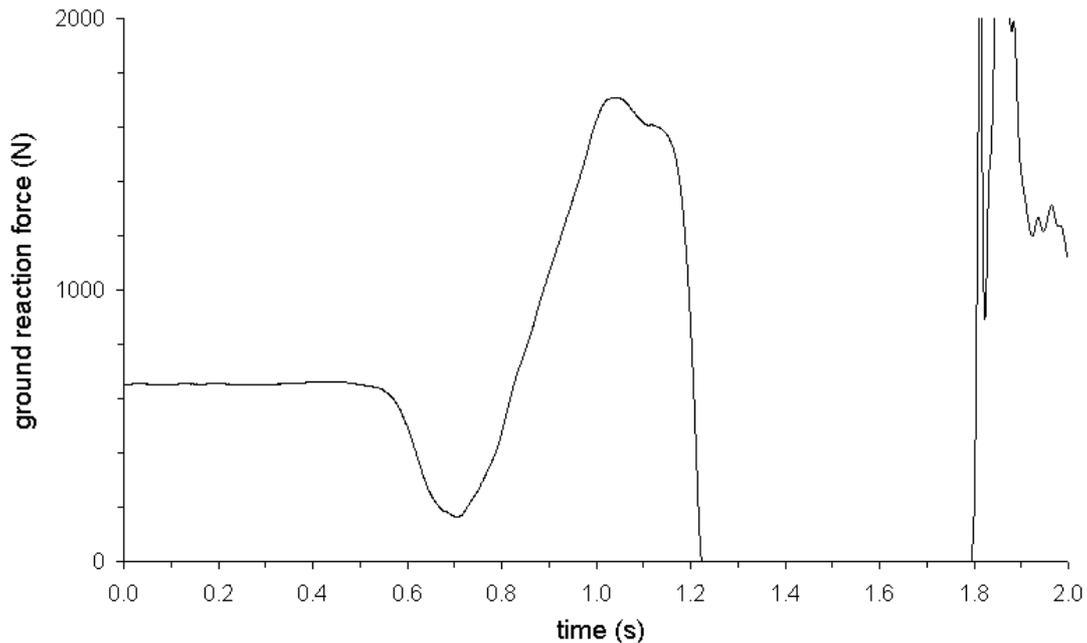
What is the jumper's vertical height at the instant of take-off? Is this what you expect?

Where on the force-time curve is the lowest point in the countermovement? Is this what you expect?

Why is the maximum vertical velocity just before take-off (and not at the instant of take-off)?

Force vs Vertical Position Curve

Place the green cursor in a region of constant force ($F_{GRF} = BW$) just before the start of the jump. Place the red cursor slightly to the right of the green cursor. Slowly move the red cursor along the time axis and watch the graph of force-position. This graph might take a while for you to interpret. Make sure you understand this graph.

Finish

When you have finished analysing the countermovement jump, click on the red **Press when Finished** button at the lower right of the **Vertical Jump** window.

2. SQUAT JUMP

From the **Operate** menu, select **Run**. The **Chose File to Read** window will appear. Select the squat jump data file (**Squat Jump.dat**) and click **Open**. The traces for a squat jump will appear. Go through the same analysis for the squat jump as was done for the countermovement jump.
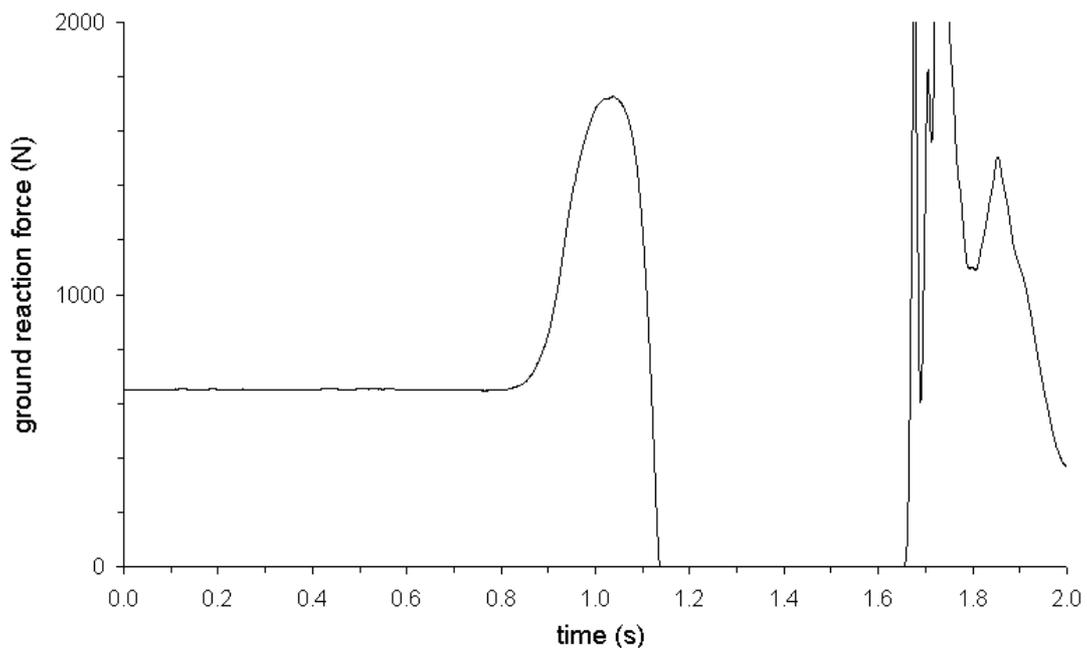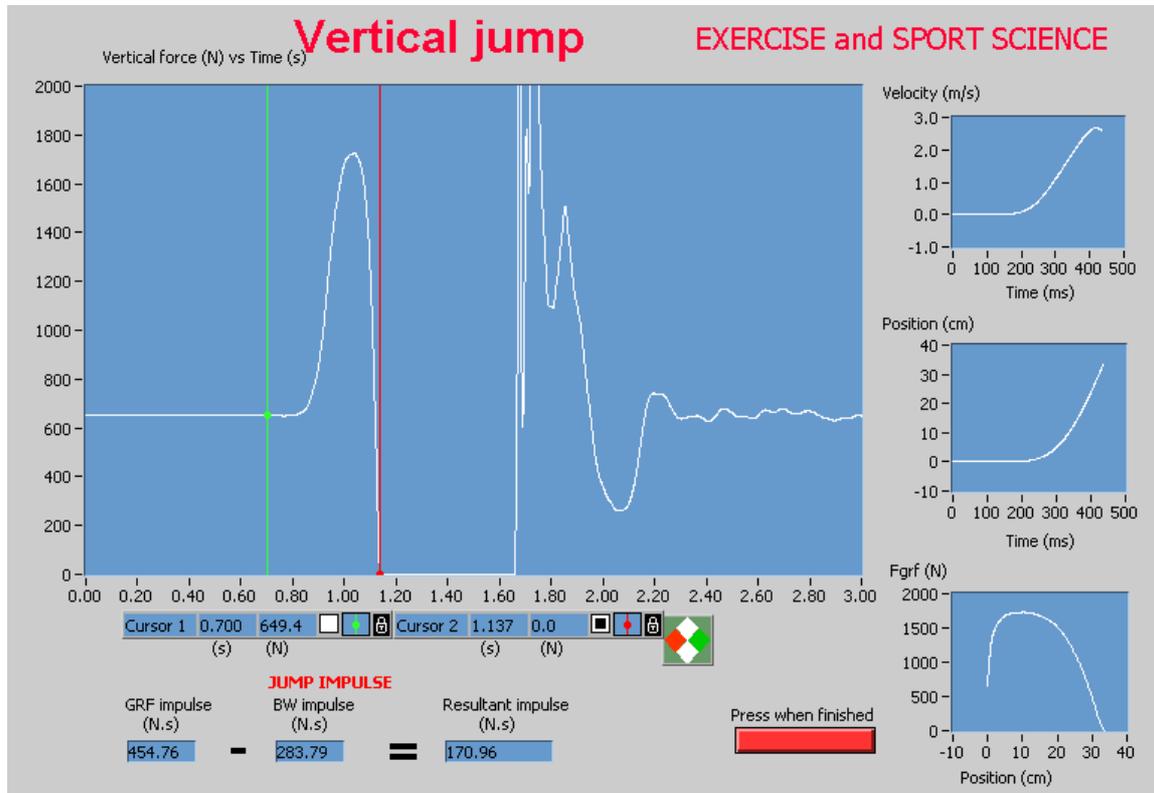
Finish

When you have finished analysing the squat jump, click on the red **Press when Finished** button at the lower right of the **Vertical Jump** window.

3. JUMP HEIGHT

Here, you will investigate two methods of calculating the height of the jump from the force platform data; (1) the flight time method, and (2) the impulse-momentum method. Both methods calculate the flight height from knowledge of the velocity of the jumper's c.m. at the instant of takeoff.

$+y$

y_{peak}, $v_{peak} = 0$

y_{flight}

$y_{take-off}$, $v_{take-off}$

take-off   *peak*
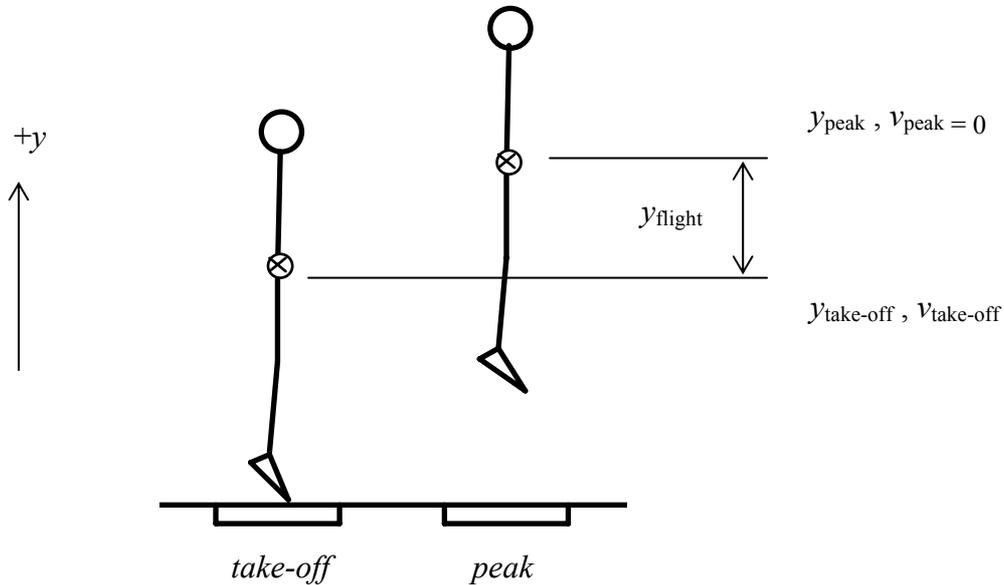
The relation between flight height y_{flight} and takeoff velocity $v_{take-off}$ can be obtained by applying the law of conservation of mechanical energy to the flight phase of the jump. The mechanical energy (E) of the jumper is the sum of the kinetic energy ($KE = \frac{1}{2}mv^2$) and gravitational potential energy ($PE = mgy$). In vertical jumping the effect of air resistance is negligible, and so in the flight phase the jumper can be considered as a projectile in free flight. The mechanical energy of the jumper at one instant is therefore the same as the mechanical energy at any other instant. We consider the changes in mechanical energy between the instant of takeoff (*take-off*) and the instant the jumper reaches the peak of the jump (*peak*).

$$E_{take-off} = E_{peak}$$

$$KE_{take-off} + PE_{take-off} = KE_{peak} + PE_{peak}$$

$$\tfrac{1}{2}mv_{take-off}^2 + mgy_{take-off} = \tfrac{1}{2}mv_{peak}^2 + mgy_{peak} \, .$$

The mass of the jumper can be cancelled from both sides of the equation, leaving

$$\tfrac{1}{2}v_{take-off}^2 + gy_{take-off} = \tfrac{1}{2}v_{peak}^2 + gy_{peak} \, .$$

At the peak of the jump the vertical velocity of the jumper is zero ($v_{peak} = 0$), so,

$$\tfrac{1}{2}v_{take-off}^2 + gy_{take-off} = gy_{peak} \, .$$

Rearranging gives,

$$y_{peak} - y_{take-off} = \frac{v_{take-off}^2}{2g} \, .$$

The flight height is then given by

$$y_{flight} = y_{peak} - y_{take-off} = \frac{v_{take-off}^2}{2g} \, . \tag{1}$$

That is, we can calculate the flight height of a jump if we know the jumper's take-off velocity.

Flight Time Method

The average acceleration, a, of a moving body is given by

$$a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$$

where v_1 and v_2 are the velocities at some initial and final times, t_1 and t_2. For a body in free flight the acceleration is the acceleration due to gravity, $a = -g$. Here, we let the initial time be the instant of takeoff and the final time be the instant of landing, and so the time of flight of the jump is $t_{\text{flight}} = t_2 - t_1$. The equation above then becomes

$$-g = \frac{v_2 - v_1}{t_{\text{flight}}}.$$

If we assume the height of the jumper's c.m. at the instant of landing is the same as at the instant of takeoff, then $v_2 = -v_1$, and so the takeoff velocity of the jumper is given by

$$-g = \frac{-2 v_1}{t_{\text{flight}}}$$

$$\therefore \quad v_1 = \frac{g \, t_{\text{flight}}}{2}$$

$$v_{\text{take-off}} = \frac{g \, t_{\text{flight}}}{2} \tag{2}$$

where we have made the substitution, $v_1 = v_{\text{take-off}}$. That is, we can calculate the jumper's take-off velocity from a measurement of the flight time of the jump (using a force platform).

Exercise: Use equations (1) and (2) to find an expression for the flight height in terms of the flight time.

$$y_{\text{flight}} = \tag{3}$$

That is, we can also calculate the flight height of a jump directly from the flight time.

Use the cursors on the force-time curve to determine:

jumper's body weight	$BW = mg$	= _____	N
flight time of countermovement jump (CMJ)	t_{flight} =	_____	s
flight time of squat jump (SJ)	t_{flight} =	_____	s

Calculate the take-off velocity and flight height for the two jumps:

For the countermovement jump (CMJ):

take-off velocity	$v_{\text{take-off}}$	= _____	m/s
flight height	y_{flight}	= _____	m

For the squat jump (SJ):

take-off velocity $v_{\text{take-off}}$ = _____ m/s

flight height y_{flight} = _____ m

Examine your values of the jumper's body weight, flight time, take-off velocity, and flight height. Do they seem reasonable? Compare the flight heights for the countermovement jump and the squat jump. Is this what you expect? Explain any differences.

Impulse-Momentum Method

The general form of the impulse-momentum relation is

$$\vec{J} = \int_{t_1}^{t_2} \vec{F}\, dt = m\,\vec{v_2} - m\,\vec{v_1}$$

where $\vec{J}$ is the impulse of a resultant force $\vec{F}$ acting on a body over a time interval t_1 to t_2. The impulse causes a change in the momentum (mv) of the body, where m is the mass of the body and v_1 and v_2 are the initial and final velocities of the body.

If you are unfamiliar with the concept of an 'integral', the most important point to remember is that $\int_{t_1}^{t_2} \vec{F}\, dt$ means "the area under the F versus t curve, between the times t_1 and t_2".

In a standing vertical jump, the forces and motion are in the vertical direction. The resultant vertical force on the jumper is $F = F_{\text{GRF}} - mg$, where F_{GRF} is the vertical ground reaction force exerted on the jumper and mg is the jumper's body weight.

Here we wish to find the take-off velocity of the jumper. We can use the impulse-momentum to find the take-off velocity if we let the initial time be the start of the jump and the final time be the instant of takeoff. The impulse-momentum relation in the vertical direction for a standing vertical jump is then

$$J = \int_{t_{\text{start}}}^{t_{\text{take-off}}} (F_{\text{GRF}} - mg)\, dt = m\,v_{\text{take-off}} - m\,v_{\text{start}}$$

At the start of the jump the jumper is stationary ($v_{\text{start}} = 0$), so

$$J = \int_{t_{\text{start}}}^{t_{\text{take-off}}} (F_{\text{GRF}} - mg)\, dt = m\,v_{\text{take-off}}$$

The impulse due to the resultant force ($F_{\text{GRF}} - mg$) can be considered as two separate impulses;

$$J = \int_{t_{\text{start}}}^{t_{\text{take-off}}} F_{\text{GRF}}\, dt - \int_{t_{\text{start}}}^{t_{\text{take-off}}} mg\, dt = m\,v_{\text{take-off}}$$

which becomes

$$J = J_{\text{GRF}} - J_{\text{BW}} = m\,v_{\text{take-off}} \tag{4}$$

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where J_{GRF} is the impulse due to the vertical ground reaction force, and J_{BW} is the impulse due to body weight.

That is, if we measure the impulse due to the ground reaction force (J_{GRF}), and subtract the impulse due to body weight (J_{BW}), we will be able to calculate the jumper's take-off velocity ($v_{take-off}$).

On the graphs of the CMJ and SJ below, mark clearly the impulse due to the ground reaction force, J_{GRF}, and the impulse due to body weight, J_{BW}, by shading the appropriate area on the graph. (You need to take care in deciding upon the appropriate initial and final times. The impulse due to the ground reaction force should be relatively straight forward. However, the body weight curve is not shown on the graph, so you will have to add a body weight curve and then shade the appropriate area between the appropriate initial and final times.)
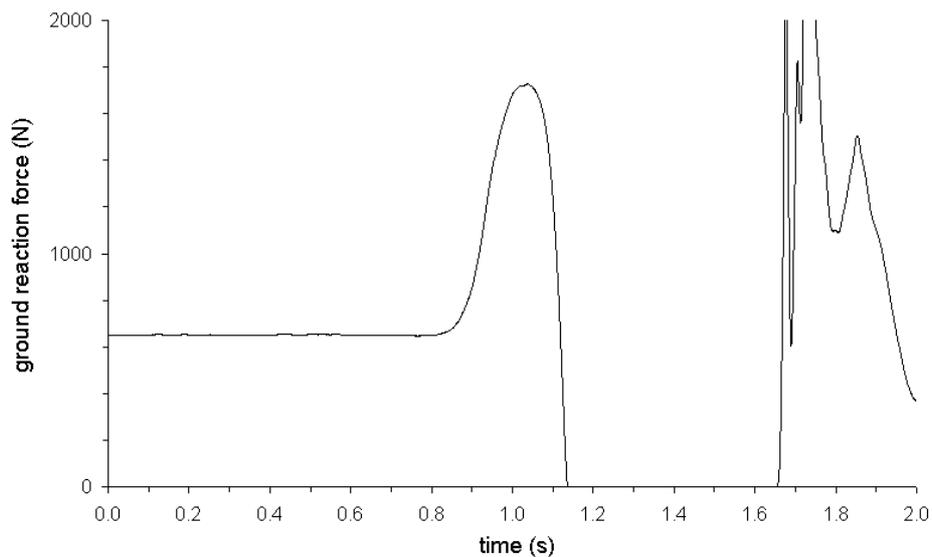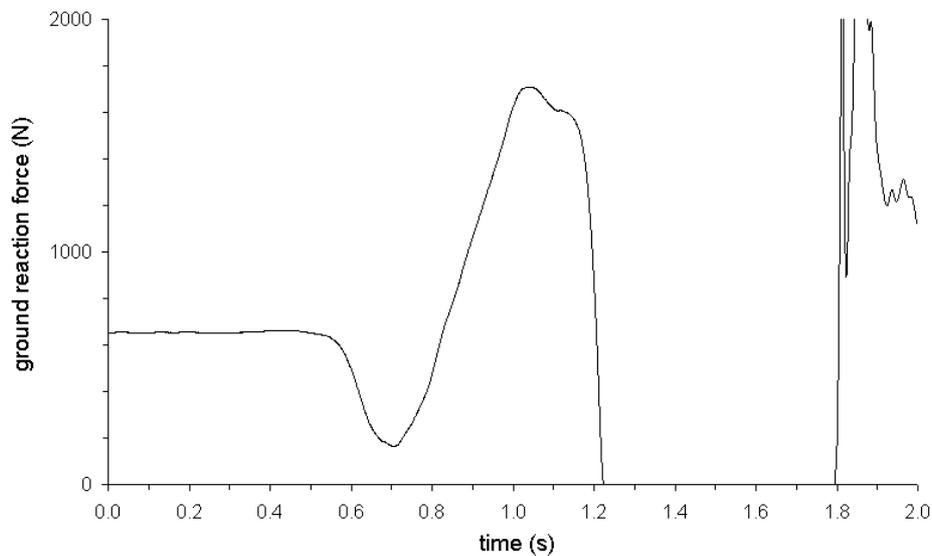
On the computer screen just below the force-time graph are boxes showing the values of the impulse of the ground reaction force (J_{GRF}), the impulse due to body weight (J_{BW}), and the resultant impulse (J). Use the cursors on the force-time curve to determine J_{GRF}, J_{BW}, and J, then use the impulse-momentum relation to calculate the take-off velocity and flight height of the two jumps.

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For the countermovement jump (CMJ):

impulse due to ground reaction force J_{GRF} =   _____   N·s

impulse due to body weight J_{BW} =   _____   N·s

impulse due to resultant vertical force J =   _____   N·s

take-off velocity $v_{take-off}$ =   _____   m/s

flight height y_{flight} =   _____   m

For the squat jump (SJ):

impulse due to ground reaction force J_{GRF} =   _____   N·s

impulse due to body weight J_{BW} =   _____   N·s

impulse due to resultant vertical force J =   _____   N·s

take-off velocity $v_{take-off}$ =   _____   m/s

flight height y_{flight} =   _____   m

Examine your values of the jumper's take-off velocity and flight height. Do they seem reasonable? Compare the values obtained using the impulse-momentum relation to those obtained using the flight time method. Explain any differences.

How do you think the computer did the calculations of impulse? That is, how does a computer find the area under a graph? (Computers perform complex calculations by doing lots of simple calculations very quickly.)

References
Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform, *American Journal of Physics*, *69*, 1198–1204.