Hooke’s law: applications of a recurring principle

Mauricio J. Giuliodori,1 Heidi L. Lujan,2 Whitney S. Briggs,2 Gurunathan Palani,2 and Stephen E. DiCarlo2

1Cátedra de Fisiología, Facultad de Ciencias Veterinarias, Universidad Nacional de La Plata, La Plata, Argentina; and 2Department of Physiology, Wayne State University School of Medicine, Detroit, Michigan

Submitted 11 June 2009; accepted in final form 3 August 2009

How We Teach

Giuliodori MJ, Lujan HL, Briggs WS, Palani G, DiCarlo SE. Hooke’s law: applications of a recurring principle. Adv Physiol Educ 33: 293–296, 2009; doi:10.1152/advan.00045.2009.—Students generally approach topics in physiology as a series of unrelated phenomena that share few underlying principles. However, if students recognized that the same underlying principles can be used to explain many physiological phenomena, they may gain a more unified understanding of physiological systems. To address this concern, we developed a simple, inexpensive, and easy to build model to demonstrate the underlying principles regarding Starling’s Law of the Heart as well as lung and arterial elastic recoil. A model was chosen because models significantly enhance student understanding. Working with models also encourages research-oriented learning and helps our students understand complex ideas. Students are drawn into discussion by the power of learning that is associated with manipulating and thinking about objects. Recognizing that the same underlying principles can be used to explain many physiological phenomena may help students gain a more complete understanding of physiological systems.

Starling’s Law of the Heart; elastic recoil; educational model

M Odell has suggested that students generally approach topics in physiology as a series of unrelated phenomena that share few underlying principles (10). He further suggested that if students recognized that the same underlying principles can be used to explain many physiological phenomena, they may gain a more unified understanding of physiological systems (10). In an attempt to follow Modell’s suggestions, we developed a simple, inexpensive, and easy to build model to demonstrate the underlying principles regarding Starling’s Law of the Heart as well as lung and arterial elastic recoil.

A model was chosen because models significantly enhance student understanding (4). Simple, inexpensive models encourage research-oriented learning and are often used to explain complex ideas because models promote logic, reasoning, and creativity (1, 2, 5–8, 11–14). Physical models relate the unknown to the familiar and provide a new perspective on information gathering. Models also encourage a see-touch interaction to supplement new information processing while promoting curiosity, healthy skepticism, objectivity, and the use of scientific reasoning (4).

Robert Hooke was a 17th century British physicist. In 1678, he proposed Hooke’s Law in his essay “Ut tensio sic vis” (9) by stating that “The power of any springy body is in the same proportion with the extension.” This statement gave birth to the concept of elasticity. Elasticity is the physical property of a material that deforms under stress but returns to its original shape (or position) when the stress is removed. In other words, Hooke’s Law (one dimension) describes the relationship between the force applied to an unstretched spring and the amount the spring is stretched when the force is applied.

Hooke’s Law is stated mathematically as follows:

\[ F = -kx \]

(1)

where \( F \) is the applied force exerted by the spring (expressed in Newtons) and \( x \) is the distance the spring has been stretched away from its equilibrium position when its subjected to the force. The equilibrium position is the position where the spring would naturally come to rest and is expressed in meters. Finally, \( k \) is the spring constant, i.e., the ratio of \( F \) and \( x \), and is expressed in Newtons/meter. Note the negative sign on the right side of the equation. This is due to the fact that the restoring force always acts in the opposite direction of the \( x \) displacement (i.e., when a spring is stretched to the left, it pulls back to the right).

Now consider Hooke’s Law in physiological terms. The force (pressure) exerted by an elastic material during restoration (recoil) is proportional to the stress (deformation or length) imposed on it. Thus, if the stress (distance) increases, the force (recoil) increases. In this way, Hooke’s Law could be used to help explain length-tension relationships of the heart (Starling’s Law) as well as elastic recoil of the lungs and arteries.

METHODS

We developed a simple, inexpensive, and easy to build model to demonstrate Hooke’s Law (Fig. 1) and to simulate these relationships. The materials required to build the model are shown in Fig. 2.

To build the model, first drill two small holes into each of the nylon washers (Fig. 2, no. 3). The holes should be on opposite sides of the center and \( \sim 0.5 \) cm from the edge of the washers. (There may be slight warping of the washers due to prolong drilling; be sure to pause drilling about every 1–1.5 min to avoid overheating the washers.) Insert a twist tie (Fig. 2, no. 4) into each of the small holes of the washers. With the twist ties, fasten each end of the extension springs (Fig. 2, no. 7) onto the washers. The washers and springs should be perpendicular to each other.

Cut a 1-cm slit in the center of one of the pieces of nonadhesive shelf liner (Fig. 2, no. 5). Place the shelf liner with the cut-out center around the luer of the syringe (Fig. 2, no. 2) and the other piece of shelf liner on the end of the syringe’s plunger. Place the syringe between the washers (now connected to the extension springs) and attach a three-way stopcock (Fig. 2, no. 6) to the syringe. Connect the aneroid manometer (Fig. 2, no. 1) to the three-way stopcock.

In this model (Fig. 1), the extension springs are the elastic structures (heart, lungs, or arteries), the syringe represents volume (heart, lung, or arterial volume), the syringe plunger is the volume controller, and the aneroid manometer is the pressure or force measurement device. Pulling the plunger downward increases the syringe volume and stretches (strain) the springs. According to Hooke’s Law, the longer the stretch on the springs, the greater the force delivered during

MODELL has suggested that students generally approach topics in physiology as a series of unrelated phenomena that share few underlying principles (10). He further suggested that if students recognized that the same underlying principles can be used to explain many physiological phenomena, they may gain a more unified understanding of physiological systems (10). In an attempt to follow Modell’s suggestions, we developed a simple, inexpensive, and easy to build model to demonstrate the underlying principles regarding Starling’s Law of the Heart as well as lung and arterial elastic recoil.

A model was chosen because models significantly enhance student understanding (4). Simple, inexpensive models encourage research-oriented learning and are often used to explain complex ideas because models promote logic, reasoning, and creativity (1, 2, 5–8, 11–14). Physical models relate the unknown to the familiar and provide a new perspective on information gathering. Models also encourage a see-touch interaction to supplement new information processing while promoting curiosity, healthy skepticism, objectivity, and the use of scientific reasoning (4).

Robert Hooke was a 17th century British physicist. In 1678, he proposed Hooke’s Law in his essay “Ut tensio sic vis” (9) by stating that “The power of any springy body is in the same proportion with the extension.” This statement gave birth to the concept of elasticity. Elasticity is the physical property of a material that deforms under stress but returns to its original shape (or position) when the stress is removed. In other words, Hooke’s Law (one dimension) describes the relationship between the force applied to an unstretched spring and the amount the spring is stretched when the force is applied.

Hooke’s Law is stated mathematically as follows:

\[ F = -kx \]

(1)

where \( F \) is the applied force exerted by the spring (expressed in Newtons) and \( x \) is the distance the spring has been stretched away from its equilibrium position when its subjected to the force. The equilibrium position is the position where the spring would naturally come to rest and is expressed in meters. Finally, \( k \) is the spring constant, i.e., the ratio of \( F \) and \( x \), and is expressed in Newtons/meter. Note the negative sign on the right side of the equation. This is due to the fact that the restoring force always acts in the opposite direction of the \( x \) displacement (i.e., when a spring is stretched to the left, it pulls back to the right).

Now consider Hooke’s Law in physiological terms. The force (pressure) exerted by an elastic material during restoration (recoil) is proportional to the stress (deformation or length) imposed on it. Thus, if the stress (distance) increases, the force (recoil) increases. In this way, Hooke’s Law could be used to help explain length-tension relationships of the heart (Starling’s Law) as well as elastic recoil of the lungs and arteries.

METHODS

We developed a simple, inexpensive, and easy to build model to demonstrate Hooke’s Law (Fig. 1) and to simulate these relationships. The materials required to build the model are shown in Fig. 2.

To build the model, first drill two small holes into each of the nylon washers (Fig. 2, no. 3). The holes should be on opposite sides of the center and \( \sim 0.5 \) cm from the edge of the washers. (There may be slight warping of the washers due to prolong drilling; be sure to pause drilling about every 1–1.5 min to avoid overheating the washers.) Insert a twist tie (Fig. 2, no. 4) into each of the small holes of the washers. With the twist ties, fasten each end of the extension springs (Fig. 2, no. 7) onto the washers. The washers and springs should be perpendicular to each other.

Cut a 1-cm slit in the center of one of the pieces of nonadhesive shelf liner (Fig. 2, no. 5). Place the shelf liner with the cut-out center around the luer of the syringe (Fig. 2, no. 2) and the other piece of shelf liner on the end of the syringe’s plunger. Place the syringe between the washers (now connected to the extension springs) and attach a three-way stopcock (Fig. 2, no. 6) to the syringe. Connect the aneroid manometer (Fig. 2, no. 1) to the three-way stopcock.

In this model (Fig. 1), the extension springs are the elastic structures (heart, lungs, or arteries), the syringe represents volume (heart, lung, or arterial volume), the syringe plunger is the volume controller, and the aneroid manometer is the pressure or force measurement device. Pulling the plunger downward increases the syringe volume and stretches (strain) the springs. According to Hooke’s Law, the longer the stretch on the springs, the greater the force delivered during...
recoil. Therefore, the model enabled us to control and change the volume while recording the pressure exerted during spring elastic recoil (Fig. 3).

RESULTS

To test this model, the spring was stretched in 5-ml increments (5, 10, 15, 20, 25, and 30 ml in random order) by pulling down the syringe plunger. The spring recoil pressure was generated by releasing the syringe plunger. The pressure at the end of each spring recoil was recorded. This procedure was repeated three times, and the data were averaged. The syringe volume was plotted against the spring recoil pressure (means ± SE), and the data were fit by a linear regression (Fig. 3). As shown in Fig. 3, the longer the stretch on the springs (i.e., increasing the syringe volume), the greater the force delivered during recoil (i.e., increasing spring recoil pressure). Thus, the model accurately reflects Hooke’s Law.

DISCUSSION

This model was used to facilitate the understanding of Starling’s Law. Specifically, the heart is an elastic structure with an anatomic organization that promotes its collapse when stretched. The term “elastic” means a material deformed by a force tends to return to its initial shape or configuration when the force is removed. In terms of Starling’s Law, end-diastolic volume (EDV; the length of the cardiac fibers) stretches the myocardial fibers and therefore determines the force of ventricular contraction (systole). That is, the greater the filling volume, the longer the stretch on the cardiac fibers and the stronger the contraction. Thus, venous return (the amount of blood returning to the heart per minute) is the main determinant of cardiac output (the amount of blood pumped out by the heart per minute).

This model was also used to demonstrate how the lungs respond during respiration. The lung is also an elastic structure with an anatomic organization that promotes its collapse (similar to a stretched spring). The elastic properties of the lung are important to bring about expiration; however, they also oppose lung inflation. As a result, lung inflation depends on the contraction of the inspiratory muscles.

The springs on the model represent the lungs’ elastic properties (surface tension plus tissue elasticity). Thus, the higher the filling during inspiration (e.g., increased tidal volume or increased syringe volume), the stronger the lungs recoil during expiration (e.g., higher pressures developed by the springs during recoil and greater emptying of the lungs). This mechanism is very important, since as tidal volumes vary, the lungs...
are able to expire air down to functional residual capacity (equilibrium volume) by elastic recoil alone (e.g., without respiratory muscle activity). Students simulated pathological conditions by using springs with different elastances [e.g., increased elastance (restrictive) or decreased elastance (obstructive)].

Another application of this model is to simulate the elasticity of the aorta. The aorta is also an elastic structure with an anatomic organization that promotes its collapse when stretched. The aorta is stretched by the blood pumped out by the left ventricle during systolic ejection (stroke volume) and returns to its equilibrium situation during diastole due to elastic recoil. This way, the force developed by the aortic recoil (e.g., spring recoil) is proportional to the strain imposed on it by the systolic volume (e.g., syringe volume). Therefore, the aorta stores energy (potential energy) during the ejection phase and subsequently releases that stored energy (kinetic energy) during diastole. By doing so, the aorta transforms an intermittent blood flow delivered by the heart into a continuous blood flow through the capillaries. This aortic behavior is very important for the exchange of nutrients at the tissue level as well as the determination of systolic and diastolic arterial pressures.

Similarly, this model is useful for understanding the myogenic concept of local blood flow autoregulation. This concept proposes that when arterial pressure increases, the increased pressure stretches small blood vessels. In response to the stretch, the smooth muscle of the vessel wall constricts or recoils. With constriction, resistance to flow increases, and blood flow is restored to equilibrium levels. Conversely, when arterial pressure decreases, the decreased pressure reduces the stretch on the vessels. In response to the decreased stretch, the smooth muscle of the vessel relax and blood flow is restored to equilibrium levels.

Finally, students gained experience with experimental procedures and statistics by testing the model, calculating statistics for the experimental trials, and plotting the data (Fig. 3). This activity generated curiosity, healthy skepticism, objectivity, and the use of scientific reasoning.

**Limitations.** Although models are effective teaching tools because they provide the student with a familiar frame of reference that is similar to the new concept being taught (3), models also have the potential to create confusion if they are oversimplified (15). In this context, it is critical to state that Hooke’s Law is not the full explanation of the relationship between resting fiber length (preload) and stroke work. Similarly, Hooke’s Law is an oversimplification of the concept of myogenic autoregulation.

With regard to the heart, a passive length-tension relationship (noncontractile or elastic components of the muscle) is obtained by stretching cardiac muscle to several predefined lengths and measuring the tension at each length. Hooke’s Law adequately describes this phenomena. An active length-tension relationship is obtained by stimulating the muscle at each predefined length and measuring the increment in tension from its passive value. Traditionally, it has been taught that the Frank-Starling mechanism was due to the relationship (anatomy) of the actin and myosin filaments within the sarcomere. As the muscle is stretched or lengthened, the number of overlapping actin and myosin units increases. Accordingly, the higher number of overlapping actin and myosin filaments results in a greater force of contraction. However, we now know that this is not true and that increases in muscle length (or preload) are associated with altered calcium handling and the affinity of troponin C for calcium. Specifically, long sarcomere length increases calcium entry from theextracellular fluid and increases calcium affinity for troponin C.

Myogenic autoregulation also has a passive and an active process. The active process occurs due to opening of stretch-mediated Ca²⁺ channels causing vascular smooth muscle contraction. Specifically, vascular smooth muscle cells depolarize when stretched, leading to contraction. With these caveats, the use of this model to demonstrate Hooke’s Law and the elastic properties of the lungs, chest wall, and great vessels is a useful tool.

Models are important because teachers tend to overrate the importance of their instruction and underrate their influence. That is, students forget much of the information they memorize and learn. Thus, attempts to teach students all that they will need to know is futile. It is important that students develop an interest and love for lifelong learning. Thus, inspiring and motivating students is critical because unless students are inspired and motivated our efforts are pointless. Once students are inspired and motivated and have a joy, excitement, and love for learning, there are countless resources available to learn more about a subject. Inspiring and motivating students is far more important for long term-success than delivering information. In this context, we observed students engaged in the construction and testing of the model and believe that these efforts inspired students for future independent learning.

**Conclusions.** In summary, this simple, inexpensive, and easy to build model enabled us to demonstrate Hooke’s Law and illustrate how physiological phenomena such as length-tension relationships of the heart (Starling mechanism), aortic and small vessel recoil, and lung recoil share underlying principles. Recognizing that the same underlying principles can be used to explain many physiological phenomena may help students gain a more unified understanding of physiolog-
ical systems (10). In addition, the students appreciated the model and stated that it was helpful for their understanding.

REFERENCES