The Itsy-Bitsy Spider: An Analysis of Spider Locomotion

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Part I –Introduction

Understanding the relationship between form and function in organisms can increase our knowledge about natural processes, especially when it comes to investigating how physical laws apply to the adaptive design of organisms. The mode of locomotion plays a major role in the evolution of many body traits. Most terrestrial organisms walk or run upright on horizontal surfaces. Organisms that climb on vertical surfaces or hang from objects most likely evolved, through natural selection, specialized modes of locomotion to optimize ease and rate of movement.

In order to move, animals need to "build up" energy and then use that energy in a controlled way. One way to do that is through the interchange of kinetic and gravitational potential energy. One method to do this is an animal moving forward over a stiffened leg. In the initial part of the cycle, some of the kinetic energy used to propel the animal forward also raises its center of mass, increasing its gravitational potential energy. As the center of mass falls, gravitational potential energy is converted back into kinetic energy which facilitates the next step. This is called the *inverted pendulum model* (Figure 1).

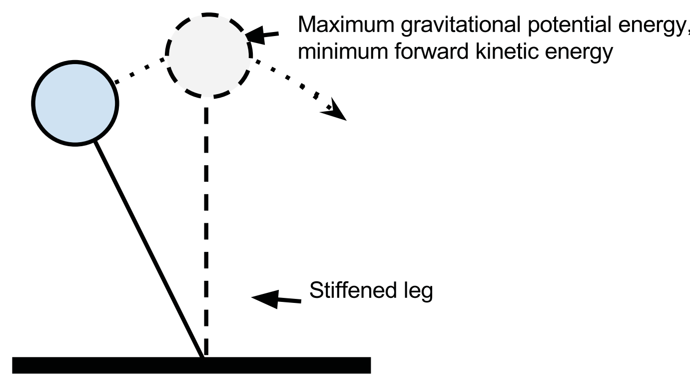

Figure 1. Inverted pendulum model. Body center of mass moving, supported by a stiffened leg.

Another model is the *spring-loaded inverted pendulum model* (Figure 2) in which the elastic elements in the leg store energy. As the center of mass moves downward under the force of gravity, the elastic elements in the leg (muscles, tendons, skeletal structure) are compressed. When these elements return to equilibrium, the center of mass is propelled upward and forward. Studies of "daddy longlegs" of the species *Leibunum vittatum* seem to follow this mode of locomotion (Sensenig and Schultz, 2007).

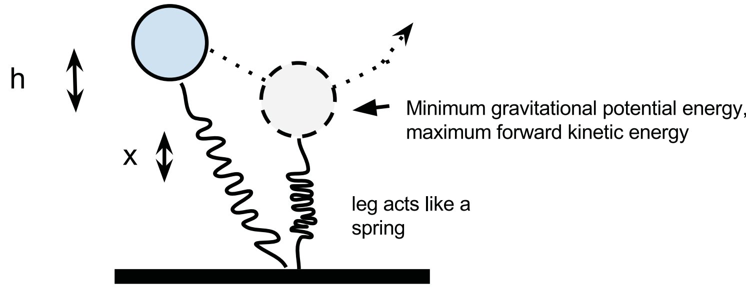

Figure 2. Spring-loaded inverted pendulum model. As a body moving forward brakes, it stores energy in the leg.

The third model is a *regular pendulum model*, which gains kinetic energy by swinging from a position of relatively high gravitational potential energy to a low position where kinetic energy is maximized (Figure 3). Hanging spiders most closely match this mechanical model (Moya-Laraño, Vinković, de Mas, Corcobado, & Moreno, 2008).

Spiders are a highly diverse group of terrestrial predators that are exceptional organisms to test evolutionary hypotheses about pendulum mechanics because there are many species that move primarily upright on a horizontal surface (picture a tarantula) and many that live hanging upside down (picture the spider that startles you by dropping from the ceiling).

Natural selection is the gradual, non-random process by which biological traits become more or less common in a population due to differential reproduction. For example, a spider group with a body type that lets it move quickly to avoid predators will live longer and have a greater opportunity to pass that favorable trait on to its offspring.

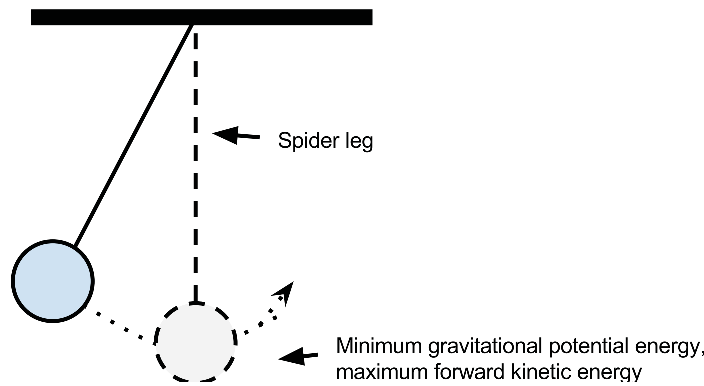

Figure 3. Regular pendulum model. Body center of mass swinging like a regular pendulum.

Some Other Information

Here are some physics concepts to help you analyze the case:

- A pendulum at the endpoint of its trajectory has energy PE_g = mgh where mg is the weight of the pendulum and h is the distance the pendulum is above or below the equilibrium position. A pendulum at the equilibrium point of its trajectory has energy KE = $(1/2)mv_{max}^2$ where m is the mass and v_{max} is the maximum speed of the pendulum.
- The energy stored in a compressed spring is given by $PE_s = (1/2)kx^2$ where k is a measure of the stiffness of the elastic medium (called the spring constant) and x is the amount the elastic material is displaced from equilibrium.

Questions

1. If you designed an animal that could walk on flat horizontal surfaces and move upside down on suspended surfaces, describe three body characteristics you would give that animal. Be specific. Don't just say something generic like "legs that can walk and grip."
2. What is the basic question of this study and why might it be an interesting and relevant topic for scientists to study?
3. What specific and measurable hypotheses (at least two) can you develop that are supported by the information presented and that address the basic question of this study?

Part II – Hypotheses

If the evolution of body shape matches simple pendulum mechanics, animals that move suspending their bodies should evolve relatively longer legs, which must confer high moving capabilities (Moya-Laraño *et al.*, 2008).

Leg Length Hypothesis

If leg length is the target of natural selection, hanging animals must have evolved disproportionately longer legs relative to their body size when compared with animals that walk standing on their legs.

Running Hypothesis

As spider size increases, running speed should increase with a greater increase for standing rather than hanging spiders.

Questions

1. Rewrite the leg length and running hypotheses of this study in your own words using the "If, then, because" format. This hypothesis must be something you can measure and observe in a short-term study.
2. Describe how you could use the concepts of kinetic and potential energy to analyze the motion of a spider.
3. Which of the two models of upright locomotion described in the introduction (inverted pendulum or spring loaded inverted pendulum) would benefit a long-legged spider running upright? Why?
4. Does the regular pendulum model favor a long-legged or short-legged spider? Why?
5. Design an experiment to test the leg length hypothesis. Describe the basic procedure, number of trials, equipment needed, and method of analysis.
6. Design an experiment to test the running hypothesis. Describe the basic procedure, number of trials, equipment needed, and method of analysis.

Part III – Experiments and Observations

Leg Length Experiment

Moya-Laraño *et al.* (2008) measured morphological leg characteristics on adult females from 105 spider species belonging to 25 spider families based on drawings from the book *The Spiders of Great Britain and Ireland*, Vol. 1 and 2 by M. J. Roberts. In order to focus on the body traits size and pendulum issues discussed in the introduction section, they measured carapace width (CW), right foreleg tibia length (FTL), and right foreleg tibia diameter (FTD). Forelegs are important for pulling the body during bridging on a silk thread, and if the pendulum hypothesis is correct they should be the most modified according to living posture. The length of the tibia is the best characteristic of leg length because it is the easiest leg segment to measure in Roberts' drawings. Tibia diameters were measured in the center of the tibias. Spider traits were directly measured to the nearest 0.1 mm from the drawings in Roberts' book by using a caliper. To validate the accuracy of the drawings, the authors measured actual spiders from 10 different families and found the CW, FTL and FTD to be highly correlated to Roberts' drawings (R=0.95-0.97).

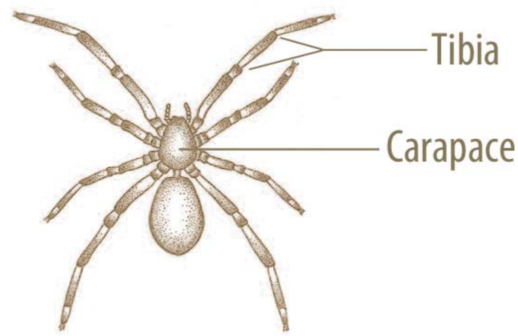

Figure 4. Spider body parts that were measured for the leg length hypothesis.

General Running Experiment

To study the performance of spiders on flat surfaces, Moya-Laraño *et al.* (2008) ran spiders on a race track (50-cm length, 15-cm width) that had a layer of fine sand as substrate. Spiders were released from the jar and chased until they moved in a straight running trajectory. Since spider mass ranged from 0.65 mg to 1,242 mg the length of the run varied accordingly (i.e., 1.8–38 cm).

All spiders, collected in southern Spain, were kept in jars of variable size according to their own size and all were used within 48 hours after collection. Trials were conducted at room temperature (range 19.7–22.7°C) and recorded with a digital video camera for later calculating speed at 30 frames/s. After trials were finished, individuals were killed by freezing and preserved for body measurements.

Questions

Explain your reasoning for each of the following questions. It will be helpful to sketch and include a graph for each.

Given the observations made as part of this study, what would the data look like:

1. If the leg length hypothesis in Part II is true?
2. If the leg length hypothesis in Part II is false?
3. If the running hypothesis in Part II is true?
4. If the running hypothesis in Part II is false?

Part IV – Results

Leg length Hypothesis

The authors observed a definite trend relating relative body size to relative leg length. This trend differed for standing and handing spiders.

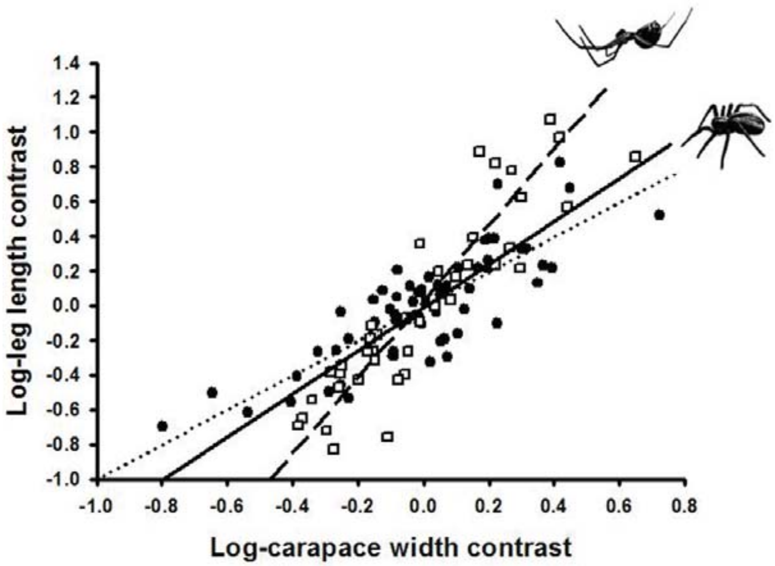

Figure 5. Body size is represented on the x-axis and leg length is represented on the y-axis. The larger the value on the axis, the greater the body size (carapace) or leg length compared to a standard linear growth model of organism size increase. For example, a value of 0.4 means the body part is larger/longer than a linear model would predict. A value of 0.8 means the body part is much larger/longer than a linear model would predict. A value of -0.4 means the body part is smaller than a linear growth model would indicate. Filled circles and solid line: standing spiders. Open squares and dashed line: hanging spiders. The logarithms were used to flatten the data. (Moya-Laraño *et al.,* 2008, Creative Commons Attribution License.)

Running Hypothesis

Species of walking and species of hanging spiders were put through the same running test. The graph below shows their speed results.

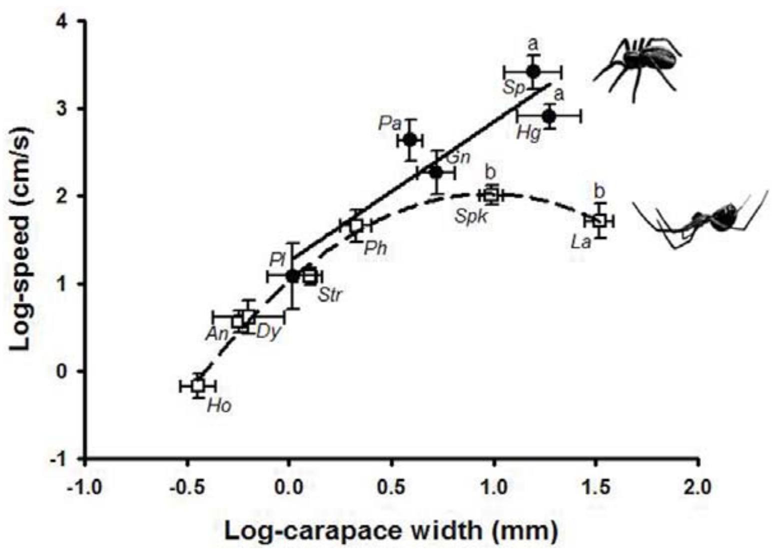

Figure 6: Body size is represented on the x-axis and spider speed is represented on the y-axis. Filled circles and solid line: standing spiders. Open squares and dashed line: hanging spiders. The letters represent the spider species used. The logarithms were used to flatten the data. (Moya-Laraño *et al.*, 2008, Creative Commons Attribution License.)

Questions

1. Summarize what Figure 5 tells you about the answer to the leg length hypothesis.
2. Summarize what Figure 6 tells you about the answer to the running hypothesis.
3. Use the principles of energy conservation to explain the results of Figure 5.
4. Use the principles of energy conservation to explain the results of Figure 6.
5. Do the data "support" the research hypotheses?
6. What general conclusions can you make from the results of this study?

References

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