Kinematics, Impulse, and Human Running

Introduction

Today you are going to explore how fundamental physics concepts are involved in something you probably often do: run. Whether you are a fan of running or not, it is an important part of many of our activities. You are going to examine how Newton's third law and impulse can be used to explain human running performance. To figure that out, you first need to know what exactly your body is doing when you run.

A runner's stride has two phases: **contact phase** and **aerial phase**. Contact phrase describes the part of the stride when one foot is in contact with the ground. Aerial phases describes the part of the stride when no feet are in contact with the ground.

Picture a runner, maybe yourself in gym class (or running into class late!) and examine the images in **Figure 1**. The runner in Figure 1 begins in contact phase, when her right foot hits the ground. From panel 1 to panel 2, the runner's left leg swings forward. As the left leg continues to swing forward in panel 3, aerial phase occurs as the right foot leaves the ground, and the runner is completely airborne for a fraction of a second while the right leg lifts and the left leg drops toward the ground. When the left foot hits the ground in panel 4, the next contact phase begins. The runner continues to switch between aerial and contact phases until they stop running.

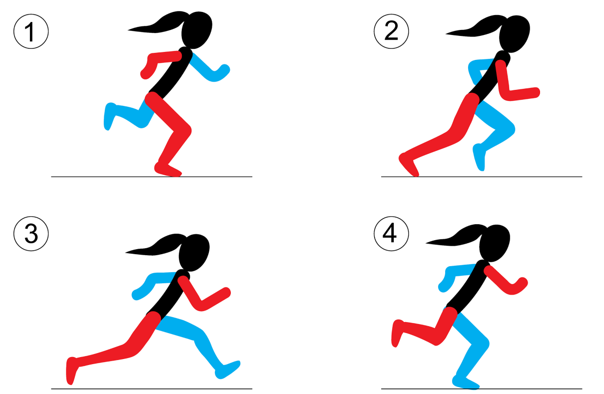


Figure 1: Half a Running Stride. This runner's stride is shown beginning in contact phase, with the right foot touching the ground. Contact phase continues as long as the foot remains in contact with the ground (panels 1 and 2). Once the right foot leaves the ground and before the left foot makes contact, the runner is in aerial phase (panel 3). The left foot then makes contact with the ground initiating another contact phase (panel 4). A full stride won't be complete until the right foot hits the ground again.

To change speed, a runner can alter different parts of this pattern of movement. Take a moment and consider these motions. If you were trying to run faster, what could you do?

It turns out, there are three ways that runners could increase their top speed by increasing their step frequency (how often they complete a full stride), increasing the force they exert to push off the ground, or spending more time in contact with the ground. The relationships among these factors with running speed is defined by the equation below.

Speed = (step frequency) × (pushing force/body weight) × (time spent in contact phase)

Note that the variables step frequency, pushing force, and time in contact phase—are directly proportional to speed, meaning that increasing any of one of these three factors will also increase speed. A runner could swing their legs faster to increase step frequency, strengthen their leg muscles to increase pushing force, and/or change their stride to spend more time pushing off the ground (and less time in the air) to increase the contact phase.

So which of these factors set the fastest of the fast runners from the rest of us? That's what you'll explore in this lesson.

What To Do

Answer the analysis questions below, reading the Bite when instructed.

Analysis Questions

1. Describe **and** explain the three ways a runner can increase their speed.

   Method 1:

   Method 2:

   Method 3:

2. In the space provided, define the two phases of running in 1–2 sentences.

   Aerial:

   Contact:

3. During which phase is the runner exerting a force to the ground? What does the ground do in return? Explain. (*Hint:* Recall Newton's laws of motion.)

As the ground exerts a force on the runner, it also creates an impulse. Recall the Impulse equation:

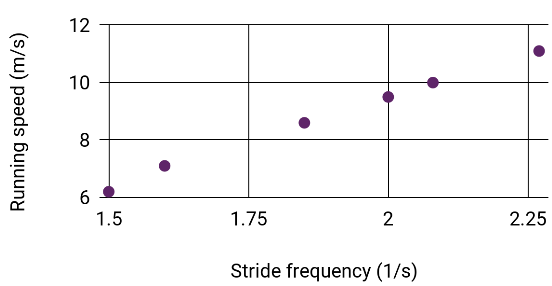
$$Impulse \ = \ Force \times change\ in\ time \ = \bar{F}\Delta t$$

$$\Delta t \ = t_{final} - t_{initial}$$

4. What information do you need to calculate your runner’s impulse during each step?

Researchers have examined how stride frequency, aerial time, contact time, and maximum pushing force each impact running speed. Take a look at the graphs below and answer Question 5.

a.



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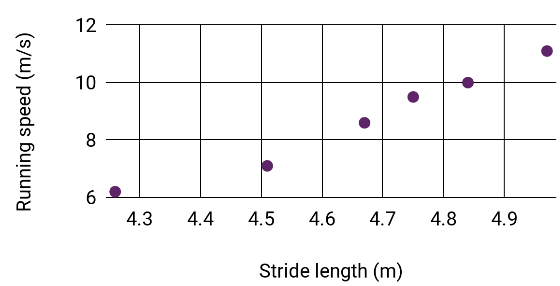

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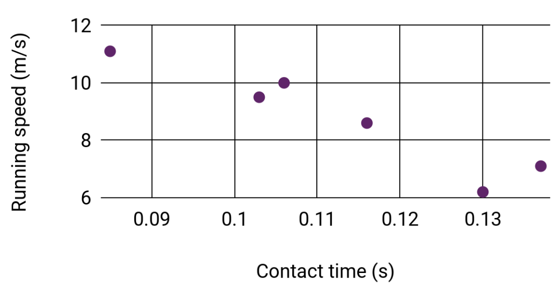

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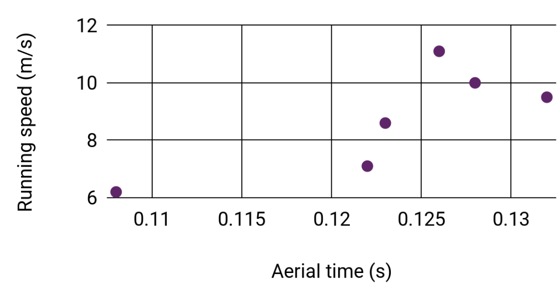

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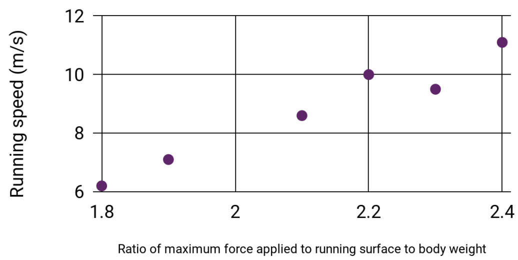

Figure 2. Relationships Between Variables Studied By the Researchers and Running Speed. a. running speed *vs.* stride length; **b.** running speed *vs.* stride frequency; **c.** running speed *vs.* contact time; **d.** running speed *vs.* aerial time; **e.** running speed *vs.* ratio of maximum force applied to running surface to body weight. *Source:* Weyand *et al.* 2000

5. Let's explore the relationship between each variable and running speed.

a. Fill in the table to describe what happens to running speed as each of the variables listed increases. Stride frequency is filled in for you as an example.

Stride Frequency **Graph a**	**Stride length** **Graph b**	**Contact time** **Graph c**	**Aerial time** **Graph d**	**Maximum force applied to running surface** **Graph e**
As stride frequency increases, the running speed increases.				

b. Based on your answers in the table above, which factor or factors do you think allow runners to run faster?

c. Which factor or factors do not appear to be related to running speed?

d. Based on your answers to part a and Question 4, as a runner increases their speed, does the impulse they experience when they are touching the ground change? Justify your response.

Already you can see that thinking about impulse can help scientists analyze complicated situations such as someone running. Impulse becomes even more useful when one considers its other definition. Impulse is equal to a change in momentum, as shown in the equation below.

$$Impulse = \overline{F}\Delta t = m\,\Delta v = \Delta p = Change\ in\ Momentum$$

$$\Delta v = velocity_{final} - velocity_{initial}$$

6. Based on these equations and your answer to Question 5d, how do you think a runner's momentum and velocity are changing during contact time?

Momentum:

Velocity (*Hint*: Think about what Newton's laws say about force and velocity. What does applying a force mean for velocity?):

Think about a runner jogging in a straight line in park. Over the course of five or ten minutes, the runner's mass and velocity are constant. Based on those conditions, you might expect the runner's change in momentum and impulse to be zero. But, this is real life, not idealized conditions like you often think about in physics class! In real life, energy is lost to heat and friction every time the runner's foot hits the ground. So, to keep running at the same velocity, the runner needs to balance that loss by adding momentum every step. This is why you have found non-zero force, impulse, and momentum in the questions above.

Let's see if your conclusions match that of the researchers and what makes an elite runner run so much faster than the rest of us.

STOP & read Science Bite:

What Limits How Fast You Can Run?

7. Did your conclusions above match that of the researchers? Explain your answer.

8. What did the researchers conclude was the most important factor in allowing elite runners to move so fast? Does that agree with the graphs you examined in Question 5? Explain your answer.

Runners that experience knee pain when running are often found to overstride, meaning that they take steps that are too big. To reduce their pain, overstriding runners have to learn to take more steps while still running at the same speed. In other words, they need to increase their stride frequency.

9. Considering your answers to Question 5a, let's determine whether increasing step frequency is good or bad advice. For each part of this question, **assume that the total impulse per stride does not change.**

  a. If you take more steps in that given time window, do you end up spending a greater, the same, or a smaller percentage of that window in contact phase?

  b. Based on your answer to Question 9a, is the runner applying more, the same, or less force to the ground in each step?

c. Based on your answer to Question 9b, is it good advice to tell overstriding runners to increase their stride frequency while running at the same speed to reduce their pain?

10. Describe the physical mechanisms that are being changed when you run faster. You may want to consider what your body is doing when you change stride frequency/aerial time, contact time, or maximum force.

11. **Connect to the Big Question** The scientists may have figured out that aerial time did not have a large impact on running speed pretty early in their study, but they they kept recording that data anyway. Why was recording this data important even though it turned out not to affect the variable they were interested in? Why do you think scientists record all of the details of an experiment they are conducting? Have you made any observations that at the time didn't seem important, but you used later on? Has there ever been a time where you wished you had recorded something that you originally didn't think was important? Explain your answer.