

Applications of Newton's Laws: Ground Reaction Forces and Gait Analysis

Learning Objectives

By the end of this section, students will be able to:

- Explain contact forces while standing and walking
- Explain the role of ground reaction forces in explaining the human gait

Math Skills

- Decompose vectors into components on a set of axes
- Vector addition

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1. Biomechanics & Contact Forces

Therapists, orthopedists, and athletic trainers often work with patients/clients who engage in activities such as walking, running, jumping, and falling for treatment or sports performance. Such activities involve the patients' interaction with the ground. The contact force we experience when interacting with the ground is called the **Ground Reaction Force (GRF)**. It is a Newton's 3rd Law reaction force that arises due to our interaction with the ground, acts simultaneously and in opposition to the body's push on the ground, and represents the sum of the normal force and the frictional forces acting on us.

View the diagram below to see the GRF forces acting on us when we stand (Figure 1 (a)) or when we push the ground during walking or running (Figure 1(b)).

Note the distinction between the force vectors that comprise a FBD (external forces acting only on the person) and the force vectors that comprise of a Newton's Third Law interacting force pair (the person pushes on the ground and the ground pushes on the person).

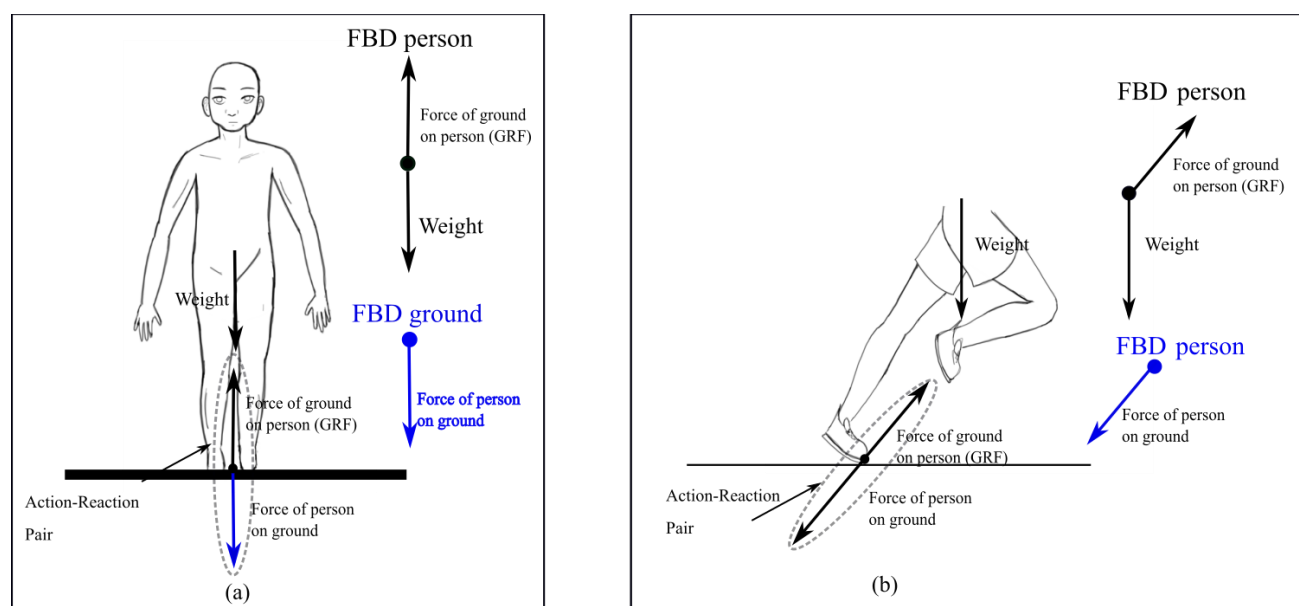


Figure 1: (a) The GRFs of a person standing still, (b) shows the GRF of a person running

In Figure 1(a), the person is standing still. The horizontal reaction forces compared to the vertical reaction forces are negligible and can be ignored. Therefore, while standing, the ground reaction force can be assumed to be vertical. In this case, the object stays still because the GRF

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of the ground pushing up on the person is equal to the weight of the person pulling them to the ground (both of these forces act on the person).

Check Your Understanding for Figure 1(a)

- 1) The person in Figure 1(a) is at rest. Define the forces acting on the person.
- 2) The person in Figure 1(a) is standing on a horizontal surface. Is there any static friction acting on the person?
- 3) Identify the interaction force between the person and the ground.
- 4) Should the force the person exerts on the ground be used in a determination of the state of motion of the person? Why or why not?

Answers

- 1) Gravitational force on the person from the Earth and the normal force on the person from the ground (GRF).
- 2) No, since there are no other forces that contribute to the person sliding.
- 3) A person pushes on the ground, and the ground pushes on the person.
- 4) No. The force the person exerts on the ground is the negative of the force the ground exerts on the person. We need to use only the forces that act **on the person** to determine the state of motion of the person. The force the person exerts on the ground factors into the state of motion of the ground.

In Figure 1 (b), when the foot pushes the ground, the ground exerts a reaction force that can be resolved along the horizontal and vertical directions. When we push vertically down on the ground, it pushes back up on us and provides the vertical component of the GRF. When we push

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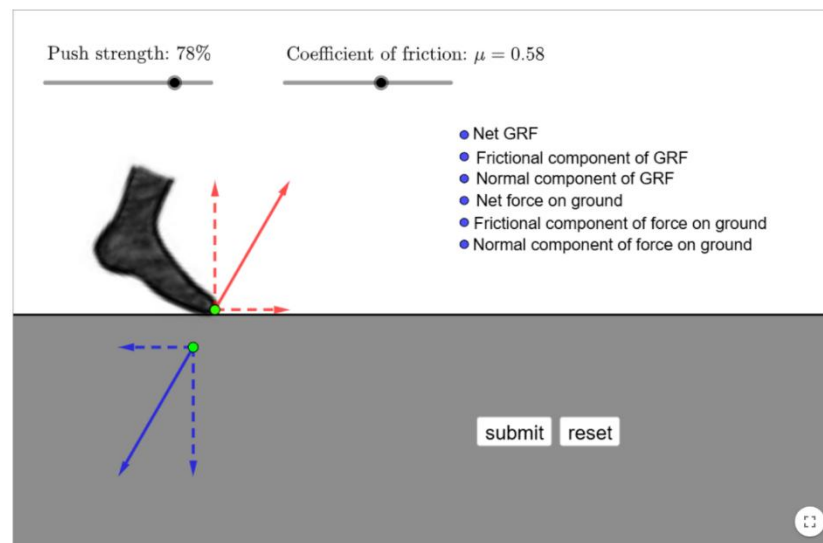
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back on the ground horizontally, it propels us forward and provides the horizontal component of the GRF. Both components are needed during walking or running. The horizontal force is

1.1 Simulation: Components of the GRF

Use the simulation below to understand the components of the GRF.

<https://www.geogebra.org/m/nhxqrwj7>



Instructions

The ground reaction force is the result of two forces acting together on the foot from the location of the ground. First, the normal force acting in the vertical direction keeps the body up. The other force is friction, which pushes the foot forward.

Pushing harder on the ground leads to an increase in the normal force, which in turn allows for a better grip (i.e., a larger friction force). How slippery the ground is also affects the nature of the friction force, as a more slippery surface (or a lesser grip) will reduce the amount of frictional force. This is described by the coefficient of static friction. In this simulation, you can

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vary both the coefficient of static friction and the strength at which the foot is being pushed, using the corresponding sliders.

The goal of the simulation is to identify the components of the GRF and its equal and opposite counterpart, which acts on the ground itself. Click and drag the text labels using the blue dots next to them. Move them to the heads of the vectors that represent the different forces acting on the foot or the ground. In the diagram, red arrows act on the foot and blue arrows act on the ground. Click "submit" to see if you have identified them correctly. Click "reset" to move them back to the default positions.

Activity 1

- 1) Label the GRF and the force of the foot on the ground. Label the components of the two forces in the simulation.
- 2) Have you ever tried to run on ice? It's tough – your body tries to move, but you can't get any traction on the ice. It is very hard to move forward. Use your vector diagram and Newton's Third Law to explain why it is so difficult to run on ice.
- 3) How would your vector diagram change if the person pushed on the ground harder?
- 4) How would your vector diagram change if the coefficient of friction between the runner and the ground increased?
- 5) When you walk or run, is friction necessary or undesirable?

1.2 GRF in the Human Performance Laboratory

Biomechanics researchers and clinical therapists study the GRF to assess the amount of force on joints during activities like walking, running, and jumping, and gain valuable information to prevent injuries, organize rehabilitation, and improve sports performance. In Human Performance Labs, GRFs are measured using force plates and pressure sensor arrays. Force plates measure reaction forces when people stand or move on them. Some force plates only measure the vertical component of the GRF, while others measure the GRF in all three directions. Pressure sensor arrays consist of many sensors located on the platform to measure the forces on smaller scales during motion. Pressure is defined as force per unit area. By measuring forces at many small locations of known areas, one can create a pressure map of the movement. Such maps are useful in determining how the body exerts force on the ground and

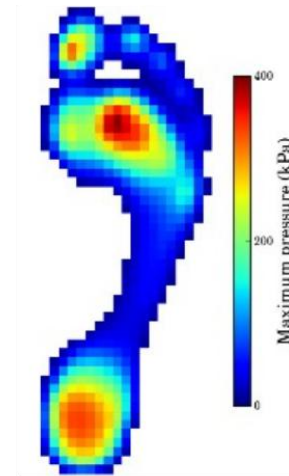
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can identify locations of high pressure. These maps can help a therapist determine the cause of injury or pain to create a plan of treatment or identify the type of intervention needed.



(a)



(b)

Figure 2: (a) A force plate; (b) foot pressure on the force plate

(a) Adapted from <https://commons.wikimedia.org/wiki/File:Stabiloplatforma-sport.JPG>; (b) adapted from https://commons.wikimedia.org/wiki/File:Example_foot_pressure.png

Self-Assess

Question: What are ground reaction forces? Name some devices used in measuring ground reaction forces.

Answer:

The contact force we experience when interacting with the ground is called the Ground Reaction Force (GRF). It is a Newton's 3rd Law reaction force that arises due to our interaction with the ground.

Force plates and pressure sensor arrays are used to measure ground reaction forces.

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2. Human Gait Analysis

Biomechanics researchers analyze gait by breaking the motion into cycles and then physically graphing GRF vs. time using a Force Platform (Force Plate).

Each cycle in the human gait is further broken into a **stance phase**, where one foot is in contact with the ground, and a **swing phase**, where the same foot swings into the air. Figure 3 (a) depicts a complete gait cycle that begins when one foot (right foot shown in green in Figure 3(a)) contacts the ground, swings, and makes the next initial contact. Figure 3(a) shows that each gait cycle is divided into the stance phase (light gray region in Figure 3(a)) and the swing phase (dark gray region in Figure 3(a)).

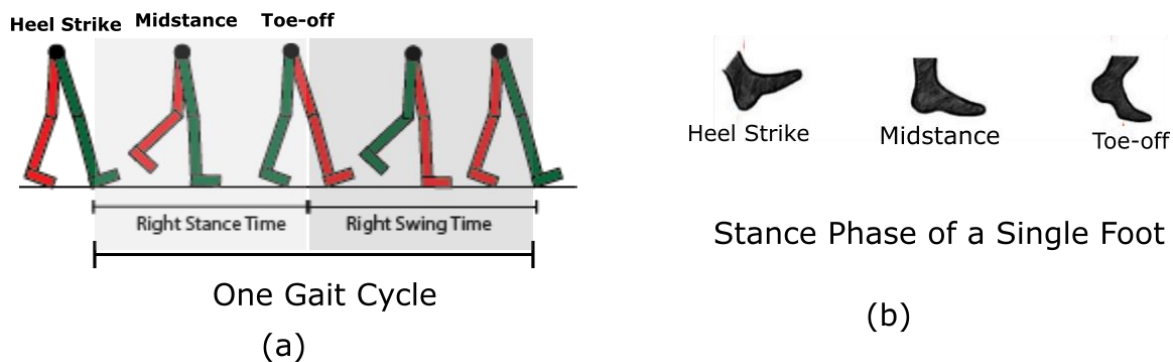


Figure 3: (a) shows a complete gait cycle. Each cycle consists of a stance phase and a swing phase. (b) shows the breakdown of the stance phase into heel-strike, midstance, and toe-off.

Adapted from https://commons.wikimedia.org/wiki/File:Gait_Cycle.png

The stance phase is further divided into **Heel Strike**, **Midstance**, and **Toe-Off** as shown in Figure 3(b). Heel strike represents the short period when the heel touches the ground. Midstance is roughly the stage when the foot completely touches the ground, and the single leg supports the entire body weight. Toe off is the short period when the toe leaves the ground. In this stage, the body is propelled forward.

Notice that during a gait cycle:

1. Right foot toe-off coincides with the left foot heel strike and vice-versa.
2. Right foot midstance coincides with the left foot swing.

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Try this Activity

Beginning by taking a step forward with your right foot, walk slowly across the room and “feel” the normal forces on your feet as you walk.

Answer the questions below:

- 1) When your right foot is in heel strike, what is your left foot doing?
- 2) As your right foot moves from heel strike to midstance, what is your left foot doing?
- 3) As your right foot moves from midstance to toe-off, what is your left foot doing?
- 4) Feel your weight move up and down as you shift from your right foot to your left foot.

2.1 Coordinate System While Walking

Let us analyze the forces during the stance phase. Figure 4 establishes the coordinate system while walking. It shows the vertical direction. The horizontal plane is further described by two perpendicular directions:

- 1) the anterior-posterior direction, which is in the direction of motion, and
- 2) the mediolateral direction, which is perpendicular to the motion.

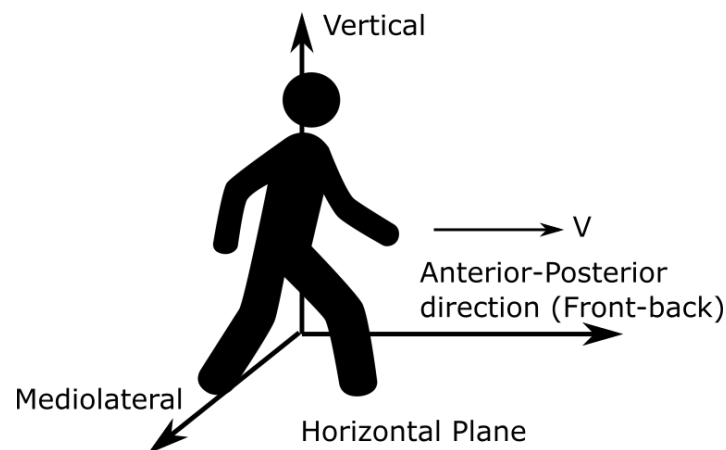


Figure 4: Directions during walking used in detecting forces. The two directions in the horizontal plane are anterior-posterior or front to back, which coincides with the direction of walking. The mediolateral direction is also in the horizontal plane but perpendicular to the anterior-posterior direction.

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2.2 Draw Force Vectors During the Stance Phase

1. Draw vectors for the GRF and the force of the person on the ground, F_{PG} , in the diagram in Figure 5 during the stance phase or use the simulation below. **Note that the person and the ground are shown as two different dots to highlight that the two forces act on different systems.** To illustrate the drawing of the force vectors, the GRF and the force of the person on the ground, F_{PG} , are drawn in Figure 5 for heel-strike.

2. Draw the vertical and horizontal components for the GRFs for all three stages of the stance phase.

Answer the following questions.

Do the GRF and F_{PG} act on the same object?

Do the GRF and F_{PG} form an action-reaction pair obeying Newton's Third Law?

How do the magnitudes of GRF and F_{PG} compare?

Note: For midstance, assume that you push the ground vertically down.

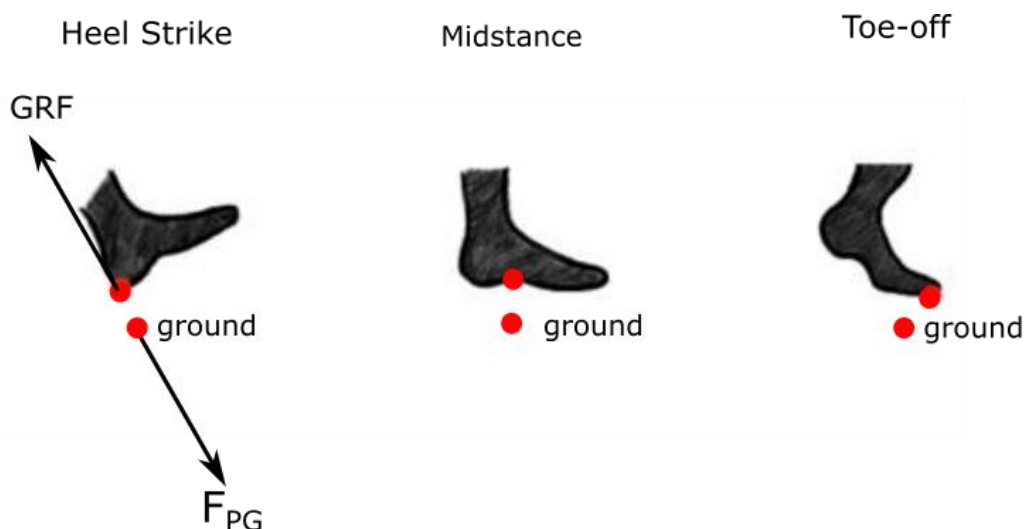


Figure 5: Draw vector diagrams of the force exerted by the person on the ground and the ground on the person during the stance phase. The forces are drawn for heel-strike.

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2.3 Simulation: Stance Phase

Instructions

Three foot-positions of the stance phase, heel strike, midstance, and toe-off, are shown below. For each of the foot positions, two forces will act on the foot-ground system. One acts on the foot, called the Ground Reaction Force (GRF). The other is equal and opposite and magnitude (as per Newton's Third Law) and acts on the ground.

For the simulation below:

<https://www.geogebra.org/m/yp6sqg2v>

1. Drag the tails of each of the six red vectors to the appropriate foot-ground system.
2. Forces acting on the foot should go on the upper green dots.
3. Forces acting on the ground should go on top of the lower green dots.
4. Click submit to see which of these vectors are in the correct location, and click reset to move all vectors back to their original positions.

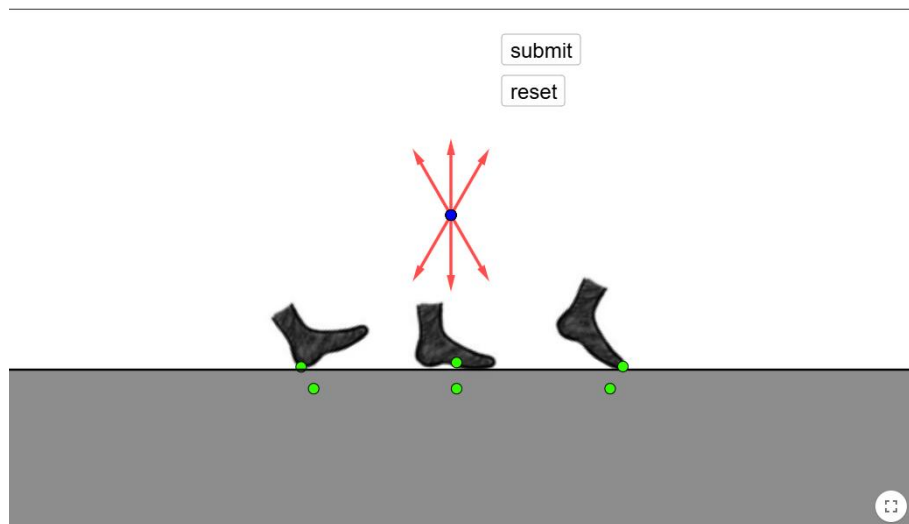


Figure 6

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3. Force-Time Graph for GRF Components

Figure 7 is a typical force-time graph for the stance phase while walking. The plot is qualitative in nature, but we can draw many inferences from it. The graph shows the vertical component of the GRF provided by the **normal force** on the person and a horizontal component of the GRF in the anterior-posterior direction provided by the **frictional force** on the person. We are going to ignore the contribution to friction from the horizontal component of the GRF in the mediolateral region in this analysis.

The blue line in Figure 7 represents the body weight of the person.

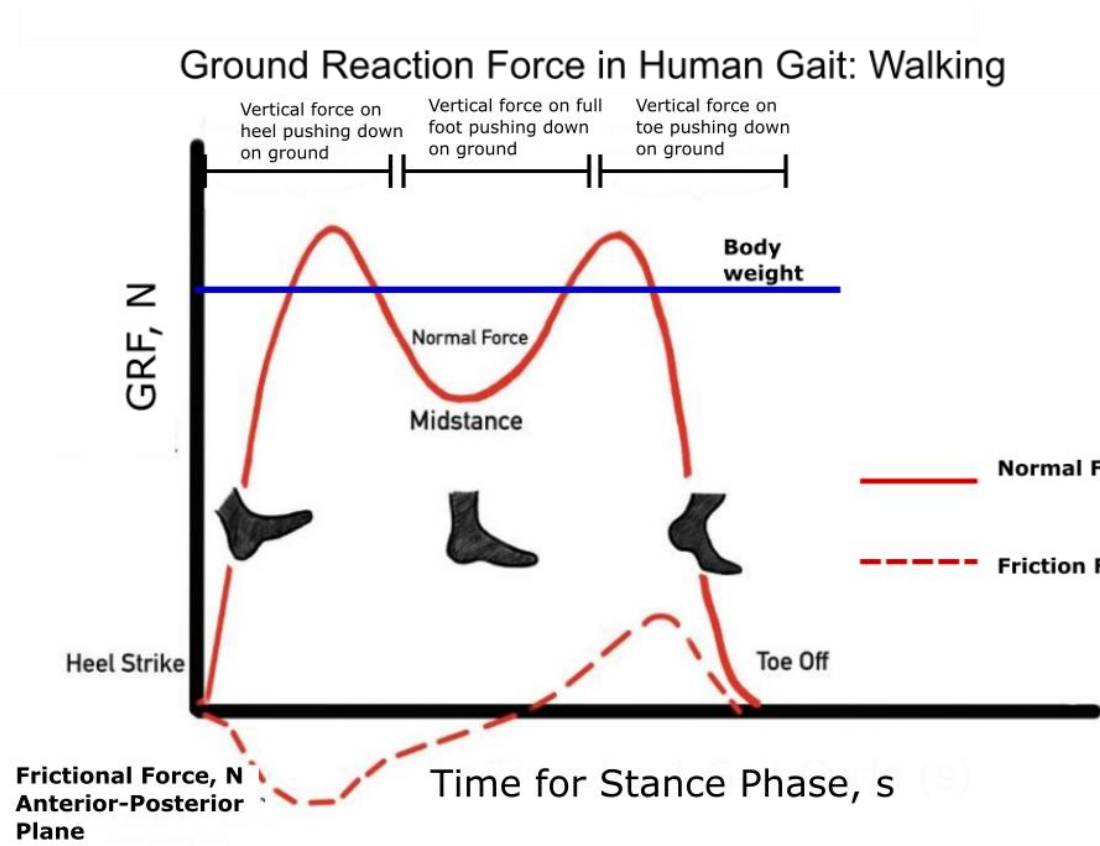


Figure 7: The figure illustrates the three important time intervals of the stance phase (Heel Strike, Mid Stance, and Toe-Off) during walking and a contact force-time graph that includes a measure of the vertical component of the GRF provided by the normal force and the horizontal component provided by the frictional force.

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Answer the Following Questions Using the graph in Figure 7.

The person in the graph in Figure 7 is taking one full step to the **right**. Define your coordinate system **for this graph** of human gait. You'll need to define the coordinate system for both vertical and horizontal directions.

- Positive vertical direction: up or down?
- Positive horizontal direction: right or left?
- Negative vertical direction: up or down?
- Negative horizontal direction: right or left?

Answers

- Positive vertical direction: up
- Positive horizontal direction: right
- Negative vertical direction: down
- Negative horizontal direction: left

Make the following observations from the graph in Figure 7. Discuss your observations with your peers or in class.

- Mark regions of largest normal force. When do they occur in the gait cycle?
- Mark regions of largest frictional force. When do they occur in the gait cycle?
- Why do you think the frictional force changes from positive to negative?
- Why do you think the normal force dips in midstance?
- What happens to the frictional force in midstance?

4. Motion Capture Graph

GRF Force-time graphs are widely used in research in such areas as gait analysis, prosthetics, orthotics, and shoe-wear design. View the image in Figure 8 from a motion-capture system and then answer the question below. To gather movement data, reflective markers are placed at key points on a patient, including legs, arms, and hips. Encircling the room are eight specialized cameras with light-emitting diodes, known as LEDs, that flash at 120 times per second and record reflections of the markers in true three-dimensional volume as the patient walks.

The **angle and position of every joint (dots and angles between segments connecting the dots**

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in Figure 8) -- ankles, hips, arms, pelvis, etc. -- is recorded in real time and expressed as stick-figure renditions of the patient walking. The red arrows in Figure 8 represent the GRFs on the two legs.

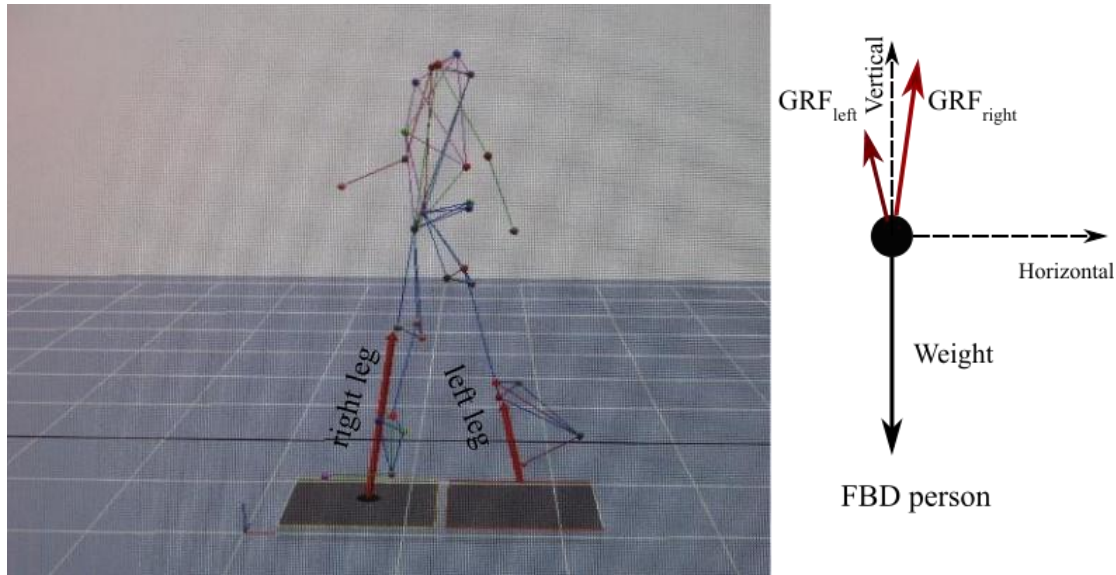


Figure 8: To gather movement data, reflective markers are placed at key points on a patient, including legs, arms, and hips. Encircling the room are eight specialized cameras with light-emitting diodes, known as LEDs, that flash at 120 times per second and record reflections of the markers in true three-dimensional volume as the patient walks. The angle and position of every joint -- ankles, hips, pelvis, etc. -- is recorded in real time and expressed as stick-figure renditions of the patient walking. Defense Dept. photo by Fred W. Baker III. The diagram on the right shows the FBD of the person.

Adapted from https://archive.defense.gov/DODCMSShare/NewsStoryPhoto/2007-06/hrs_070321-D-1852B-004.jpg

Check Your Understanding

Use the motion capture diagram to predict the stage of gait analysis of the person whose data is being collected. You can try to simulate this stage (heel strike, midstance, or toe-off) with your own body. Try to feel the uneven nature of the GRFs on the two feet.

Is there a difference in the GRF acting on each leg? If so, predict some possible reasons why.

Net Force in the Vertical and Horizontal Directions

Using the FBD Figure 8, do the following.

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1. Study the FBD of the person in Figure 8.
2. Resolve all forces in terms of their components in the vertical and horizontal directions. Label the components of each force.

Net force in the vertical direction

1. What is the net force in the vertical direction? Make sure to include the signs of the components and the magnitude of the components.
2. Is the net force in the vertical direction **always** zero?
3. If the net force in the vertical direction is not zero, when is it positive and when is it negative? What is the net vertical force responsible for?
4. What should the **average net vertical force** during one gait cycle be?

Net force in the horizontal direction in the anterior-posterior direction

1. What is the net force in the horizontal direction?
2. Is the net force in the horizontal direction **always zero**?
3. If the net force in the horizontal direction is not zero, when is it positive and when is it negative? What is the net horizontal force responsible for?
4. If the person walks with constant velocity, what should the **average net horizontal force** during one gait cycle be?

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5. GRF during Running and Walking

Figure 9 shows the force-time graph for the normal force of the GRF while walking and running in terms of body weight.

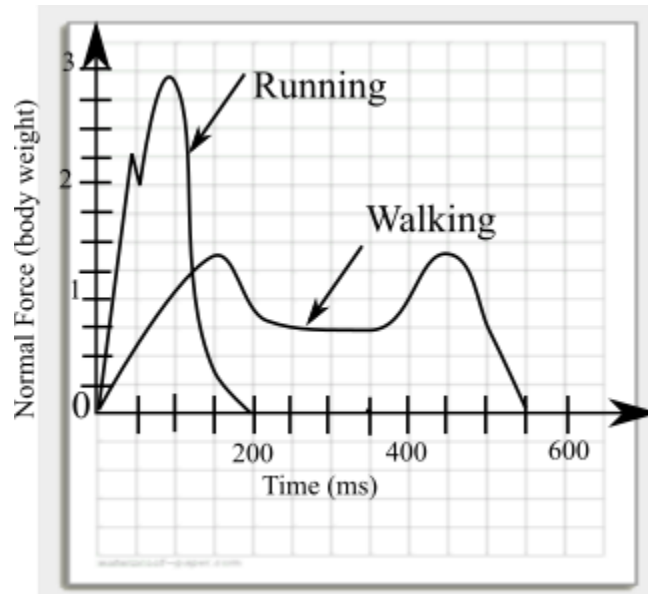


Figure 9: Normal force during running and walking

Make the following observations.

1. For which plot is the normal force greater? Compare in terms of body weight. What does a higher normal force say about the net force in the vertical direction? What implications will this have for the total time in the air?
2. For which graph is the **contact time** smaller?

Discuss with your class how these differences can impact sports performance.

Self-Assess

Question: What are the important phases in the human gait cycle?

Answer:

The important phases of human gait during walking are 1) the stance phase, and 2) the swing phase. The stance phase is further divided into heel strike, midstance, and toe-off.

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6. Ground Reaction Forces & Injury

The GRF is responsible for the forces that are exerted on your feet, knees, and all the way up the kinetic chain of your body. If you jump and land hard on the ground, the ground will push back up hard on you – this is the cause for many joint injuries and an area of investigation for many orthopedists, prosthetists, physical therapists and occupational therapists, and athletic trainers. Use the image in Figure 10 to answer the questions below the diagram.

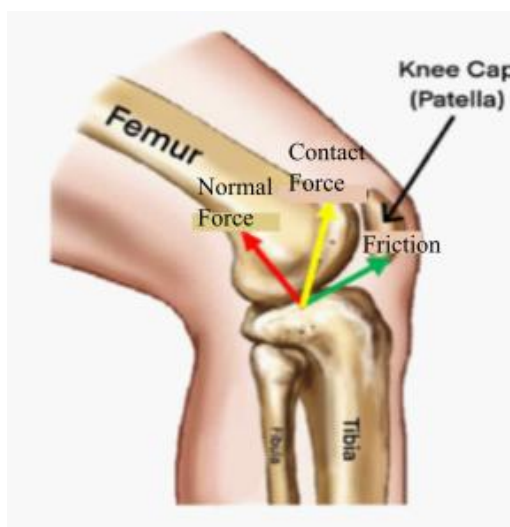


Figure 10: The knee joint. The force on the femur (thigh bone) by the tibia/fibula (leg bones). The contact force is shown in yellow, the normal force in red, and the friction force is shown in green.

- 1) Draw a vector diagram (Figure 11) to illustrate what would happen to the contact force the tibia exerts on the femur (magnitude and direction) if this person landed very hard on the ground from a fall. Leave the frictional force the same.
- 2) Draw a vector diagram to illustrate what would happen to the contact force the tibia exerts on the femur for a patient with osteoarthritis. Assume the normal force remains constant.
- 3) How does the contact force the tibia exerts on the femur compare to the contact force the femur exerts on the tibia?

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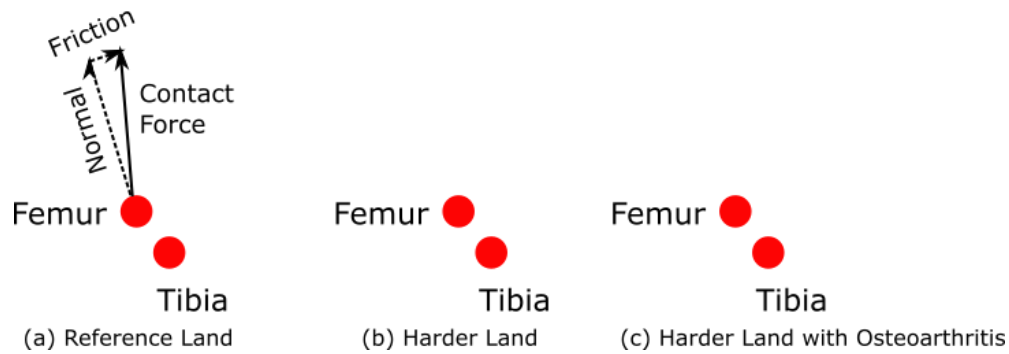


Figure 11: Draw vector diagrams of the forces on the femur and the tibia with their components in a knee joint during landing. An example of the force on the femur due to the tibia is shown in (a).

Large contact forces can damage our knees. Fortunately, our body has developed a sort of “shock absorber” system to protect our femur and tibia from contact forces when we walk, run, or jump. **Error! Reference source not found.** illustrates a more complete image of the anatomical knee. Note the cartilage covering the ends of the bones at the knee joint. Cartilage acts as a shock absorber that cushions the bones, allowing them to move smoothly. Cartilage can become damaged through arthritis or by an accident (i.e., skiing accident, etc.), leading to stiff knee joints. In many of these cases, a knee replacement will be necessary to reduce pain in the knee joint. As discussed earlier in this chapter, synovial fluid is found in the synovial cavity between the femur and tibia. The principal function of synovial fluid is to reduce friction between the articular cartilage of synovial joints during movement. Figure 12 also shows the ligaments that connect the femur and tibia, and the tendons that connect the muscles that provide force to move the bones.

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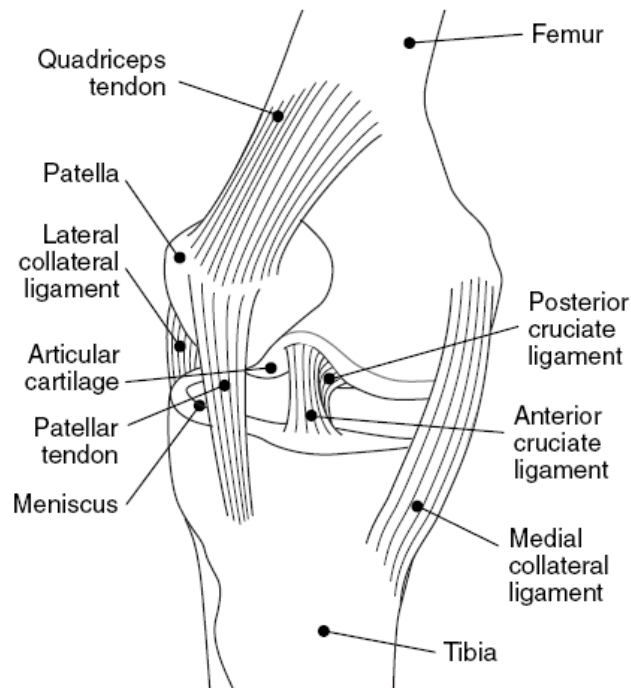


Figure 12: Anatomical image of the knee (image from public domain)

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