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A model of locomotor-respiratory coupling in quadrupeds

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Giuliodori MJ, Lujan HL, Briggs WS, DiCarlo SE. A model of locomotor-respiratory coupling in quadrupeds. *Adv Physiol Educ* 33: 315–318, 2009; doi:10.1152/advan.00057.2009.—Locomotion and respiration are not independent phenomena in running mammals because locomotion and respiration both rely on cyclic movements of the ribs, sternum, and associated musculature. Thus, constraints are imposed on locomotor and respiratory function by virtue of their linkage. Specifically, locomotion imposes mechanical constraints on breathing that require the respiratory cycle to be synchronized with gait. Thus, many mammals, including humans, synchronize respiration with the movement of the limbs during locomotion. For example, quadrupeds synchronize locomotor and respiratory cycles at a 1:1 ratio (stride/breath) over a wide range of speeds. Interestingly, quadrupeds maintain an almost constant stride frequency (and therefore respiratory frequency) at different speeds. To increase speed, quadrupeds lengthen their stride. Accordingly, to increase minute ventilation, quadrupeds must increase tidal volume since respiratory rate is coupled with stride frequency. We developed a simple, inexpensive, and easy to build model to demonstrate this concept. A model was chosen because models significantly enhance student understanding. Students are drawn into discussion by the power of learning that is associated with manipulating and thinking about objects. Building and using this model strengthen the concept that locomotor-respiratory coupling provides a basis for the appropriate matching of lung ventilation to running speed and metabolic power.

tidal volume; respiratory cycle; minute ventilation; running; teaching

DURING GALLOPING, many species exhibit a phase-locked, 1:1 coupling of breaths and strides (12, 17). This may be mediated by the fact that the thorax is alternately loaded as the forelimbs strike the ground (aiding expiration) and stretched as the forelimbs reach toward the next ground contact in the free-flight phase (aiding inspiration) (3). Importantly, many quadrupeds maintain an almost constant stride frequency (and therefore respiratory frequency) at different speeds (11). To increase speed, quadrupeds lengthen their stride. Accordingly, to increase minute ventilation, quadrupeds must increase tidal volume since respiratory rate is coupled with stride frequency (1, 2).

To demonstrate this concept, we developed a simple, inexpensive, and easy to build model. A model was chosen because models significantly enhance student understanding (6). Simple, inexpensive models encourage research-oriented learning and are often used to explain complex ideas because models promote logic, reasoning, and creativity (4, 5, 7–10, 13–16). 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 (6).

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METHODS

We developed a simple, inexpensive, and easy to build model to demonstrate locomotor-respiratory coupling in quadrupeds (Fig. 1). The materials required to build the model are shown in Fig. 2.

The Respiratory System

Step 1. To build the respiratory system, drill a 3-mm hole next to the luer in the 60-ml Becton-Dickinson catheter tip syringe body (Fig. 2, no. *1*, arrow) and insert the three-way valve (Fig. 2, no. *2*) into the hole. Secure the three-way valve in place with a glue gun (Fig. 3, no. *2*). The valve will allow you to purge air from the syringe as you insert the balloon (lung) and "set up" the system (see below).

Step 2. Place the 4-cm-long piece of tubing (6 mm outside diameter × 3 mm inside diameter; Fig. 2, no. *5*) perpendicular to the syringe, between the luer and the syringe body (Fig. 3, no. *5*). Secure the tubing in place with glue from a glue gun.

Step 3. Tie (with suture) the 4-in. balloon ("lung;" Fig. 2, no. *3*) tightly to the 15-cm piece of tubing (Fig. 2, no. *4*). Be certain that there are no air leaks between the balloon and the tubing. To check for leaks, pump air into the balloon with a syringe connected to the opposite end of the tubing.

Step 4. Remove the plunger from the syringe (Fig. 2, no. *1*) and put the tubing with the balloon attached (Fig. 2, nos. *3* and *4*) into the syringe body. Advance the tubing through the luer. From the outside of the syringe, pull the tubing and balloon into the luer (Fig. 3). To avoid air loss from the syringe through the luer, seal the luer with glue from a glue gun (Fig. 3).

Step 5. Drill a 5-mm hole through the syringe plunger (Fig. 2, no. *1*, and Fig. 3) 1 cm from the end (the end where you hold the plunger with your hands). This completes the construction of the respiratory system.

The Quadruped

Step 1. Drill a 5-mm hole completely through four of the five long threaded tubes exactly 4.5 cm from the end (Fig. 2, no. *9*). These four tubes will function as the legs (Fig. 4, no. *9*).

Step 2. Drill a 5-mm perpendicular oval completely through the center of one of the short threaded tubes (Fig. 2, no. *12*). This oval will function as a "slot" to allow the model to move as part of the hip girdle (Fig. 4, no. *12*).

Step 3. Drill a 5-mm perpendicular oval completely through the center of the T-connector (Fig. 2, no. *11*). This oval will also function as a "slot" to allow the model to move as part of the shoulder girdle (Fig. 4, no. *11*).

Step 4. Attach a coupler (Fig. 2, no. *10*) to each of the four long threaded tubes on the end farthest from the hole (Fig. 2, no. *9*). The couplers will function as the hooves (Fig. 4, no. *10*). Attach the elbow coupler (Fig. 2, nos. *7* and *8*) to the opposite end. These will become part of the hip and shoulder girdles (Fig. 4, nos. *7* and *8*).

Step 5. To complete the hip girdle, attach the short threaded tube with the 5-mm slot (Fig. 2, no. *12*) to the elbow couplers (Fig. 4, no. *8*) on two of the long threaded tubes that function as legs.

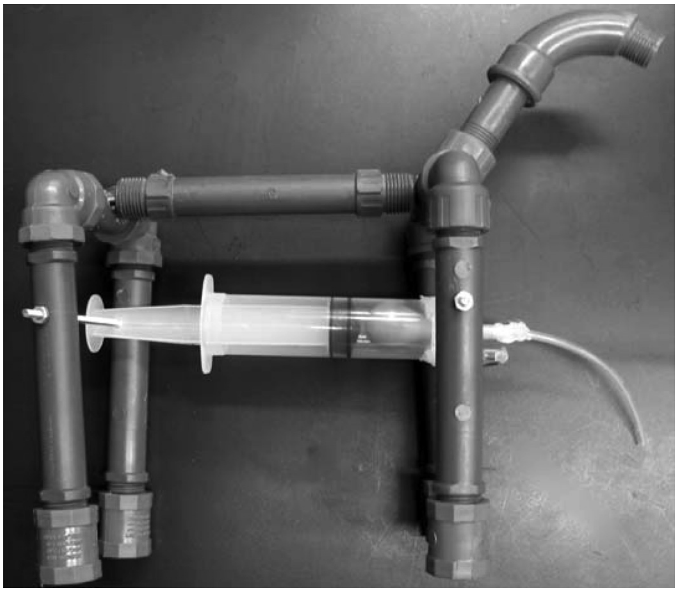


Fig. 1. The simple, inexpensive, and easy to build model to demonstrate locomotor-respiratory coupling in quadrupeds.

Step 6. To complete the shoulder girdle, attach the T-connector with the 5-mm slot (Fig. 2, no. *11*) to the elbow couplers (Fig. 4, no. *7*) on two of the long threaded tubes that function as legs.

Step 7. To create the base of the neck (Fig. 4, no. *12a*), attach the short connector without the hole (Fig. 2, no. *12a*) to the T-connector (Fig. 2, no. *11*) at the perpendicular opening (Fig. 4).

Step 8. To build the head, attach the curved coupler (Fig. 2, no. *6*) to the short connector without the hole (Fig. 4, no. *12a*).

Step 9. To connect the shoulder girdle with the hip girdle, place the 23-cm long rod (Fig. 2, no. *13a*) lengthwise through the center of the long connector without the hole (Fig. 2, no. *9a*) and through the T-connector hole of the shoulder girdle as well as the slot of the short connector that functions as the pelvic girdle (Fig. 4).

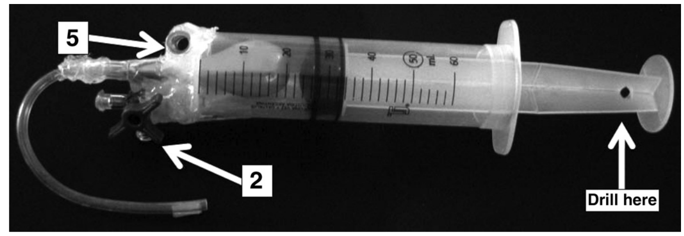


Fig. 3. The completed respiratory system. *2*, Secure the 3-way valve in place with a glue gun here; *5*, place the 4-cm-long piece of tubing (6 mm outside diameter × 3 mm inside diameter; Fig. 2, no. *5*) perpendicular to the syringe here, between the luer and the syringe body.

Step 10. Secure the shoulder and hip girdle together by placing two 8-mm nuts (Fig. 2, no. *14*) on the ends of the rod.

Connecting the Respiratory System to the Quadruped

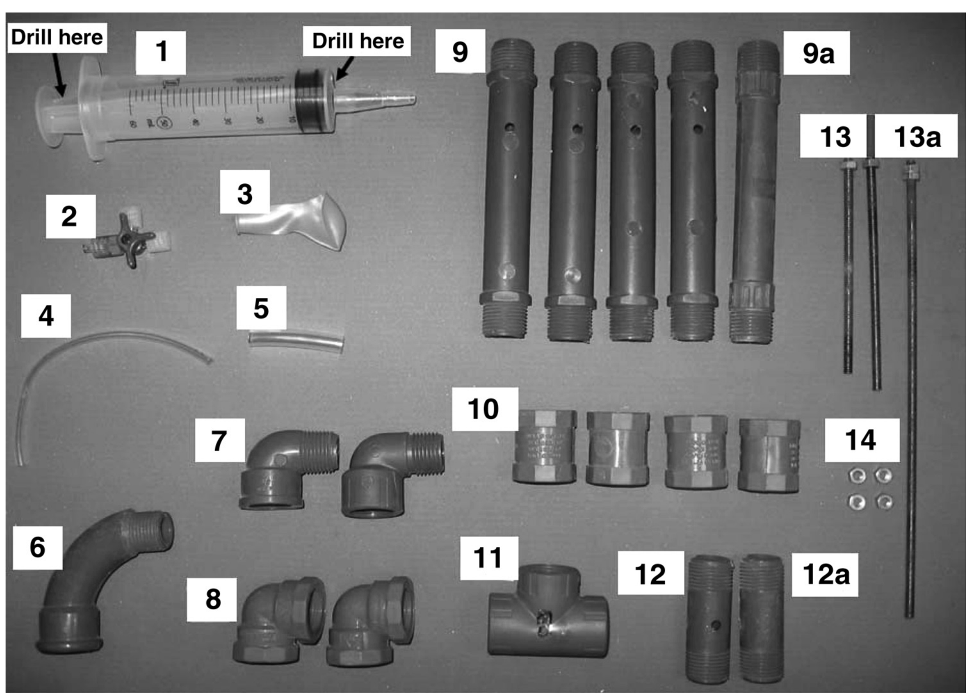
Step 1. Place one 11-cm-long rod (Fig. 2, no. *13*) through the holes of the long threaded tubes that function as the hindlimbs and through the hole in the syringe plunger (the syringe plunger should be between the legs). Secure this in place by attaching an 8-mm nut on the both ends of the rod (Fig. 4).

Step 2. Place the other 11-cm-long rod through the long threaded tubes that function as the forelimbs and through the tube attached to the syringe (the tube should be between the legs). Secure this in place by attaching an 8-mm nut on the both ends of the rod.

The three-way valve (Fig. 3, no. *2*) is used to set the initial (at rest) balloon volume since it allows us to control the pressure within the "pleural space." Once lung volume is set at the desired level, the valve should be closed for the model to work properly.

In this model, the syringe represents the quadruped body (thorax and abdomen) and the plunger is the diaphragm and abdominal viscera. The syringe is attached to the forelimbs, and the plunger is attached to hindlimbs. This important linkage couples the movement of the limbs with the movement of the plunger within the syringe. Specifically, the body is stretched and the plunger is pulled outward as the forelimbs reach toward the next ground contact in the free-flight

Fig. 2. Materials required to build the model. *1*, 60-ml Becton-Dickinson catheter tip syringe body; *2*, three-way valve; *3*, 4-in. balloon; *4*, 15-cm-long piece of tubing; *5*, 4-cm-long piece of tubing; *6*, curved coupler; *7*, elbow couplers; *8*, elbow couplers; *9*, four long threaded tubes (with holes); *9a*, long threaded tube without a hole; *10*, four couplers; *11*, T-connector; *12*, one short threaded tube with a hole; *12a*, short threaded tube without a hole; *13*, two 11-cm-long rods; *13a*, 23-cm-long rod; *14*, four 8-mm nuts.



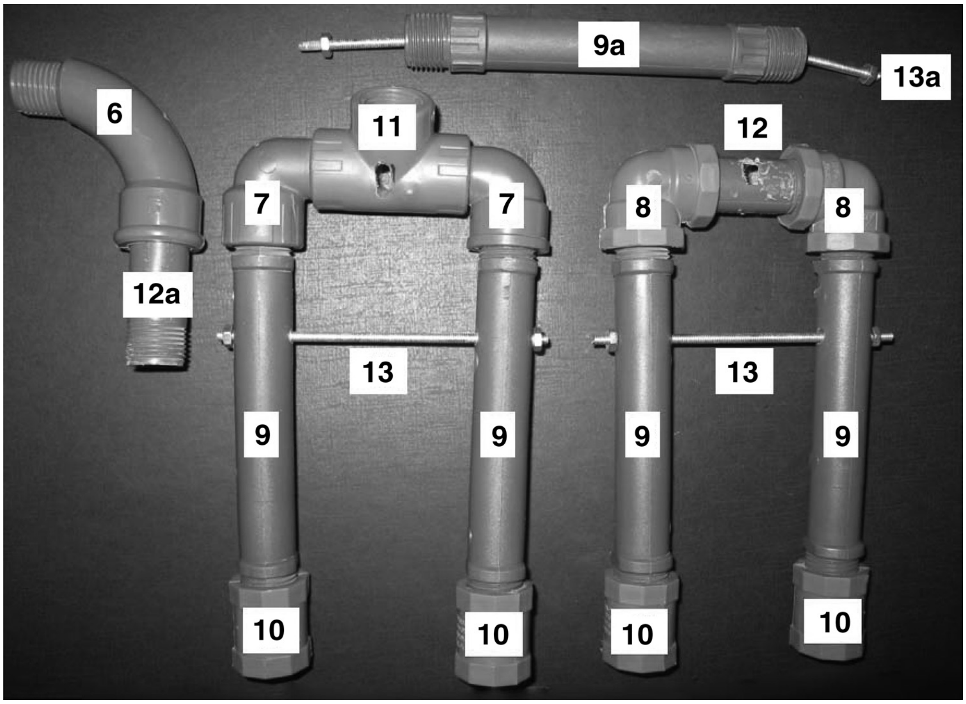


Fig. 4. The partially completed quadruped. *6*, The head; *7*, hip girdle; *8*, shoulder girdle; *9*, four tubes that function as the legs; *9a*, tube that functions as the torso; *10*, couplers that function as the hooves; *11*, oval "slot" to allow the model to move as part of the shoulder girdle; *12*, oval "slot" to allow the model to move as part of the hip girdle; *12a*, base of the neck; *13*, leg connector; *13a*, torso connector.

phase [aiding inspiration when the fore- and hindlimbs are separated (Fig. 5*A*)]. This causes the syringe volume to increase, and air flows into the lungs (balloon). This models what happens when quadrupeds have their hindlimbs on the ground and are thrusting forward. Conversely, the thorax is loaded as the forelimbs subsequently strike the ground (aiding expiration) because the fore- and hindlimbs move closer together (Fig. 5*B*). During this event, the syringe volume decreases because the plunger is pushed up into the syringe and air flows out of the lungs (balloon). This models what happens when quadrupeds have their forelimbs on the ground and their hindlimbs are moving forward.

RESULTS

To test this model, stretch the forelimbs forward while maintaining the hindlimbs stationary on a smooth surface. Air will enter the lungs (i.e., the balloon will expand). This models the quadruped thrusting forward and reaching toward the next ground contact in the free-flight phase, thus aiding inspiration. Next, hold the forelimbs stationary on a smooth surface and move the hindlimbs forward. Air will exit the lungs (i.e., the balloon will collapse). This models loading the forelimbs as the forelimbs strike the ground and the hindlimbs move forward, thus aiding expiration. As shown in Fig. 5, *A* and *B*, the model accurately reflects locomotor-respiratory coupling in a quadruped.

DISCUSSION

This simple, inexpensive, and easy to build model enabled us to demonstrate locomotor-respiratory coupling in quadrupeds during running. Most importantly, we observed engaged and inspired students because the model created a joy, excitement, and love for learning and made learning fun. The students, in our opinion, appreciated building and working with the model and said it was helpful to their understanding of the topic. These are important considerations because a report from the Association of American Medical Colleges (AAMC) and the Howard Hughes Medical Institute (HHMI) strongly stated that "Curiosity, skepticism, objectivity, and the use of scientific reasoning are fundamental to the practice of medicine. These attributes should permeate the entire medical education continuum."

Most of the information that our students will use in their future careers is not known today and must be learned after

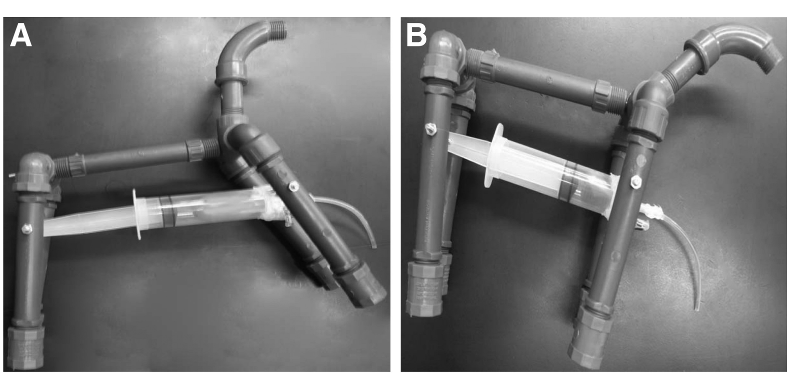


Fig. 5. To test this model, stretch the forelimbs forward while maintaining the hindlimbs stationary on a smooth surface. Air will enter the lungs (i.e., the balloon will expand) (*A*). This models the quadruped thrusting forward and reaching toward the next ground contact in the free-flight phase, thus aiding inspiration. Next, hold the forelimbs stationary on a smooth surface and move the hindlimbs forward. Air will exit the lungs (i.e., the balloon will collapse) (*B*). This models loading the forelimbs as the forelimbs strike the ground and the hindlimbs move forward, thus aiding expiration. *A* and *B* show that the model accurately reflects locomotor-respiratory coupling in a quadruped.

graduation. Furthermore, not all that is known can be taught in 4 yr, and not all that is taught can be learned or remembered. Thus, attempts to teach students all that they will need to know is futile. Rather than attempting to teach students all that they will need to know we should inspire and motivate our students. Once students are inspired and motivated, countless resources are 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 student for future independent learning.

Although humans use a bipedal gait and the forearms no longer contact the ground during running, locomotion and respiration remain coupled. This occurs because the shoulders, arms, head, and neck are coupled to the thorax by a series of muscles [sternocleidomastoid, scalene muscles, serratus anterior, levator scapulae, pectoralis major, pectoralis minor, upper trapezius, latissimus dorsi, erector spinae (thoracic), iliocostalis lumborum, quadratus lumborum, and subclavius] supporting the ribs and sternum. Thus, in the upright posture, the thorax is supported by a muscular sling that provides cycles of loading and unloading during forearm motion and running. In addition, the body is alternately accelerated and decelerated in the vertical planes (3) causing the abdominal contents to shift position within the abdominal cavity and function as a "visceral piston." The visceral piston couples respiration by altering intra-abdominal and intrathoracic volume and pressure (2). The dominant coupling ratio for humans is 2:1 over a wide range of speeds and strides frequencies (2); however, slow running speeds are often associated with a 4:1 ratio.

It is important to note that although locomotion and respiration are coupled in humans during upright gait, the coupling is more complex for humans than for quadrapeds. The complexity occurs because stride frequency is generally faster than respiratory frequency (2:1 over a wide range of speeds; however, slow running speeds are often associated with a 4:1 ratio). Hence, a single respiratory cycle will coincide with several "locomotor cycles," and, typically, inspiration will occur during one (or several) stride(s) and expiration will occur during a subsequent stride (which does not differ from the "inspiratory stride" in terms of arm movement or vertical acceleration/deceleration). Thus, students must be aware that although locomotion and respiration are coupled in humans during upright gait, the mechanisms underlying this coupling are more complex.

Conclusions

In summary, it is well known that many mammals, including humans, synchronize respiration with limb movement during locomotion. For example, many quadrupeds synchronize locomotor and respiratory cycles at a ratio of 1:1 (stride/breath) over a wide range of speeds. We created a simple, inexpensive, and easy to build model to demonstrate this coupling. Using this model, we observed engaged and inspired students because the model created a joy, excitement, and love for learning and made learning fun. The students appreciated building and working with the model. In addition, the students appreciated the model and stated that it was helpful for their understanding.

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