Arthropod Olympics

Stacked Graphs and Biophysics with Spring-Loaded Arthropods

Image and caption from article "Arthropod Olympics" on ScienceNews by A Smith.
"Backflipping arthropods called globular springtails can vault themselves up to 60 millimeters high and spin up to 29 times in the blink of an eye. Two springtails jump off a platform in a lab in this high-speed camera footage."

A data activity and lesson plan made in partnership with

ScienceNewsLearning

Teacher Note:
This activity is best used as a way for students to explore the researcher's data like the scientists themselves. A suggested progression includes:

1) Have students read the Science News article and use the Science News Learning discussion to review how the research team collected data by analyzing high-speed footage.
2) Have students complete this DataClassroom Activity
3) Use the Science News Learning activity as an extension or assessment to have students design an experiment to measure another Olympic-worthy arthropod.

Note that this activity is not meant as a thorough introduction to stacked graphs in physics, but rather as an opportunity for students to practice their application in the context of data analysis.

Background

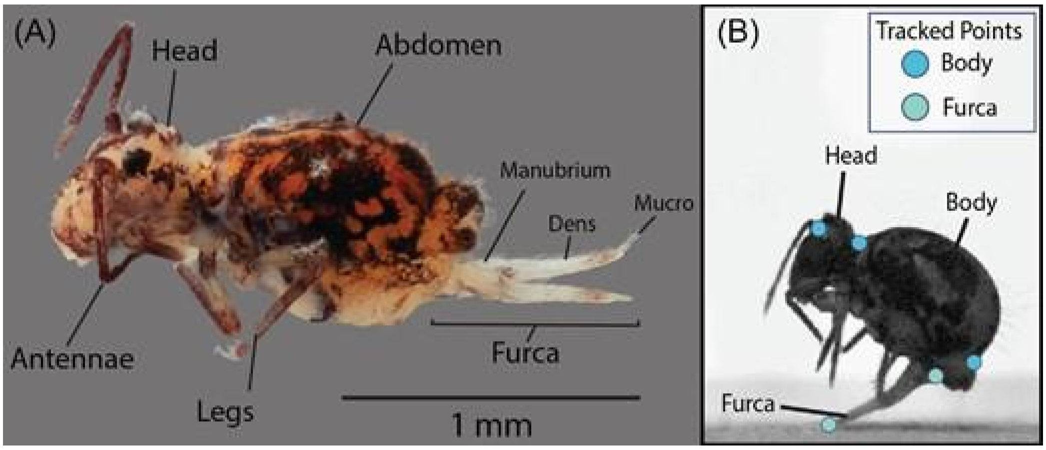
Evolution has produced a stunning diversity of ways that an animal can move. Jumping, running, climbing, sliding, slithering, swimming, walking, and drifting are just a few of the myriad of ways that animals move through the different environments on our planet. Biomechanists are scientists that explore this diversity of animal movement in a physics-heavy branch of biology that specializes in describing the ways that animals move. Photography has long been an important tool in biomechanics studies, but high speed photography has given scientists more power than ever before to record and analyze fast animal movements in great detail.

The spinning jump of the tiny springtail, *Dicyrtomina minuta*, is an extraordinary example of animal movement. Most springtails are omnivors, live in moist soil and leaf litter, and can be recognized by their furca . This forked tail-like appendage protrudes from the abdomen and allows the springtail to use an incredible method of escaping predators. When a hungry spider or beetle gets too close for comfort, the springtail can launch itself spinning into the air by pushing off the ground rapidly with the furca. In doing this, the springtail launches its body into the air more than 60mm despite its 1-2mm body length, while spinning at up to 368 rotations per second. This is roughly the equivalent of a human jumping from the ground, up to the torch on the Statue of Liberty, while spinning more than 300 times faster than an olympic gymnast doing a back flip. To the predator, the springtail has just vanished into thin air!

Recently, a pair of scientists from North Carolina State and Georgia Tech Universities used high speed photography to record and analyze the jumping performance of a springtail. They watched the jumping motion with close-up photography that recorded the jump at an astonishing 40,000 frames per second. They then analyzed this video, capturing the motion beginning just five frames before furca release and ending just after the springtail becomes airborne, to produce numeric data that includes velocity, distance, angle, and acceleration. The scientists tracked specific reference points on the animal's head, body, and furca (Fig. 1) within the video to get these data.

In this activity, you will use the actual data collected by the scientists to make graphs and describe the jumping motion of the springtail in detail much in the way that was done in the original study.

DataClassroom



*"**Fig. 1** Dicytromina minuta springtails are found in the top layers of leaf litter. (A) Light microscope image of D. minuta showing a lateral view with posterior end of the animal to the right. Anatomical reference points relevant to body orientation and jumping morphology are shown on the panel. The collophore is underneath the body and not everted and therefore not visible in the image. (B) A D. minuta springtail during a jump where the furca is pushing down on the substrate and lifting the springtail into a jump. Circles on the body represent the points tracked during a jump and used to calculate jump kinematics." [Figure and caption from the original paper.]*

Dataset

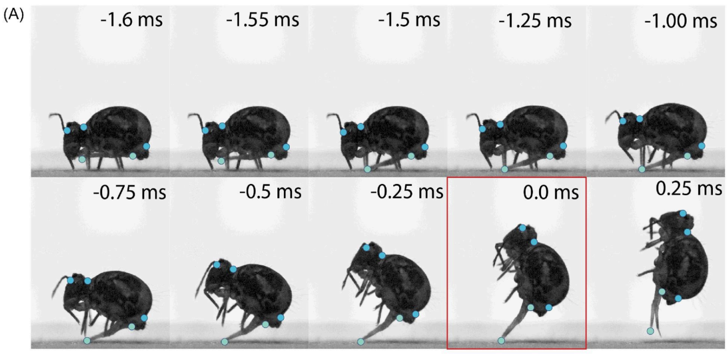
This dataset is found in supplementary materials from the paper titled: ["Jumping Performance and Behavior of the Globular Springtail *Dicyrtomina minuta*"]. Data were collected by tracking location via video analysis of springtail jumps, and turning that analysis into numeric measures of linear and angular distance, velocity, acceleration. Data were taken at time intervals of 0.03 milliseconds during the jump process, starting just before the jump begins to just after the furca leaves the ground and the springtail becomes airborne. This produced a dataset with 66 observations (rows in the dataset) covering a moment that was just 1.61 milliseconds in total.

Note that this dataset only captures the launch portion of the jump and ends at the point where the springtail leaves the ground (Fig. 2).

A A Smith, J S Harrison, Jumping Performance and Behavior of the Globular Springtail *Dicyrtomina minuta*, *Integrative Organismal Biology*, Volume 6, Issue 1, 2024, obae029, https://doi.org/10.1093/iob/obae029

Variables

Time (ms): This numeric variable is a reference point to moments when data were recorded during the springtail jump. The time marker t=0ms represents the moment the furca has left the surface that the springtail was jumping from. Negative values of time are before this moment, and positive values of time indicate the springtail is fully ballistic (or airborne). Measured in milliseconds.



"Fig. 2 Liftoff process from furca release until airborne. (A) Anatomical reference points and sequential

extracted frames from a single sequence captured at 40,322 frames per second showing furca release, body rotation, and initial liftoff. Time stamps indicate milliseconds relative to the last point of contact with the ground (outlined)."Integr Org Biol, Volume 6, Issue 1, 2024, obae029,

Distance (mm): This numeric variable describes the linear motion of the springtail, as measured from the center of mass. Measured in millimeters.

Velocity: This numeric variable represents the linear velocity of the springtail, as measured from the center of mass. Measured in millimeters/second

Acceleration: This numeric variable calculates the linear acceleration of the springtail, as measured from the center of mass. Measured in millimeters/second/second.

AngleVelocity (deg/s): This numeric variable indicates the angular velocity of the rotating springtail. Measured in degrees/second.

AngleAcceleration (deg/s/s): This numeric variable measures the angular acceleration of the rotating springtail. Measured in degrees/second/second.

FurcaAngleVelocity (deg/s): This numeric variable indicates the angular speed and direction of deployment of the springtail's furca during launch and flight. Measured in degrees/second.

FurcaAngleAcceleration (deg/s/s): This numeric variable calculates the angular acceleration of the springtails furca during deployment. Measured in degrees/second/second.

Activity

Make Predictions:
Take a look at this video from the research project to help make a prediction.

1. Linear velocity is how fast an object moves in a straight line (meters/sec). Angular velocity is how fast an object spins in a circle (degrees/sec or radians/sec). After watching the video above, do you think springtails move faster in terms of linear or angular velocity?

Students should be able to see from the video that springtail spin (angular velocity) is much higher than the linear velocity and distance it moves.

After completing the activity, students will discover that the angular velocity is much greater than the linear velocity.

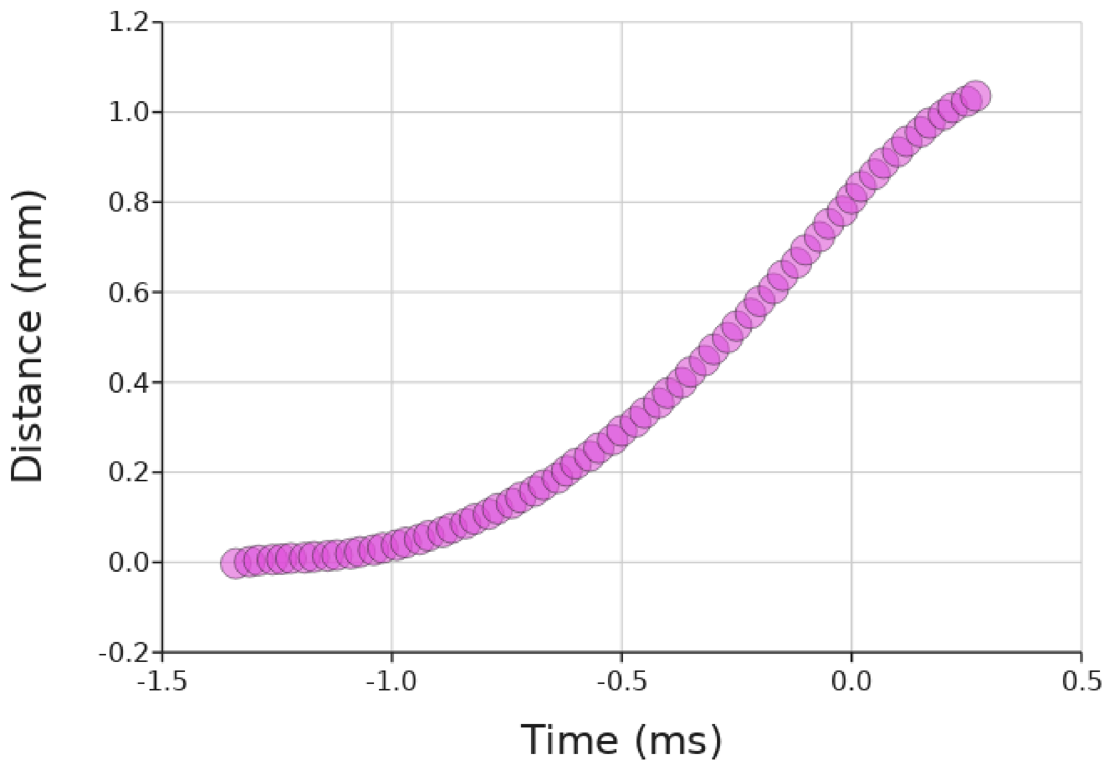
2. Part of this activity will explore how fast the springing mechanism (a springtail's furca) moves to get the springtail flying. How do you think the speed of the furca's movement will compare to angular or linear velocity it generates for the springtail?

   Students will either answer they think the furca moves faster than angular (spin) velocity or slower, as well as rank if it moves faster or slower than linear velocity.

   After completing the activity, students will discover that furca velocity is even greater than angular or linear velocity.

Explore the Data:
Part 1: Linear Velocity

3. Use the graphing tools to visualize how distance changes over time. Set **Distance (mm)** as the y-variable and **Time (ms)** as the x-variable. Screenshot the graph below:

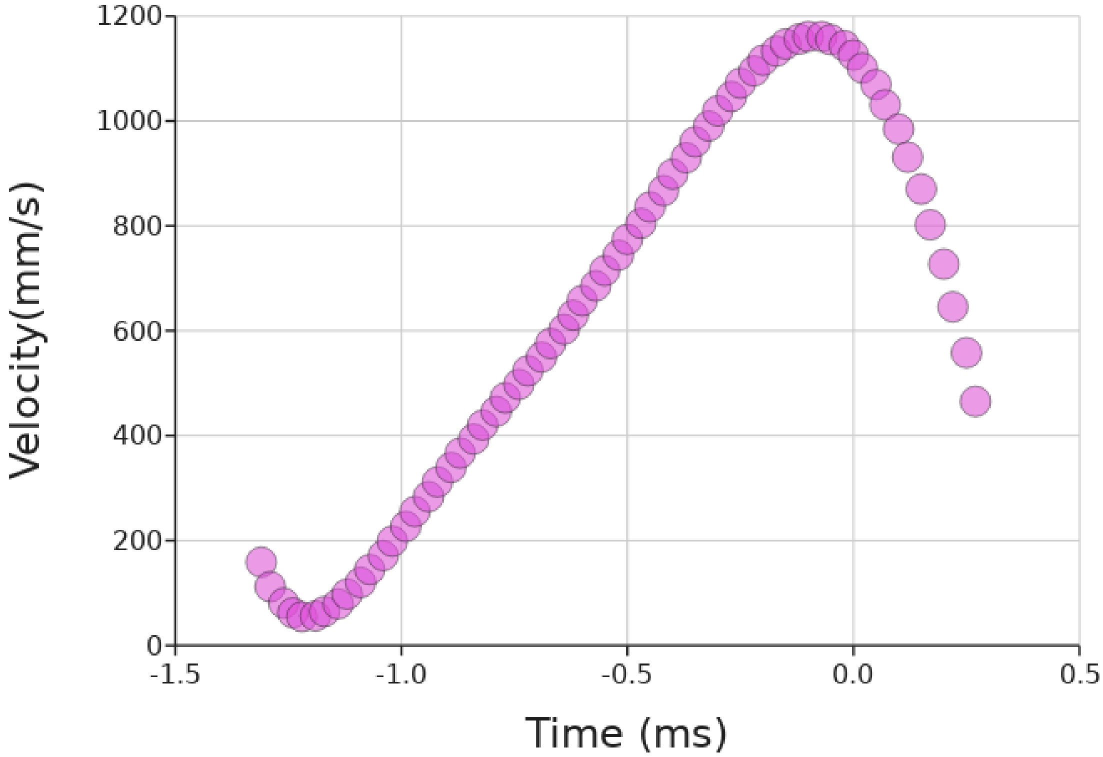


4. Describe the motion of the springtail, based on this graph. Use phrases

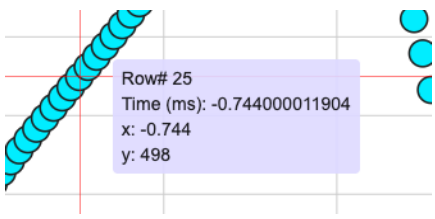
that describe its speed and location.

Students may give an answer like:
The springtail movement starts off slowly at first, and then begins to move faster (around t=-0.75 ms). Then it starts to move more slowly (after t=0ms). It moves in the same direction the whole time, and in total moves just over 1 mm over a time span of less than 2 ms.

5. Change your graph to view linear velocity over time. Use the graph tools and set **Velocity (mm/s)** as the y-variable and keep **time (ms)** as the x-variable. Screenshot the graph below:



6. Describe the velocity of the springtail over time during the launch, based on this graph. Use specific moments in time to help describe any changes (hint: put your mouse cursor over any of the points to see the exact time value).



The springtail begins with a decreasing velocity (but still positive value, indicating that it is moving away from the ground) until about t=-.2ms.

After that, velocity increases (still moving away from the ground) at a constant rate.

At around t=-.07ms the velocity change begins to slow, and then begins to decrease in value (but does not reach zero in this dataset. The springtail is still moving away from the ground).

Note: A big student misconception can be addressed here - decreasing velocity does not mean NEGATIVE velocity. It is a good point to check and see if students understand how the slope of a v vs. t graph does not indicate direction like a d vs. t graph does. Instead, the positive or negative value of velocity indicates direction. For this graph, all values are positive.

The motion provided in this answer should align to the motion description they provide in #4, where the springtail is always moving away from the ground.

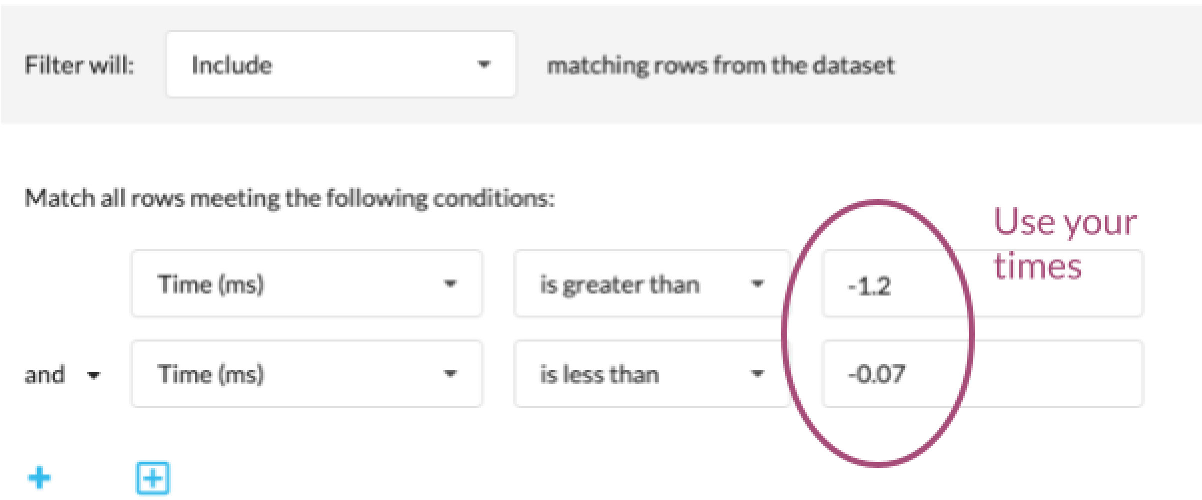
7. What is the max linear velocity the springtail reaches?

   Students should give a value around 1161 mm/s

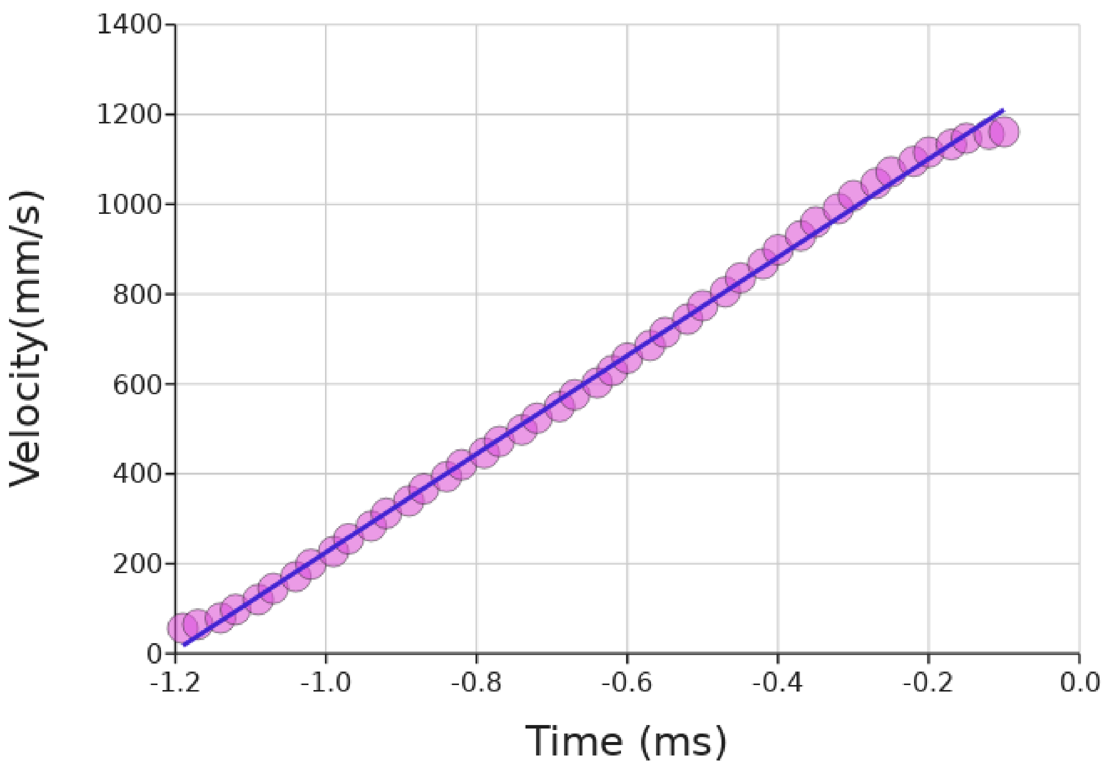
8. Acceleration is defined as a change in velocity. Based on your velocity graph, where is **positive acceleration** taking place? If physics says you must have a force to have acceleration (F=ma), what may be happening to the springtail during that duration?

   The springtail is undergoing positive acceleration during the time of constant, increasing velocity. (t= -1.2ms to -0.07ms). This is the time that the furca is deployed and pressing against the ground!

9. Let's predict linear acceleration, using our velocity vs. time graph. Exclude datapoints (use the [filter funnel option]() in the graph tab) which are outside the times we predict the furca is pushing the springtail into the air. Your filter options should look something like this:



Once your filter is on, add a [regression line]() for your smaller dataset. Screenshot your new graph below:

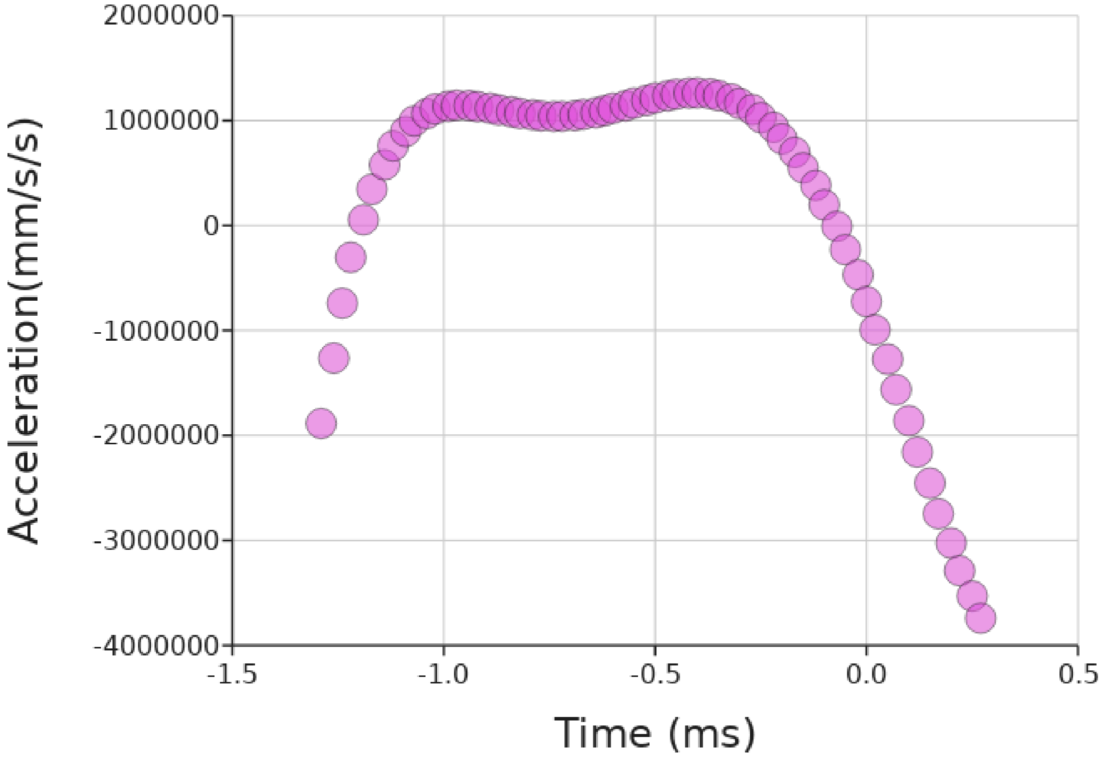


What on your graph represents acceleration? What is the value? Include units in your answer:

Students should identify that the **slope of the line of best fit** on a v vs. t graph is acceleration. The slope value should be around 1118 mm/s/ms. This number may vary a bit depending on which datapoints have been excluded but will be around that value.

Return your graph to include all datapoints before proceeding. To do this, go back into the funnel filter and click "Clear all excludes" button.

10. Change your graph to view linear acceleration over time. Use the graph tools and set **Acceleration (mm/s/s)** as the y-variable and keep **time (ms)** as the x-variable. Be sure to undo your regression line. Screenshot the graph below:



11. Describe the acceleration of the springtail, using the data in the above graph. Discuss what's happening between t= -1ms and t= -0.25ms. How does this relate to your prediction from #8? Does it also match your value you found in #9?

The acceleration holds constant for more than 0.5 ms near 1,000,000mm/s. It aligns with the idea that there is a force present (because there is acceleration) and is being exerted in the positive direction.

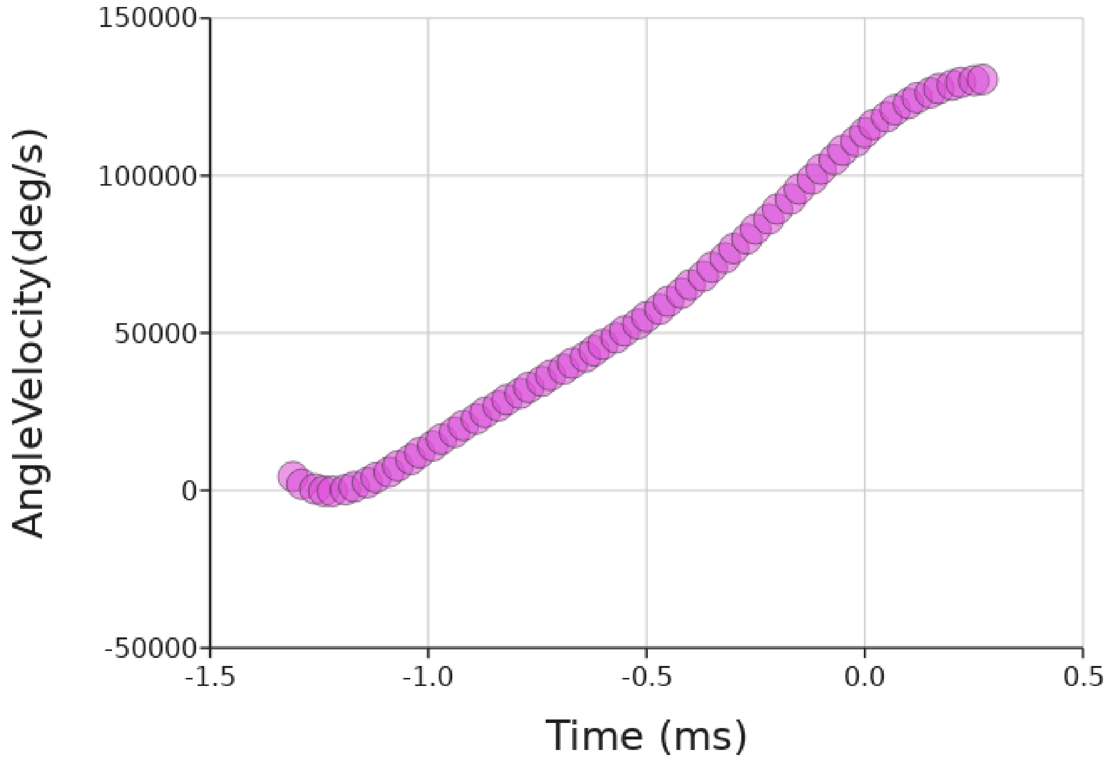
For value matching #9: this value should match their slope value, but it will be off by a factor of 10^3, because acceleration is in mm/s/s not mm/s/ms like our v vs. t graph.

12. Discuss what's happening to acceleration after t= -0.25ms and your prediction of what is happening with the springtail.

At this point, force is less and acceleration begins to decrease over time. While the furca is still pushing against the table (it continues to do so until t=0) the video shows that towards the end of the deployment, it is just the tip of the furca touching the table. It is likely that less force can be exerted by just the tip of the furca, therefore decreasing the acceleration.

Part 2: Rotational Motion

13. Use the graph tools and set **AngleVelocity (deg/s)** as the y-variable and keep **time (ms)** as the x-variable. Screenshot the graph below:



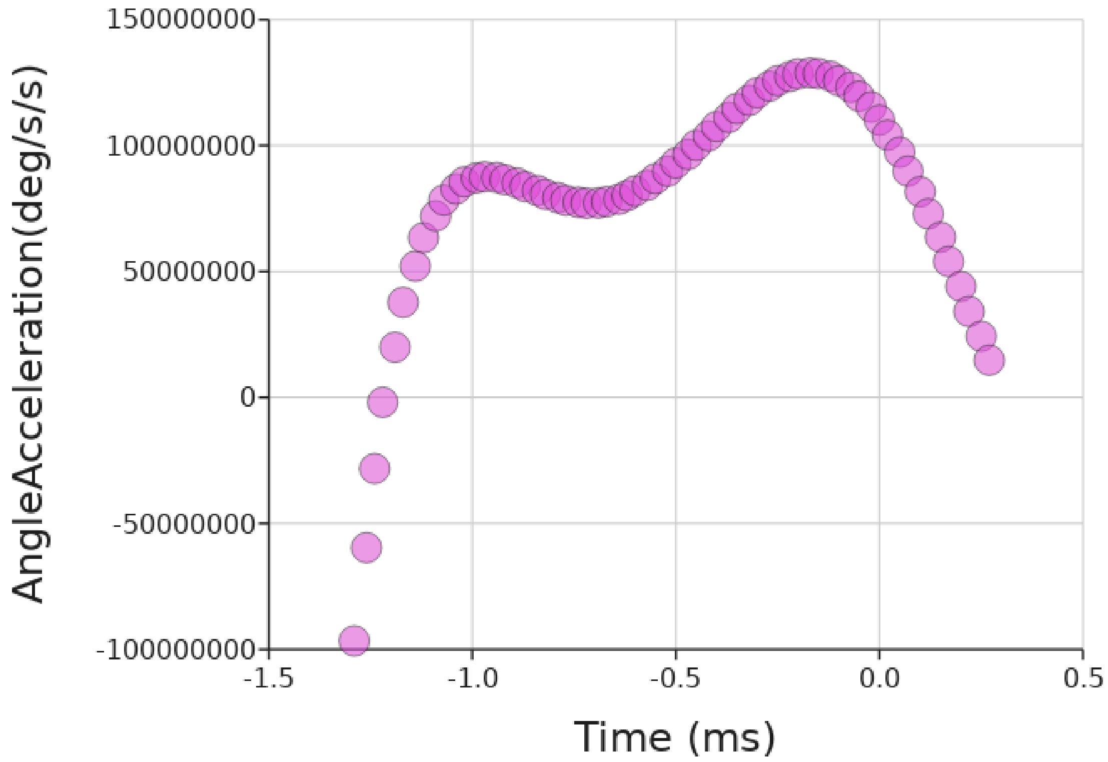
14. From our earlier graphs (in part 1), we know when the furca is pushing the springtail into the air. What do you notice about the angular velocity of the springtail during this time? What do you expect the rotational acceleration graph to look like?

The increase in angular velocity is generally constant (we have an almost linear slope)! We would expect the acceleration graph to have a (general) flatline during that time, showing that acceleration is constant (but not zero)

15. What is the max rotational velocity the springtail experiences?

Students should give a value around 130,500 deg/s

16. Use the graph tools and set **AngleAcceleration (deg/s/s)** as the y-variable and keep **time (ms)** as the x-variable. Screenshot the graph below:



17. How does this graph align with your predictions in #14?

Student answers should discuss that this graph may look like it's "hinting" at a flatline but acceleration is actually changing over the time the springtail is launching. This is due to the launching mechanism: in the simplest sense, the furca's angle is changing over time. It's interesting (but makes sense) that the angular acceleration peaks right before the furca loses contact with the table.

This is a great moment for students to see that real data isn't always as clean as theoretical data, but does still display the concepts seen in classic "stacked graphs".

Torque!

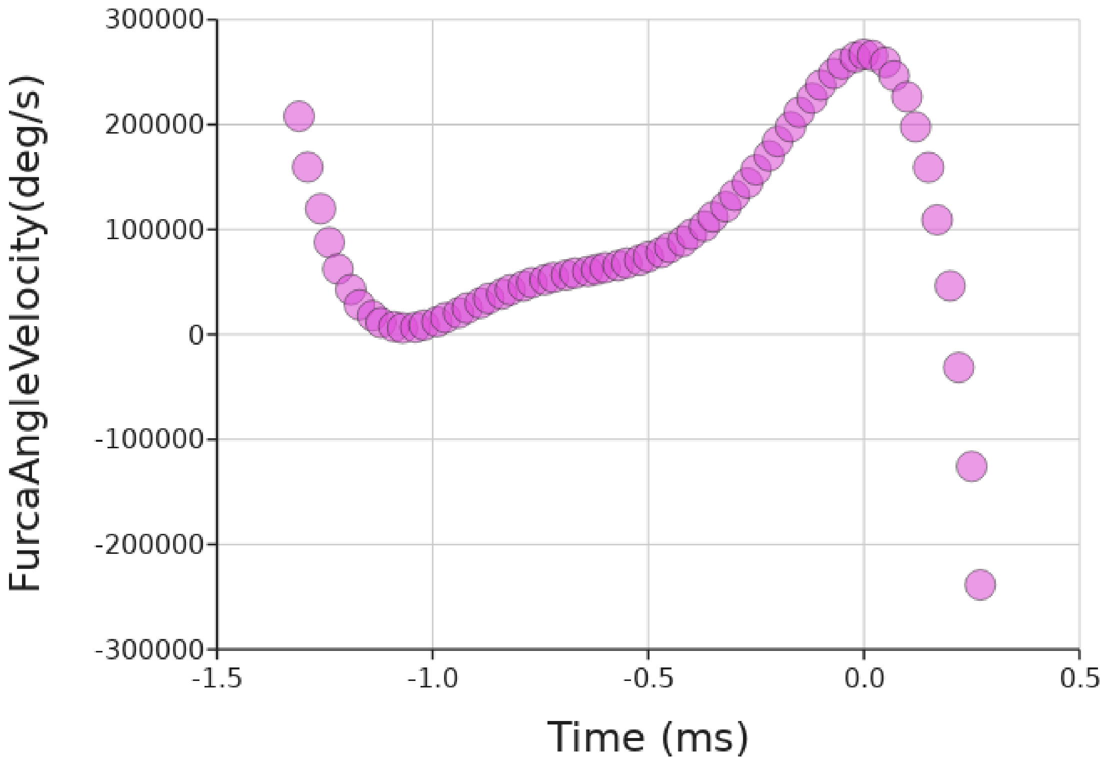
Teacher discussion: An interesting discussion around Torque could come into play here. We have removed the **Angle of Furca** data from this dataset (to simplify for students), but the furca is at a 90* angle between time t= -0.15ms and -0.12ms. Based on the torque equation...

Torque = radius * Force * sinϴ

...it aligns that torque would be highest at this moment.

Part 3: Motion of the springtail's spring tail

18. Use the graph tools and set **FurcaAngleVelocity (deg/s)** as the y-variable and keep **time (ms)** as the x-variable. Screenshot the graph below:



19. What is the peak angular velocity of the furca?

Students should provide an answer around 267000 deg/s.

20. Looking back at the max velocity values we gathered from part 1, 2 and 3, rank the values from least to greatest. (Check out your answers to #7, #15, and #19).

Note: to convert angular values to linear, use the length of the springtail to be 1mm (or radius from center of mass as 0.5mm), and the length of the furca to be 0.66mm.

Linear velocity: **1,161 mm/s**
Rotational velocity of springtail: 130,500 deg/s
Rotational velocity of furca: 267,000 deg/s

If you wanted to convert these values to be the same units...

Rotational velocity of the springtail (if r = 0.5mm approx - measurement of Springtail from center of mass)
130,500 deg/s * 0.5mm = **65,250 mm/s**

Rotational velocity of furca (if r= 0.66mm approx)
267,000 deg/s * 0.66mm = **176,220 mm/s**

21. How does this match your predictions from #1 and #2?

Student answers should compare their predictions to their results - I was able to predict correctly, or I put the springtail's rotational velocity higher than it should have been, etc.

The furca has the fastest velocity, but the springtails spin is incredibly fast compared to it's linear motion through the air.

Part 4: Full Jump Analysis

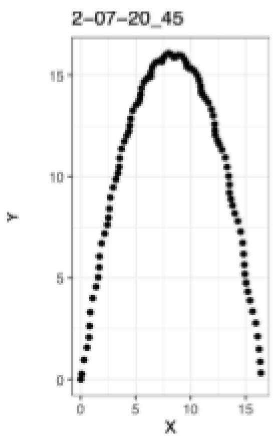
22. Below are graphs of data from a springtail's full jump. This includes data from the launch portion (like what you analyzed above) to the point where the springtail returns to the ground.

Note: **Time is delineated differently here** from the "launch only" graphs of Part 1-3. No longer is t=0s the moment where the furca leaves the table. It is now the moment the furca is deployed initially.

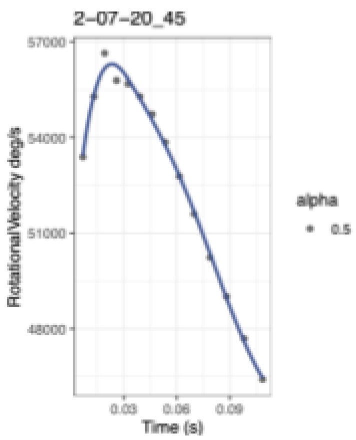
You can see the **first** graph (x vs. y) displays an "image" of the jump as the springtail moved through the air, providing it's location in x and y coordinates.

Looking at the units and axis descriptors of the second and third graph, which is showing linear velocity, and which is showing the springtails angular velocity?

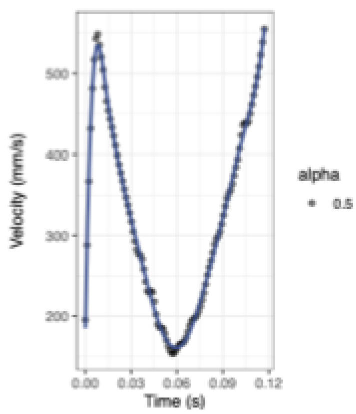
Graph 1



Graph 2



Graph 3



Graph 2 - rotational velocity of springtail (deg/s)

Graph 3 - Linear velocity (mm/s)

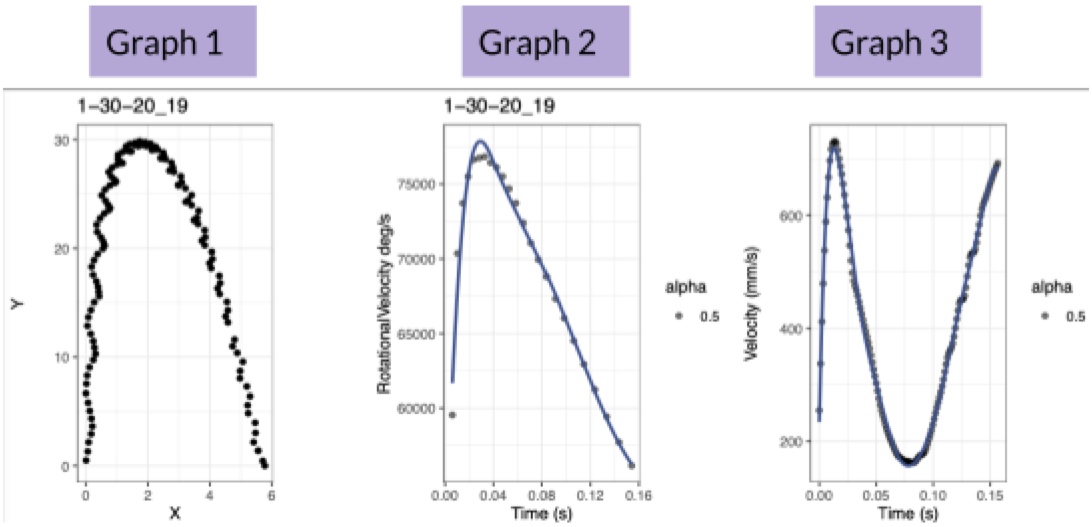
23. Identify key moments of each graph (highs and lows, and what is physically happening at those moments)

Graph 1 - The high point of the graph is the point where the springtail has reached its highest point and is starting to return to the table / surface. It is kind of like a picture of it's entire jump.

Graph 2 - The highest value is the max velocity the springtail reaches - this is the moment when the furca has left the surface and is no longer applying a force. The springtail starts to slow it's spinning at that point.

Graph 3 - The rapid increase in linear velocity happens as the springtail furca pushes it upwards, peaking above 500 mm/s. The springtail's linear velocity then slowly slows down as it reaches it's peak trajectory, where linear velocity should reach about zero (though with spin it's not as clean). As it approaches the earth again, it speeds back up to almost it's max velocity (conservation of E).

24. This next set of data is from a different springtail launch. What looks different from the previous set of data and what looks the same? What might be the reason for these differences?



The biggest difference is Graph 1, with the waves as the springtail moves its way upwards. Perhaps the springtail jumped in a direction different than expected, (making a lopsided graph and not a centered parabola) and also the spins are very obvious in this image.

Graph 2 and 3 are generally unaffected by the wildness of the spins recorded in Graph 1. However, the springtail does not get back up to it's max velocity in graph 3, like it did in the first set of graphs.

25. In this analysis we looked at data from just one springtail. But we know that there is variation in the natural world! If we had data from 100 springtails, what kinds of scientific questions could you answer using this kind of data (different distance, velocity, and acceleration data)? List one or two questions below.

Example questions:

- Does age of springtail affect velocity or jumping height?
- Do some springtail trigger into jumping sooner than others? Do they have different max values for velocity or acceleration?
- If required to jump in quick succession (furca is deployed with minimal rest time) does that affect height of jump over time?
- How does the length of the furca affect the jump height or angular velocity?