Kangaroo metabolic energy: Day 3 of the Kangaroo Locomotion Case Study

(Teacher notes in blue, with sample student predictions and brief discussion of correct answers to analysis questions.)

Names:

Kangaroos use two different types of locomotion. **Please watch the video provided of a young kangaroo using both types of locomotion.** The first type of locomotion utilizes a distinctive gait for slow speeds (<6km/hr.) referred to as pentapedal locomotion. This mode utilizes both hind and forelimbs as the kangaroo stretches out, as well as a muscular tail that helps support the animal's body weight while it repositions its hind legs to reset the cycle. At faster speeds, kangaroos switch to bipedal hopping, which relies on their muscular hind limbs to generate propulsion. As you analyze each type of locomotion, keep in mind its distinctive features such as: **maneuverability** – ability to quickly change direction, **stability** – resistance to tipping by maintaining center of mass over contact points with the ground, **metabolic energy cost of transport** – the number of Calories burned through metabolism per distance travelled, **musculoskeletal biomechanics** – how muscles, bone, and connective tissue produce movement.

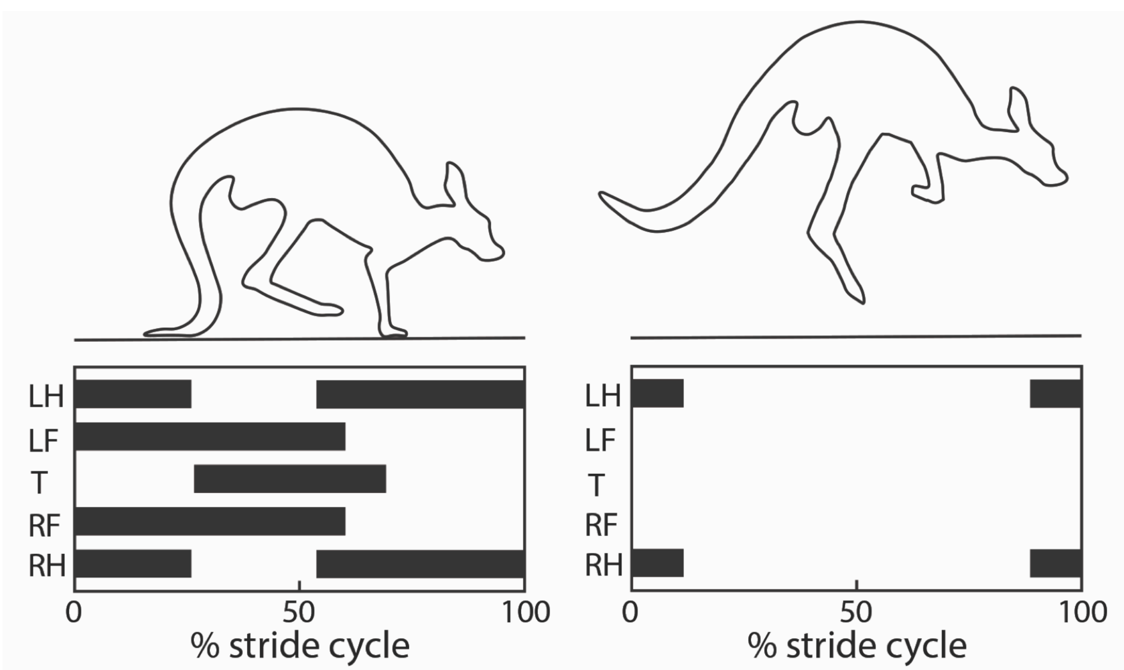


Illustration of kangaroo pentapedal and bipedal hopping locomotion gaits. Chart of limb-ground contact patterns: LH: left hind leg; LF: left front leg; T: tail; RF: right front leg; RH: right hind leg

Questions:

1. If a kangaroo is traveling 4.2 km/hr, what type of locomotion will the kangaroo most likely use? What about at 15.0 km/hr?

Since it is stated above that kangaroos generally use pentapedal locomotion when moving below ~ 6 km/hr, it is likely using this type at 4.2 km/hr, and it is most likely hopping at 15.0 km/hr since that is well above 6 km/hr. (Students should outline their quantitative reasoning for their answer.)

2. What type of locomotion do you think provides the greatest stability during movement? Explain your reasoning.

Pentapedal locomotion provides more contacts with the ground and a lower base of support for increased stability. It would also be reasonable to suggest that being closer to the ground will result in less gravitational potential energy, and lower potential energy is associated with increased stability. (Great answers would include reference to the diagram showing prolonged ground contact with more points spread out over the center of gravity.)

3. What type of locomotion do you think provides the greatest maneuverability during movement? Explain your reasoning.

Since hopping is used at greater speeds and is a more "dynamic" form of locomotion, it will have greater maneuverability than pentapedal.

Alternatively: Hopping results in more time being out of contact with the ground, which limits the percentage of the stride cycle that is available for changing direction, so pentapedal could be considered more maneuverable.

(Students should provide clear, consistent reasoning for their choice.)

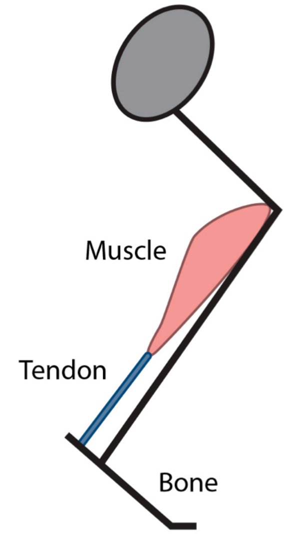
4. Which limbs seem to be most important for propulsion in pentapedal and bipedal hopping gaits? (Hint: use the duration of contact with ground to support your reasoning).

All four legs and the tail are important for pentapedal movement, with each limb making prolonged contact with the ground. For hopping, only the hind legs make ground contact for a limited amount of time.

5. Compare and contrast the function of the tail in pentapedal and bipedal gaits of kangaroo locomotion. (Hint: observe the tail position in figure 1 and in the video provided)

The tail contacts the ground and supports the kangaroo's weight and may even produce forward thrust during pentepedal locomotion. During hopping, the tail is important for proper balance during hopping, but does not directly contribute forward movement.

Many organ systems must work together for animals to move through their environment. Muscles generate contraction forces, which pull on the skeletal structure via elastic tendons to produce limb movement. Other systems such as respiratory and circulatory systems provide oxygen, which is used in metabolism to produce the chemical energy needed for muscle contraction and active movement. Tendons serve a structural support role and a potential source of mechanical energy.



Rates of oxygen (O_2) consumption can be used to estimate metabolic energy consumption during exercise, since anaerobic metabolism does not significantly contribute to total energy production. For most mammals, oxygen consumption, and thus metabolic energy expenditure increases proportionally with speed. Animals increase the speed of locomotion by increasing the frequency of limb movement (stride frequency) and the distance each limb movement produces (stride length), although both features may not be increased to the same extent.

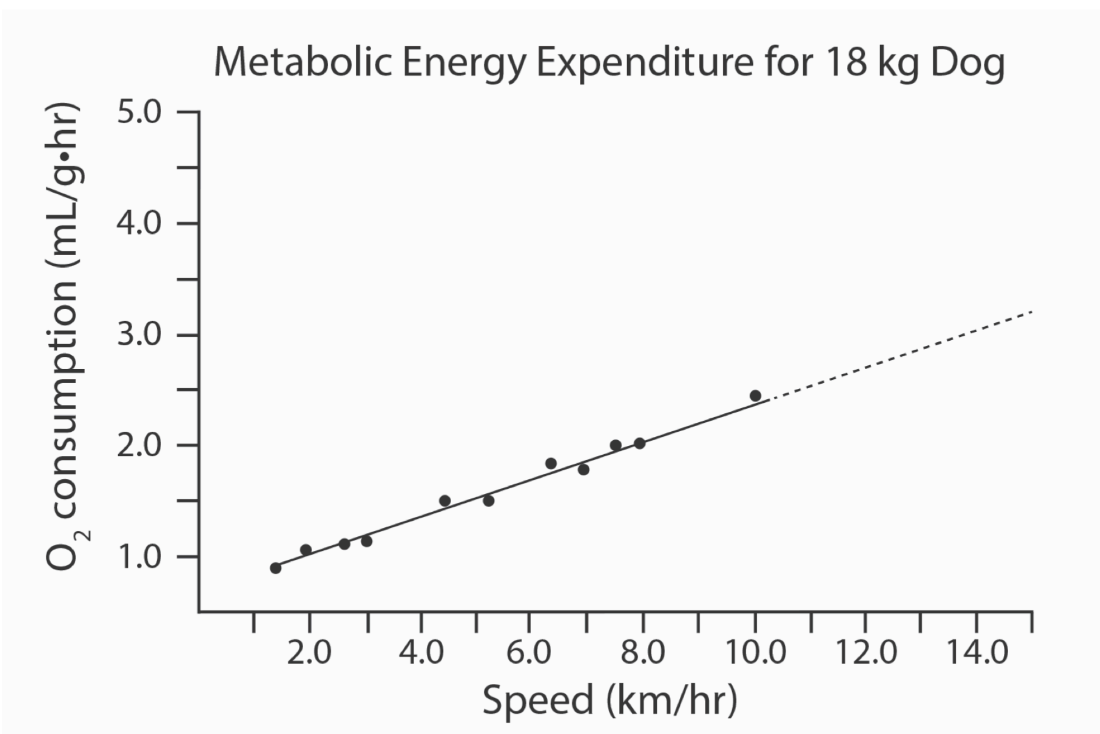


Figure adapted from data reported by Taylor et al., 1970.

Questions:

1. Increasing stride frequency requires significantly more metabolic energy expenditure, while increasing stride length does not significantly affect metabolic demand. How do you think muscle activity and tendon function contribute to increasing stride frequency and stride length? Explain your reasoning.

Muscles use metabolic energy to produce force that moves an animal's limbs and propels the animal forward during locomotion. Since stride frequency requires the active movement of limbs and stride frequency requires more metabolic energy expenditure, it is likely that muscle activity is primarily required for increasing stride frequency. Since tendons connect muscles to the skeleton, they are passively involved in increasing stride frequency.

Tendons have the ability to stretch more than muscles and can store elastic potential energy. The range of limb movement is important to increase stride length, which will depend on tendon function. It is reasonable to assume that recruitment of more muscle groups or a greater degree of muscle contraction may be necessary to increase stride length voluntarily.

Students should use reason-based arguments for their conclusions, as well as reasonably understand the proper roles of muscles, tendons, or the skeletal system.

2. Using the graph above, what do you think the relative importance of increasing stride frequency and stride length is for increasing speed by a four-legged mammal (dog)? Explain your reasoning.

As a dog's speed increases, its metabolic energy expenditure increases proportionally. Therefore, dogs seem to rely on increasing stride frequency for increasing speed, since stride frequency is related to metabolic energy expenditure. (Students should make reference to the data on the graph as part of their reasoning for their answer.)

Some students may go further and notice that stride frequency increases proportionally, but not at the same rate. If stride frequency increased at the same rate as speed, the slope of the linear fit would be ~ 45˚ angle. Since the graph's slope has a smaller angle, another factor must also be contributing to the speed increase. It is likely that both stride frequency and stride length both increase with increasing speed. This is reflected in the changing of gates for dogs: walk, trot, and galloping, which largely affects stride length instead of frequency. (The grade level and context that this lesson is adapted to will impact how detailed students observations will be.)

Kangaroos use a metabolically expensive pentapedal gait at slow speeds. However, in contrast to other mammals, metabolic energy expenditure does not increase proportionally with speed. At higher speeds, kangaroos switch to a hopping bipedal gait, which results in oxygen consumption slightly decreasing with increasing speed. Kangaroos have been observed to travel at sustained speeds of 40 km/hr with bursts of speed up to 65 km/hr.

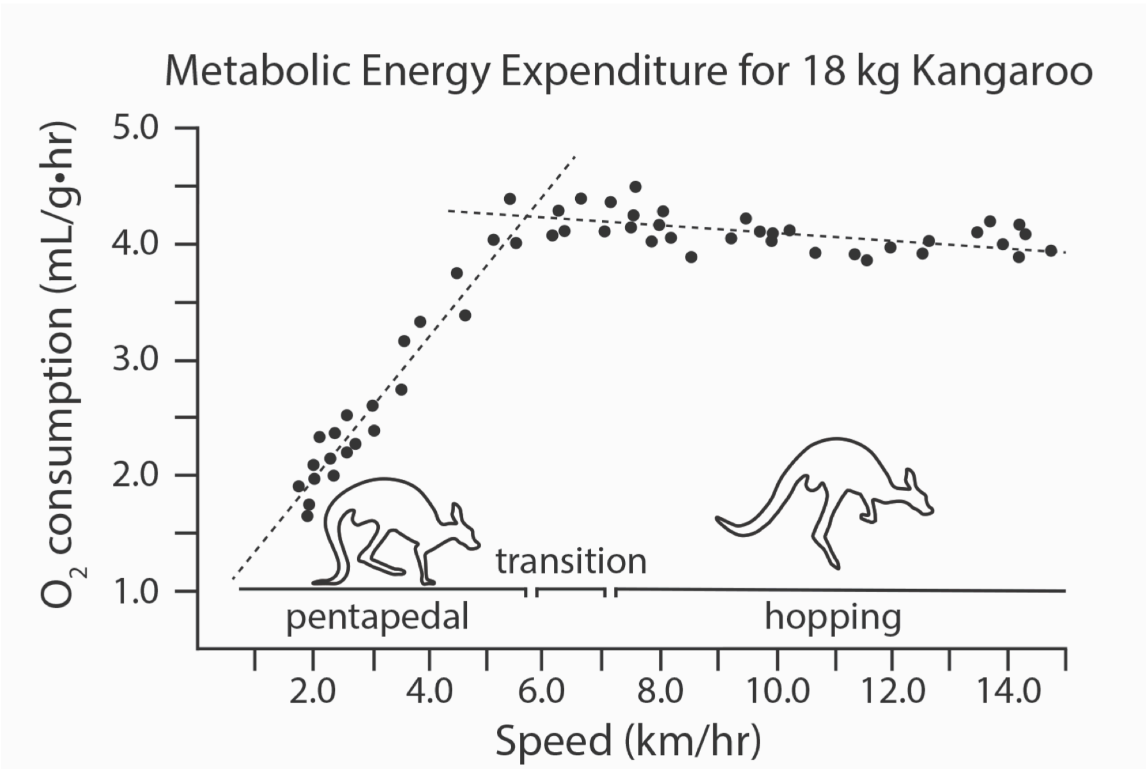


Figure adapted from data reported by Dawson and Taylor, 1973.

3. Explain why you think the kangaroo transitions from pentapedal to bipedal hopping around the 6 – 7 km/hr speed range. (Hint: If the kangaroo continued to use pentapedal locomotion at higher speeds, what would the oxygen consumption vs. speed graph look like?)

Metabolic energy demand increases with increasing speed for pentapedal locomotion. If the kangaroo continues to use pentapedal locomotion at higher speeds, the kangaroo will use more metabolic energy reserves than if it switches to hopping. Kangaroos switch gates at a speed where it would maximize metabolic energy efficiency. [Note: this is generally true for switching gates for most animals.] (Students should use the graphical data to support their reasoning.)

4. Compare the trends of oxygen consumption for pentapedal and bipedal hopping gaits of kangaroos with the trends found in a dog of similar size. Using the graphs above, explain how you think kangaroos alter stride frequency and stride length in each locomotion gait to increase speed.

Pentapedal locomotion used by kangaroos shows a similar trend to the dog, with increasing speed is associated with increasing metabolic energy expenditure. These trends are consistent with increased stride frequency being an important mechanism for increasing speed. In contrast, during hopping, kangaroos do not use more metabolic energy. This suggests that hopping allows kangaroos to use an increase in stride length to increase speed. The large range of speeds that kangaroos can use hopping in this way suggests that hopping is unique as an animal gait for the range of stride length it can operate at.

Some students may go further and explain that pentapedal and hopping gaits used by kangaroos are more metabolically expensive compared to the movement of a dog. The advantages of kangaroo gaits either are not related to metabolic energy efficiency, or manifest in conditions not observed on the graphs. [Note: Kangaroo hopping becomes more energetically efficient at higher speeds and larger animal masses.]

5. Why do you think the rate of metabolic energy demand in kangaroos remains constant or slightly decreases with increasing speed for bipedal hopping locomotion? Does the kangaroo use other source(s) of energy to increase speed? (Hint: refer to your previous data analysis and comparison of a ball bouncing and kangaroo hopping.)

As stated for question 4, kangaroos are likely mainly increasing stride length, which does not require as much metabolic energy expenditure. In addition, the metabolic energy expenditure slightly decreases as speed increases during hopping. This could be explained if the kangaroo uses more elastic potential energy to supplement muscle force production during hopping. The harder the kangaroo impacts the ground, the more elastic potential energy could be stored.

6. Kangaroos are unique in that increasing speed can be uncoupled from metabolic demand. What tissue type allows the kangaroo to accomplish this? Explain your reasoning.

With the reasoning that kangaroos used stored elastic potential energy to uncouple metabolic demand from increased speed, it is likely that tendons in the hind legs are the most important tissue for this effect. Muscles tend to maintain a consistent length and do not stretch enough to contribute significantly to elastic potential energy. Tendons are capable of stretching and storing elastic potential energy.

Extension Questions:

Kangaroos are grazing animals, which spend much more time moving with a slow pentapedal gait than hopping quickly. Yet, the anatomy of a kangaroo seems to have been adapted for metabolically efficient hopping locomotion with the development of large hind limbs.

1. What evolutionary advantages do you think have been selected for in the development of the kangaroo's anatomy as it relates to locomotion? Discuss both locomotion gaits.

Open-ended answers can range over many topics, with reasoning. If kangaroos underwent an evolutionary selection for hopping instead of pentapedal movement, then the reasons for adaptation should focus on hopping. One potential that hopping was the feature of selection could be that athletic performance features like speed and maneuverability provide selective advantages. Since kangaroos are herbivores, selection based on athletic performance is likely related to avoidance of predation.

Alternatively, the ability to move long distances with strong endurance may have conferred an evolutionary advantage on populations. Though it seems less likely, the development of large hind limbs may have conferred a sexual selection advantage if mating displays were somehow related to these features.

Pentapedal locomotion, which utilizes the thick muscular tail as a fifth limb, may be advantageous if it is confers increased stability for better foraging, mate competition (kangaroo boxing?), etc. It could also be reasonable that pentapedal locomotion is a byproduct of selecting a large mass, muscular tail for improved balance and maneuvering during hopping locomotion.

2. Would you expect a kangaroo ancestor that lived in lush jungles with plentiful food available to develop similar locomotion gaits? Explain your reasoning.

If you suppose that the primary evolutionary selection pressure for kangaroos is fast, metabolic energetically efficient locomotion, it would follow that arid, open environments may be an important source for evolutionary selection. Arid environments with limited nutrition and sparsely located sources could select for a fast, efficient mode of locomotion.

Lush jungles would limit the speed with which a kangaroo could move, and other features would likely be important in that environment such as: acceleration, increased maneuverability, and versatility. Also, animals in jungles are typically smaller with lower top speed movement, which seems to be a direct counter-selection to the advantages to kangaroo hopping.

For analyzing student dialogue, teachers may choose to utilize a Quantitative Literacy Assessment Rubric (Boersma et. Al)

Boersma, S., Diefenderfer, C., Dingman, S. and Madison, B. 2011. Quantitative reasoning in the contemporary world, 3: Assessing Student Learning. Numeracy, 4 (2). https://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=1080&context=numeracy (accessed February 28, 2020).