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# Engage Your Physics Students with Vernier Video Analysis

Experiments

**Projectile Motion**

**Analysis of Jumping**

Workshop Presenter

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# Projectile Motion

## Introduction

Up to this point it is likely that you have examined the motion of an object in one dimension only—either falling vertically under the influence of Earth's gravity or on a horizontal or inclined surface.

In this experiment, you will examine the behavior of a projectile—an object moving in space due to some initial launching force. Such an object can undergo motion in two dimensions simultaneously. Using the Vernier Video Analysis app, you will compare features of the position *vs.* time and velocity *vs.* time graphs with those of one-dimensional motion.

## Objectives

In this experiment, you will

- Use video analysis techniques to obtain position, velocity, and time data for a projectile.
- Analyze the position *vs.* time and velocity *vs.* time graphs for both the horizontal and vertical components of the projectile's motion.
- Create and analyze your own video of an object undergoing projectile motion.

## Materials

Vernier Video Analysis app in a web browser on a computer, Chromebook, **or** mobile device  
camera capable of recording digital video (e.g., the camera on a phone or tablet)  
tripod or other equipment to support the device used to record the video  
meter stick or some other object to provide scale  
projectile: a brightly-colored ball works well  
video editing software (optional)

## Pre-Lab Investigation

Your instructor will launch a projectile. Observe its motion carefully, then discuss its position *vs.* time and velocity *vs.* time behavior. Sketch a graph of the projectile's horizontal velocity *vs.* time, and sketch another graph of vertical velocity *vs.* time. Share your sketched graphs with your group or with the class.

## Procedure

### Part 1 Analysis of an existing video

1. Launch Vernier Video Analysis. Import the movie "Basketball Shot." Play the movie once so you can be familiar with the motion. You will analyze the video in the steps that follow.
2. Make the movie window large enough to easily see the projectile. There are two ways to do this: 1) Click or tap the handle on the divider between the video and the other elements on the screen, and drag the divider to the right, or 2) use View,  $\square$ , to remove the graph and data table from view.
3. Click or tap Reset Video,  $\blacktriangleleft$ , and then use Step Forward,  $\blacktriangleright$ , and Step Back,  $\blacktriangleleft$ , to advance the movie to the frame in which the ball is released from the person's hands.
4. Set the origin and the scale in the video.
  - a. Click or tap System,  $\uparrow$ . You will see new icons appear for Scale and Origin. Scale,  $\frac{m}{s}$ , is already selected.
  - b. Move the centers of the scale circles to align with the ends of the meter stick in the movie.
  - c. Verify that the length and units are set correctly (should be 1 m).
  - d. Click or tap Origin,  $\odot$ . Drag the axes to set the location of the origin. In this video, the origin is the location of the ball in the frame when the ball leaves the person's hands.
5. You will be marking the location of the basketball as it moves during the video. By default, each time you mark the object's location, the movie advances by just one frame. For this video analysis, it is better if the movie advances more quickly.

To change the setting, click or tap Advanced Video Options,  $\star$ . Change the Advance Frames setting to 2 or 5 frames, and then dismiss the window to save your changes.

6. Mark the location of the basketball as it moves during the video.
  - a. Click or tap Add,  $\dagger$ .
  - b. Decide where on the basketball you will mark its location (e.g., center, top edge, or other). It is important to be consistent when marking the location; always place the crosshairs on the same location on the ball.
  - c. Position the crosshairs at the chosen location on the ball, and then click or tap to add the first point. **Note:** If you are using a phone or tablet, once you place the crosshairs you can click or tap anywhere in the video frame.
  - d. Continue this process to the end of the movie. Should you wish to edit a point, click or tap Edit,  $\mathbb{R}$ . This allows you to move or delete a mismarked point. **Note:** In order to be sure you are moving the correct dot, click or tap Trails,  $\cdot$ , to hide all the marked points except the one in the frame you are viewing.
7. Use View,  $\square$ , to display the graph, and hide the video and data table.
8. Vernier Video Analysis defaults to display both the  $x$  and  $y$  positions of the object as a function of time. You may find it easier to examine the position vs. time graph of just one of

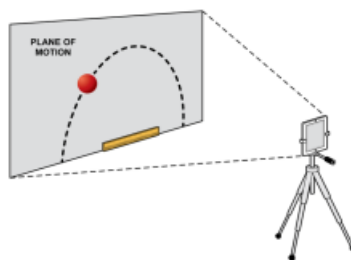
these components at a time. To change which data are displayed on a graph, click or tap the vertical axis label to open the Plot Manager. Turn off the y position (Y) data.

9. Do Part 1 of the Analysis, then return to Part 2 to continue with the procedure.

## **Part 2 Production and analysis of your own video**

For this part, you need a device capable of recording video such as a digital camera or smartphone; it can be the same device you used in Part 1 for Vernier Video Analysis. Keep the following tips in mind when you shoot your video.

- It is best to have a plain background that provides sufficient contrast with the object you are investigating. Good lighting is essential; recording outside on a cloudy day will provide better light than recording inside.
- Set up the device on a tripod so that it is pointed squarely at the background, and so that the plane of motion is perpendicular to the view.
- Position the camera as far from the plane of motion as is practical in order to reduce problems with scaling and parallax. Use the zoom feature to fill the screen with the motion.
- The object used for scaling must be in the same plane as the motion of the projectile (see Figure 1).



*Figure 1*







- Once you have captured your video, transfer the video to the device you will use for the analysis, if necessary. Optional: If you have captured more video than you need, trim the video to contain just the motion you plan to analyze.
10. Capture video of your object undergoing projectile motion.
  11. Import your movie into Vernier Video Analysis.
  12. Follow Steps 2–8 of Part 1 of the Procedure, and then complete the analysis.

## **Analysis**

### **Part 1 Analysis of an existing video**

1. Examine the graph of  $x$  position vs. time. If it appears to be linear, fit a straight line to your data. If the slope of the graph appears to change abruptly, select each segment, one at a time, and fit separate straight lines to each portion of the graph that appears to be linear.
  - a. Click-and-drag or touch-and-drag across the graph to select the portion of the graph that appears linear.

## ***Projectile Motion***

- b. Click or tap Graph Tools, , choose Apply Curve Fit, and apply a linear curve fit.
    - c. Repeat Steps a and b for additional linear regions of the graph, if desired.
  2. Write the equation that describes the  $x$  position *vs.* time behavior of the ball in each segment; be sure to include units.
  3. Based on what you have learned in previous experiments, write a description of the horizontal component of the motion of the projectile. Note when any change in the horizontal component of the motion occurs.
  4. Now, examine the graph of  $y$  position (Y) *vs.* time.
    - a. Click or tap the vertical axis label to open the Plot Manager. Turn on the  $y$  position and turn off  $x$  position.
    - b. Fit an appropriate curve to this graph (or to each portion of the graph). To do this, click or tap Graph Tools, , choose Apply Curve Fit. Select the curve fit model that best fits your data, and apply the curve fit.
    - c. Write the equation that describes the  $y$  position *vs.* time behavior of the ball in the first segment; be sure to include units.
  5. Based on what you have learned in previous experiments, write a description of the vertical component of the position of the projectile.
  6. Now, to test your analysis in Step 5, examine the graph of  $y$  velocity *vs.* time.
    - a. Click or tap the vertical axis label to open the Plot Manager. Turn on  $y$  velocity (Y Velocity) and turn off  $y$  position.
    - b. Click-and-drag or touch-and-drag across the graph to select the portion of the graph that appears linear.
    - c. Click or tap Graph Tools, , choose Apply Curve Fit, and apply a linear curve fit. Fit a straight line to the first portion of the graph only, if there are multiple linear regions.
    - d. Repeat Steps b and c for additional regions of the graph, if desired.
  7. What can you say about the rate of change of the  $y$  velocity as a function of time? How does the value of the slope of the linear fit compare to the acceleration of a freely falling object? Summarize in a sentence or two.
  8. Compare the  $a$  and  $b$  parameters (including values and units) of the curve fits you performed in Step 4 to the slope and intercept of the linear fit you performed in Step 6.
  9. Explain the differences in the horizontal and vertical components of the velocity of the projectile in terms of the force(s) acting on the projectile after it was launched.
  10. Display the velocity vectors for the motion of the projectile, and then explain how the vectors correspond to the motion of the projectile in the vertical and horizontal directions. To display the velocity vectors, follow these steps:
    - a. Use View, , to display the video if it is hidden.
    - b. Click or tap Vectors, , to add a vector display. (Click or tap Add, , if the Vectors option is not visible.)

- c. Enable the velocity vectors only. To do this, click or tap the visibility toggle next to Velocity until Components,  $\mathbf{v}$ , is displayed.
- d. Adjust the Scale Factor and Vector Frequency so you can clearly see the vectors.
- e. Explain how the displayed vectors correspond to the motion of the projectile in the vertical and horizontal directions that you have also described with graphs and equations.

## **Part 2 Production and analysis of your own video**

11. Perform the analysis of your movie as you did with the video provided to you in Part 1.

## **Extensions**

1. Suppose that, in the shooting of your video, you placed the meter stick used for scaling against the wall you used for your background. However, the plane of the ball's motion was 0.50 m in front of the wall. The distance between the camera and the wall was 5.0 m. Would this error result in a value for the acceleration of gravity in your analysis of the  $y$  velocity *vs.* time graph that was smaller or larger than the accepted value? By what factor would this value differ from the expected value? Explain using a diagram.
2. Repeat the production and video analysis of a projectile, but this time use an extended body (i.e., an object that cannot be readily modeled by a point-particle). Consider carefully how best to mark the position of such an object during its motion. Interpret your position *vs.* time and velocity *vs.* time graphs as you did for Part 1.
3. Using either the analysis of the basketball shot sample video or the analysis of the video you created, model the vertical motion based on ideal conditions. Create a new calculated column and use the initial upward velocity of the object and the acceleration of gravity to calculate the ideal vertical velocity. Use the graph to compare the video-based velocities with the model-based velocities. Suggest reasons for any discrepancies.

**Note:** Instructions for creating a calculated column are found in the Vernier Video Analysis User Manual, <http://www2.vernier.com/manuals/video-analysis-manual.pdf>





# Analysis of Jumping

## Introduction

Vertical jump tests are often used by physical trainers to assess leg strength. Simple alterations in the way a vertical jump is performed can alter the amount of force that is produced during the jump, affecting the results. A common testing technique is to have a subject perform a standing vertical jump. To limit interactions from the upper body, the subject may be asked to perform the vertical jump with the arms restricted. This restricted jump is also referred to as a squat jump. To do a restricted jump, the subject keeps their hands on their hips or waist when performing the vertical jump.

Force plates are often used to measure the peak force in these types of strength tests, but force plates can give counterintuitive results. For example, a large person can produce a good deal of force, but they may not be able to jump as high or accelerate as fast as a smaller person. Therefore, in some situations, peak acceleration may be a better measure of leg strength. If you know the peak acceleration, you can use the subject's mass to calculate peak force without the need for a force plate.

The jumping motion can be divided into four distinct phases: the preparatory phase where the subject crouches in preparation for the jump, the push phase where the subject pushes off the ground, the rising phase where the subject's feet have left the ground and the subject rises until they reach a maximum height, and the falling phase where the subject falls back to the ground. Using vertical motion data associated with the push and rising phases of a vertical jump, you can determine several factors commonly used to measure the leg strength of a test subject.

In this experiment, you will use Vernier Video Analysis app to examine the motion of a test subject performing two standing vertical jumps. The first jump will be a restrictive jump where the test subject holds their hands on their waist during the jump. The second jump will be a full vertical jump where the test subject's arms and hands are free to move. Using the analysis features in the app, you will compare the vertical displacement, as well as the peak accelerations and peak forces generated during these two jumps from the provided video. As time permits (or as required by your instructor), you can complete one or more of the extensions or design your own investigation using videos of jumps that you record.

## Objectives

- Use video analysis techniques to obtain position, velocity, and time data for a human subject jumping.
- Analyze the  $y$  position and  $y$  velocity vs. time graphs for the subject as they jump in two different ways.
- Calculate acceleration using a calculated column to find the maximum acceleration during each jump.
- Use the mass of the subject to calculate peak force during each jump.
- [Extensions] Create and analyze your own videos of a person jumping in different ways.

## Materials

Vernier Video Analysis App in a web browser on a computer, Chromebook, or mobile device

"Jump-Restricted" video file

"Jump-Full" video file

## Pre-lab Investigation

Your instructor will select a volunteer to perform a standing vertical jump with their hands on their hips or waist. The test subject should stand with their side facing the class so everyone can clearly see their legs bend and then straighten during the jump.





Observe the motion of the jump carefully. Sketch and discuss position *vs.* time and velocity *vs.* time graphs that include all four phases of the vertical jump: preparatory, upward push, rising, and falling. Compare your graphs with those created by the other people in your group as well as your classmates.

## Procedure

### Part 1 Restricted Jump



1. Launch Vernier Video Analysis and import the movie "Jump-Restricted". Play the movie once or twice so you are familiar with the motion.
2. Make the movie window large enough to easily see the subject. There are two ways to do this: 1) Click or tap the handle on the divider between the video and the other elements on the screen, and drag the divider to the right, or 2) use View,  $\square$ , to remove the graph and data table from view.
3. Use Step Forward,  $\rightarrow$ , and Step Back,  $\leftarrow$ , to advance the movie to the frame where the subject is fully crouched and just begins to move up vertically during the jump. This is the beginning of the upward push phase of the jump.
4. Set the origin and the scale in the video.
  - a. Click or tap System,  $\updownarrow$ . You will see new icons appear for Scale and Origin. Scale,  $\updownarrow$ , is already selected.
  - b. Move the centers of the scale circles to align with the ends of the red bar closest to the subject. The red bar is 2 meters in length, so adjust the displayed length to 2 m.
  - c. Click or tap Origin,  $\odot$ . Drag the axes to set the location of the origin, which in this video is at the base of the subject's feet.
  - d. Rotate the axes about the origin so that the X axis is parallel to the red bar.
5. You will be marking the location of the subject as they jump during the video. By default, each time you mark an object's location, the movie advances by just one frame. For this video analysis, it is better if the movie advances more quickly.

To change the setting, click or tap Advanced Video Options, . Change the Advance Frame setting to 5 frames, and then dismiss the window to save your changes.

6. Mark the location of the subject as they move during the jump.
  - a. Click or tap Add, .
  - b. Click or tap Trails, , to hide all marked points except the one in the frame you are viewing. This will make it easier to mark your points.
  - c. The subject is wearing black pants with white stripes on the thigh. Locate where the center stripe ends at the waist, and use this point as your marking position of the subject. It is important to be consistent when marking the location; always place the crosshairs on the same location on the subject.
  - d. Position the crosshairs at the chosen location on the subject, and then click to add the first point. **Note:** If you are using a phone or tablet, once you place the crosshairs you can click or tap anywhere in the video frame.
  - e. Continue marking points through the entire rising phase of the jump. To help with analysis, mark at least three points of the descent (after the subject has reached the peak height).
  - f. Review your marked points. Should you wish to edit a point, click or tap Edit, . This allows you to move or delete a mismarked point.
7. Use View, , to display the video and graph, and hide the data table. Click-and-drag or tap-and-drag the divider between the video and graph so you can easily see both elements.
8. Vernier Video Analysis defaults to display both the  $x$  and  $y$  positions of the object as a function of time. For a vertically moving object like the vertical jumper, you want to examine the graph of the  $y$  component only. Click or tap the vertical axis label on the graph to open the Plot Manager. Turn off the X column so only  $y$  position (Y) vs. time is plotted.
9. Save your Video Analysis file.
10. Do Part 1 of the Analysis, then return to Part 2 to continue with the procedure.






## **Part 2 Full Jump**


In this part, you will analyze a video that shows the same subject performing a full vertical jump in which their hands are free to move.

11. Click or tap File, , choose New Experiment, and import the movie "Jump-Full". Play the movie once or twice so you are familiar with the motion.
12. Repeat Steps 2–8 to analyze the full jump video. **Note:** If needed, use Step Forward, , to skip past a frame (without marking a point) when the subject's waist is blocked by his arm.
13. Save your Video Analysis file, then continue with Part 2 of the Analysis.

# Analysis

## Part 1 Restricted Jump

1. Examine the graph of  $y$  position (Y) vs. time.
  - a. Describe the motion of the subject over the course of the rising phase of the jump. Do you see regions of the graph where the subject accelerated? Explain how you know the jumper is accelerating.
  - b. Tap on the point on the graph that corresponds to the maximum displacement of the hips (height).
  - c. Drag the Examine line back and forth around this point. Observe and note what is happening in the video. With respect to the phases of a jump, what is the significance of this point in the jump? Pay close attention to the feet and knees. Are the feet at their highest point for the jump? Look at the knees; are the legs tucked in or are they fully extended?
  - d. Dismiss the Examine line. Click or tap Graph Tools, , and select View Statistics. Record the vertical amplitude of the jump ( $\Delta y$  from the statistics details), then dismiss the Statistics details box.
2. Examine the graph of  $y$  velocity (Y Velocity) vs. time.
  - a. Click or tap the vertical axis label on the graph to open the Plot Manager. Turn off the Y column and turn on the Y Velocity column so only  $y$  velocity vs. time is plotted.
  - b. Tap on the point on the graph that corresponds to the maximum velocity.
  - c. Drag the Examine line back and forth around the maximum velocity. Observe and note what is happening in the video at maximum velocity. With respect to the phases of a jump, what is the significance of this point in the jump? Pay close attention to the feet and knees. Are the feet still on the ground? Are the legs still crouched or are they fully extended?
  - d. Dismiss the Examine line. Click or tap Graph Tools, , and select View Statistics. Record the maximum velocity then dismiss the Statistics details box.
3. Create a calculated column to find the  $y$  acceleration of the subject as they jumped.
  - a. Use View, , to add the data table to your display.
  - b. In the data table, click or tap Column Options, , for Y Velocity and choose Add Calculated Column.
  - c. Enter **Y Acceleration** as the name of the column and **m/s<sup>2</sup>** as the units.
  - d. Select Insert Expression. Choose 1st Derivative (Y, X).
  - e. Verify that Y Velocity has been selected for the Column Y box and that Time has been selected for the Column X box.
  - f. Click or tap Apply.
4. Examine the graph of  $y$  acceleration (Y Acceleration) vs. time.
  - a. Use View, , to remove the data table from your display.
  - b. Click or tap the vertical axis label on the graph to open the Plot Manager. Turn on the Y Acceleration column and turn off all other columns so only  $y$  acceleration vs. time is plotted.

- c. Tap on the point on the graph that corresponds to the maximum acceleration.
  - d. Drag the Examine line back and forth around the maximum acceleration. Observe and note what is happening in the video. In which phase of the jump is the subject? Are they in the beginning, middle, or end of that phase? Pay close attention to the feet and knees. Are the feet still on the ground? Are the legs still crouched or are they fully extended?
  - e. Dismiss the Examine line. Click or tap Graph Tools, , and select View Statistics. Record the maximum acceleration of the jump, then dismiss the Statistics details box.
5. Calculate the peak force during the jump using the formula  $\Sigma F = ma$ . Assume that the subject in the video has a mass of 70 kg.
  6. Save your Video Analysis file.

## **Part 2 Full Jump**

7. Repeat Analysis Steps 1–5 for the full jump.
  - a. Compare the position of the feet and knees for the full jump and the restricted jump for these conditions:
    - i. The jumper is at the highest point in the jump.
    - ii. The jumper's maximum Y Velocity.
    - iii. The jumper's maximum Y Acceleration.
  - b. Note the position and direction of motion of the arms for the conditions noted above.
  - c. Record the following values for the full jump.
    - i. The vertical amplitude ( $\Delta y$ ) of the jump.
    - ii. The maximum velocity achieved during the jump.
    - iii. The maximum acceleration achieved during the jump.
    - iv. The peak force during the jump.
  - d. Do the graphs for the full jump appear similar to the graphs you observed for the restricted jump? If not, how are they different?
8. Compare the vertical amplitude, maximum velocity, maximum acceleration, and peak force for the two jumps. Does a restricted jump appear to change the maximum acceleration and peak force generated during a vertical jump? Explain why you think that is.
9. Save your Video Analysis files.

## **Extensions**

Many of the extensions involve making your own video of a subject jumping. You will need either a digital camera or some other device capable of recording video; it can be the same device that is running Vernier Video Analysis. Ask your instructor for additional tips for making your own videos. Your instructor can find these in Appendices A and B of this book.

## *Analysis of Jumping*

### **Production and analysis of your own video**

- Once your jumper has been selected, have them practice jumping vertically a couple of times. Make sure the subject uses proper technique when jumping.
- Verify that the vertical jumps can be captured on video.
- Because the jumps happen quickly, you should use the "slow motion" video capture feature on your device. You will want to make sure you can capture the entire video sequence at the same frame rate using "slow motion" before starting your experiment.

Investigate one of these extension ideas, or design your own experiment to investigate.

1. Compare the effect of jumping off a small stool and then performing the vertical jump. A step stool should work for this exercise. Have the subject jump off the step stool, land, crouch, and then perform a vertical jump. This should be done as quickly as possible. Only analyze the rising phase of the vertical jump. Compare the results to Parts 1 and 2 of this exercise. Explain your results.
2. Analyze vertical jumps of a subject wearing a 5–10 lb weight vest. Record any change in velocity, acceleration, and force that occurs when the subject's weight is increased while performing a vertical jump.
3. Analyze a running vertical jump. Have the subject sprint and then perform a vertical jump or leap. Have the subject leap as high as they can into the air. Use the analysis steps in Part 1 to analyze the vertical amplitude, maximum velocity, maximum acceleration, and peak force produced when performing a running vertical jump.
4. Compare a person performing a layup in basketball to a running vertical jump. If you know of someone who can "dunk" a basketball, investigate the vertical velocity and acceleration when performing a "dunk." Compare the results you find to the results when performing a running vertical jump. Use the same subject for comparisons.
5. Investigate the role of crouching on peak acceleration. Does the depth of the crouch produce a greater acceleration? Design an experiment that investigates this question.
6. Use the provided videos or create your own to investigate the motion of the knee during a jump. How do the maximum displacement, velocity, and acceleration of the knee compare to that of the waist?
7. Use the provided videos or create your own to investigate the motion of the ankle during the jump. How does the maximum displacement, velocity, and acceleration of the ankle compare to the knee and the waist?
8. Use the provided "Jump-Full" video or create your own to investigate the motion of the elbow or hand during the jump. Determine when peak velocity and acceleration happens for the elbow or hand. Compare this to when peak velocity and acceleration happens for the waist.
9. Compare vertical jumps where the legs are kept relatively straight during the jump to jumps where the legs are tucked under the jumper.
10. Compare jumps from athletes that participate in different sports.