Running Power Definition and Utility

Dr. Kristine Snyder
with scientific advisors Shalaya Kipp, M.S.
and Prof. Wouter Hoogkamer

"All models are wrong. Some models are useful." - George E. P. Box

1 Motivation and Organization

There has been significant confusion lately as to what different running power values mean, how they relate to power values in cycling, and what metrics are consistently useful. One of the fundamental issues in using power as a surrogate for effort in running is that the physically defined metrics may not be the ones that a runner may find useful, whereas the useful metrics may be more difficult to calculate. The purpose of this article is to define the various types of power involved in running, to describe the different models used to estimate power and their various scales, and then to discuss the potential utility of each of these power measures.

Creating this explanation was challenging. The goal for this document was for everything to be written in a way that someone who just wanted the basics could get what they needed without being overwhelmed, while also including the kind of detail an academic would require and the informed, intelligent runner might really want and appreciate. So, this first piece is an overview of the types of power and other metrics involved in running, with more detailed pieces to follow on specific topics where necessary.

2 What is Power?

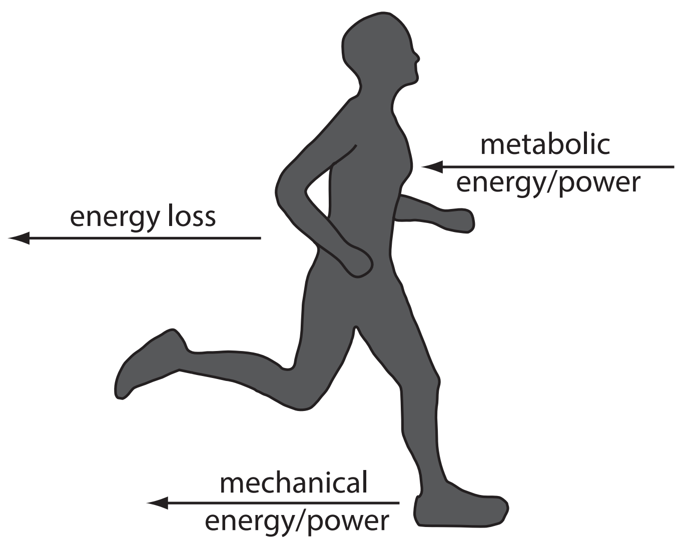

Figure 1: Conversion of metabolic power to mechanical power, with energy loss.

In running, there are two main definitions of power:

1. **Mechanical power-** The work/energy output per second. The mechanical power the body exerts on the outside world and to move the limbs relative to the body, or the output power produced by the muscles to move the body in running. This is usually measured in Watts (Joules/second) and normalized by mass, giving Watts/kg.

2. **Metabolic power-** The work/energy input of the locomotor muscle per second. The amount of metabolic energy per second the body has to use to run. This is also measured in Watts/kg, though is also often converted into calories.

Mechanical power tends to be useful for analyzing the biomechanics, especially joint-by-joint mechanical power, whereas metabolic power is often more useful for evaluating overall effort.

3 Mechanical Power

3.1 At the organismal (body) level

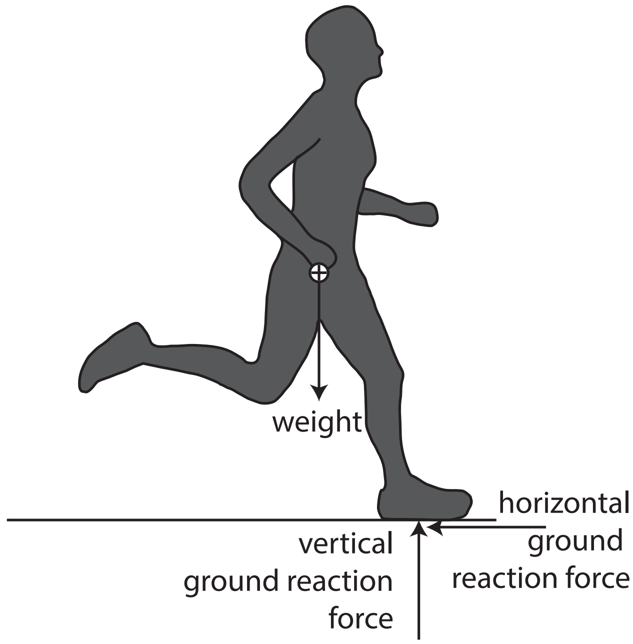

Figure 2: Forces involved in a whole body mechanical system during running.

The simplest way to model the body in running is as a point mass that acts upon and is acted upon by the outside world. To determine overall body mechanical power, the body is typically assumed to be just a point mass, the potential and kinetic energy of the center of mass are summed to get the total work, and that value is then divided by time. Alternatively, power can be determined by multiplying forces acting on the center of mass times the velocity. However, this model only takes into account the interaction of this assumed point mass with the environment, and does not capture the power necessary to move the limbs relative to the body.

In level steady-state running, ignoring losses, this value is zero, so, when using body mechanical power as a correlate for effort, often only the positive power contributions and not the negative ones are included.

$$P = \frac{\Delta E_{KIN} + \Delta E_{GPE+}}{\Delta t} \tag{1}$$

Further note that this equation only includes the mechanical power involved in interacting with the environment, not with the limbs moving relative to the body.

3.2 At the joint-by-joint level

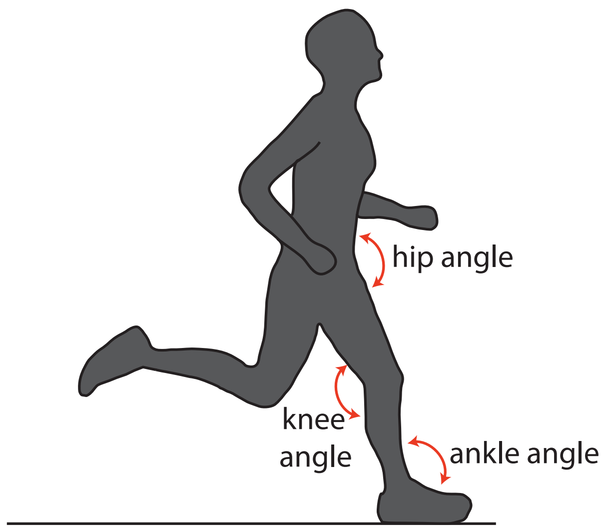

Figure 3: Definition of lower limb joint angles during running. Extension is considered positive, and flexion is considered negative.

The body is not a point mass, but a series of connected segments, so instead mechanical power in running is examined at a joint-by-joint level. Rather than assuming the body is a point mass, this way of determining mechanical power includes all joints and calculates power at each joint using the forces under the feet, the masses of the body segments, and the angular velocities of the joints and adds these quantities altogether. This allows for more specificity on where the power is being produced, as well as allowing for changes that occur in swing as opposed to only stance. Note however, that biarticular muscles (muscles that cross two joints) allow for the transfer of power between joints.

To calculate power on a joint-by-joint basis, the process starts at the foot. The moment (torque) around the ankle due to the force of the ground on the foot, the movement at the foot, and the weight of the foot, along with the ankle angular velocity, are used to calculate ankle power. Similar calculations are performed at the knee and the hip. These values are summed together to get mechanical work, with power being calculated as work/time. To calculate joint power in a lab, optical motion capture is used to track the motion of the limbs, and force plates are used to determine the forces under the feet.

4 Metabolic Power

In a lab, metabolic power (P_{MET}) is generally calculated via indirect calorimetry, which uses expired gas measurements, assumptions or knowledge of substrate utilization, and formula(e) to determine steady-state energy consumption. While a person is running, the amount of oxygen they consume and the amount of carbon dioxide they produce is measured by using a mask placed over their nose and mouth. Metabolic power is then calculated from these **steady-state** oxygen and carbon dioxide values. The following commonly used equation comes from (Péronnet and Massicotte, 1991).

$$P_{MET} = 16.89VO_2 + 4.84VCO_2 \tag{2}$$

Indirect calorimetry only accounts for aerobic processes. Therefore it alone is not accurate when people are working hard enough that they're also using anaerobic metabolic processes. The true gold standard would be doubly labeled water, in which subjects are given water labeled with deuterium (^2H) and ^{18}O, which are then used to determine the elimination rate of CO_2, or direct calorimetry, in which the energy expenditure is determined by measuring how much heat is produced by an individual in a tightly enclosed measurement chamber, but these measurements would be more prohibitively difficult.

Estimating metabolic power without indirect calorimetry involves using knowns about running conditions, environmental conditions, and user anatomical, biomechanical, and physiological data to estimate the in lab values as accurately and precisely as possible.

5 Relating Mechanical to Metabolic Power

5.1 Efficiency

Efficiency is the ratio of the mechanical power production divided by the metabolic power consumption. On the surface, this seems simple, but it is not as simple in running as it can be in other activities. In positive power production, when the muscles are producing power by contracting concentrically (shortening), efficiency is $\sim$25%. Note: the word contraction just implies muscles are active. They can contract concentrically (while shortening), isometrically (while staying the same length), or eccentrically (while lengthening), Efficiency values can be significantly higher in movements that involve negative power (via eccentric contractions) or energy recycling, but can vary, particularly as incline increases.

5.2 Efficiency is simple in cycling

In cycling the mechanical system is constrained, because 1) force is produced and not absorbed (via shortening muscles through a concentric contraction), and 2) no mechanical energy is recycled. The constrained mechanical system during cycling allows for a strong

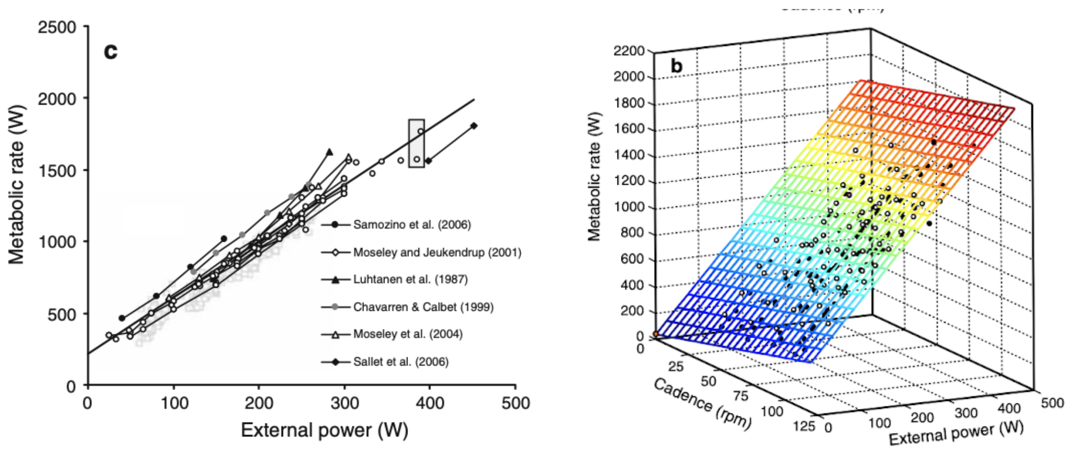

Figure 4: How mechanical (external) power and metabolic rate (power) compare in cycling. Figures taken from the review paper by (Etterna and Loras, 2009).

correlation between mechanical and metabolic power. Because positive muscle power has an efficiency of ∼25%, the metabolic power is essentially just four times the mechanical power. The correlation between the two power values is 0.97, very high (Ettema and Loras, 2009). Further, because cycling is a highly constrained system with a known, consistent foot trajectory, mechanical power is easy to measure. Consequently, it is common to measure mechanical power and accurately use it as a correlate for metabolic power.

5.3 Why is the relation between mechanical and metabolic power more complex in running?

There are a number of differences in running that make the relation between mechanical and metabolic power more complex than cycling.

1. **The mechanical system is less constrained.** The amount of force produced and the metabolic energy required to produce that force each depend mainly on two things: the length and velocity of the muscle fiber producing that force. When the system is less constrained, these can vary more and have a larger effect on the change in metabolic energy required.

2. **Forces are both produced and absorbed by the body.** Because the efficiency for force absorption is higher than the ∼25% for positive force production, the overall efficiency is no longer ∼25%. However, the actual efficiency varies based on how much of each force is produced.

3. **Energy can be recycled.** In running, elastic energy can be stored in the tendons and other elastic tissues, and then returned. Additionally, there is a metabolic benefit

to shortening a muscle after it has been stretched. These changes also increase the efficiency above 25%, but it can be difficult to determine how significant a role these factors play.

Because of these differences, mechanical power and/or efficiency are not consistently the best indicators of effort in running across conditions, so an alternative metric that correlates better with effort is often used instead.

5.4 An alternative to efficiency for a more complex system: economy/cost of transport

Running economy is not the same thing as running efficiency, though they are related. Running economy is traditionally determined by measuring the rate of oxygen or energy consumed at a given speed. When expressed relative to body mass, running economy can have the units of oxygen (mlO2/kg/min) or energy (J/kg/min or W/kg). Your running economy could be better because you do less mechanical work to run at a given speed but have a typical mechanical to metabolic efficiency. It could also be better because you are more efficient, in that you perform the typical mechanical work, but it incurs less metabolically due to other factors, such as more effective elastic energy storage and return.

One of the most common ways to represent economy is by cost of transport, or the energy cost per unit distance. Cost of transport is calculated by taking the mass-specific energy cost per second (as described in the previous paragraph), and dividing by the speed, and is measured in J/kg/m. You can think about cost of transport as the energy it costs to run per meter or mile at a given speed; it is essentially the inverse of miles per gallon in a car.

6 What metric is most meaningful for a runner?

6.1 Metabolic importance

Generally, people, largely subconsciously, choose to move in a way that minimizes metabolic energy use. People use the stride length (Hogberg, 1952; Snyder and Farley, 2011), stride width (Donelan, 2001; Arellano and Kram, 2011), stride frequency (Hogberg, 1952; Snyder and Farley, 2011), speed (Inman et al., 1981), and gait (Cavagna et al., 1987) that minimize metabolic variables, though sometimes it is metabolic rate (energy/time) that matters and sometimes it is cost (energy/distance) that matters.

Metabolic energy expenditure is also the predominant determinant of performance in endurance running races and a critical element of optimizing training (Noakes, 2003; Daniels, 2013). In racing, the goal is to have minimal energy at the finish line, not to burn out before and not to have a lot left afterwards. To do this effectively, you want to have as

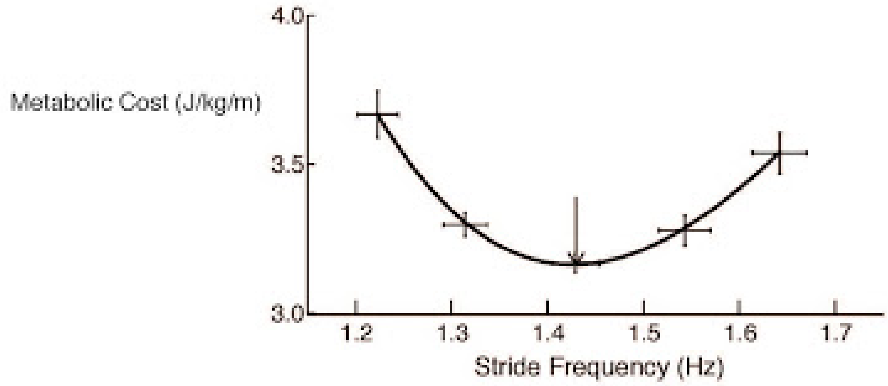

Figure 5: A graph of stride frequency vs. metabolic cost adapted from (Snyder and Farley, 2011) shows how humans use metabolic rate/cost to optimize their running form. Note that because these data were all collected at 2.8 m/s, the approximately parabolic shape is the same for stride frequency vs. metabolic rate/power.

good an estimate as possible of how much metabolic energy your body consumes at each point of the race. Essentially, what most runners want from a power number is a better estimate of effort than they can determine themselves and a way to log this value over time. By having the best estimate possible of metabolic power, runners can consciously make decisions using data their body already unconsciously uses.

6.2 Utility of other metrics

Though metabolic power under given conditions comes close, there is no one silver bullet to measure your running efficacy. Cyclists use a faster than metabolically optimal cadence and pay a small metabolic price so that they can avoid large muscle and tendon forces (Etterna and Lornas, 2009). In some downhill and other energy absorbing actions, muscle moments or other measures also seem to be more of a determining factor in what is the optimal method to use than metabolic power (Dean, 2013). Avoiding injury can outweigh minimizing effort.

6.3 What is the solution?

Because no one metric entirely captures running efficacy under all conditions, it is important to collect as much precise, accurate, and useful biomechanical and physiological data during training as is feasible. It is then necessary to share the most useful metric(s) to the runner in close to real time, as well as to determine values for other useful metrics for later use, along with guides for interpretation of their meaning. It would be ideal to be able to directly measure oxygen consumption during training, but, currently, even if it were affordable, it is impractical, if not impossible, to run with a portable metabolic system every day. Further, even if it were practical, metabolic rate would only be updated every breath plus processing time, and would not capture anaerobic metabolism. Heart rate devices are wearable and offer a commonly used metric, but heart rate is slow to reflect a change in metabolic requirements and also can be affected by stress, immune response, and other factors unrelated to instantaneous metabolic demand. Note that we define instantaneous metabolic demand to be the metabolic power due to aerobic and anaerobic sources, similar to oxygen demand in (Gløersen, 2019). Currently, the best option is to have a wearable device that offers an accurate, precise close-to-real-time correlate for instantaneous metabolic demand, but also determines other metrics, biomechanical and physiological, for post-run analysis.

7 Conclusion

The fundamental purpose of this document is to define the different types of running power, the models used to estimate them, and to discuss each power measure's utility. There are two fundamental types of power in running: mechanical power (energy exerted by the body on the environment and to move the limbs per second) and metabolic power (energy used by the body per second). Each can be modeled with varying degrees of accuracy/precision depending on the data and assumptions used to build the model. The question of which value to use fundamentally comes down to utility. Which measure is most useful for running power across different people, running conditions, and environmental conditions? If you want to use one power number to estimate your effort and determine your pacing, there is a preponderance of evidence showing that your body already fundamentally uses metabolic power/cost, or more accurately, instantaneous metabolic demand, which lacks the time delay of metabolic power. Being consciously aware of the metric your body is subconsciously using can help you make choices to optimize your training and performance.

References

[1] Péronnet, F., and Massicotte, D. (1991). Table of nonprotein respiratory quotient: an update. *Canadian Journal of Sport Sciences = Journal Canadien des Sciences du Sport,*, *16 1*, 23-9

[2] Ettema, G., and Lorås, H. W. (2009). Efficiency in cycling: a review. *European Journal of Applied Physiology, 106*(1), 1-14.

[3] Hogberg, P. (1952). How do stride length and stride frequency influence the energy-output during running?. *Arbeitsphysiologie 14*, 437-441.

[4] Snyder, K. L., and Farley, C. T. (2011). Energetically optimal stride frequency in running: the effects of incline and decline. *Journal of Experimental Biology, 214*(12) 2089-2095.

[5] Donelan, J. M., Kram, R., and Kuo, A. D. (2001) Mechanical and metabolic determinants of the preferred step width in human walking. *Proceedings of the Royal Society of London. Series B: Biological Sciences, 268*(1480), 1985-1992.

[6] Arellano, C. J., and Kram, R. (2011). The effects of step width and arm swing on energetic cost and lateral balance during running. *Journal of Biomechanics, 44*(7), 1291-1295.

[7] Inman, V.E., Ralston, and Todd. (1981). Human Walking. Williams and Wilkins, Baltimore.

[8] Cavagna, G. A., and Kaneko, M. (1977) Mechanical work and efficiency in level walking and running. *The Journal of Physiology, 268*(2), 467-481.

[9] Dean, J. C. (2013). Proprioceptive feedback and preferred patterns of human movement. *Exercise and Sport Sciences Reviews, 41*(1), 36.

[10] Tim Noakes. (2003) The Lore of Running. Human Kinetics, Champaign, IL.

[11] Jack Daniels (2013) Daniels' Running Formula Human Kinetics, Champaign, IL.

[12] Gløersen, 0. N. Gilgien, M. Dysthe, D.K. Malthe-Sørenssen, A. Losnegard, T. J. Oxygen Demand, Uptake, and Deficits in Elite Cross-country Skiers during a 15-km Race *Medicine and Science in Sports and Exercise*