PHYSIOLOGY

Walking Made Simple

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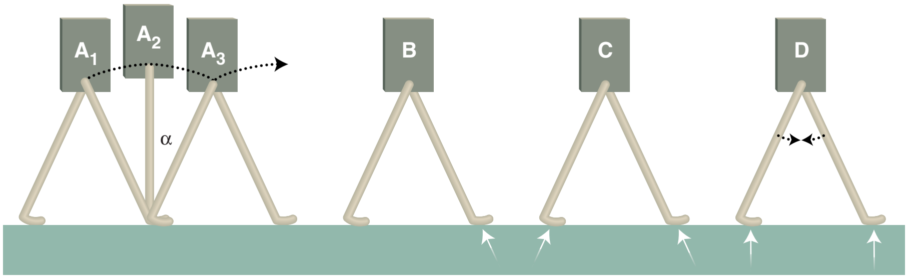
The obvious way to make a humanlike robot walk is to provide it with motors to drive every joint, and a computer to control them. The computer tells every joint what its angle should be, at every stage of the stride. Many successful robots have been made in this way. The best ones imitate a human walk quite well, but require complex, fast, precise control mechanisms, and use far more energy than a walking human would. In contrast, passive-dynamic walking robots are simple mechanical devices composed of rigid parts connected by joints that are able to walk in a stable fashion down a slope even though they have no motors or controllers. In a recent *Science* paper (*1*), Collins *et al.* describe their design of several new robots inspired by passive-dynamic walkers. These new robots have much simpler control systems than those of powered robots, but walk at least as well as they do, and at lower energy cost.

To understand and appreciate these new robots, we need to know something about human walking and its energy cost. The cost of transport for human (or animal) locomotion is defined as (energy cost)/(body weight × distance traveled). It may seem perverse to use weight rather than mass in this formula, but it makes the cost of transport dimensionless. The energy cost may be defined as the food energy consumed (giving the metabolic cost of transport), or as the mechanical work performed (the mechanical cost of transport). Measurements of oxygen consumption show that for humans walking at the most economical speed (about 1.3 m/s), the metabolic cost of transport is about 0.2. The corresponding mechanical cost of transport is about 0.05 (our muscles work with efficiencies of around 0.25) (*2*).

We have to do work, when we walk, to overcome friction in our joints (*3*) and to counter air resistance (*4*), but the work needed for these purposes is far too small to explain the observed costs of transport. In principle, no other work is needed to travel at constant speed over level ground. In the absence of friction and air resistance, a wheeled vehicle given an initial push would roll on for ever over rigid level ground. Why does walking require more energy than ideal locomotion on wheels?

A simple model will help us to answer that question (*5*). The figure depicts a biped with rigid legs of negligible mass. In each step, it rises and falls along an arc of a circle. Similarly, because we keep each leg straight while its foot is on the ground, we rise and fall in each step, more or less along an arc of a circle. The biped slows down as it rises and speeds up as it falls. Kinetic energy is converted to gravitational potential energy and back again, as in a swinging pendulum. No work is needed as the model moves from position (A_1) to position (A_3) in the figure. At position (A_3), however, the vertical component of the body's motion must be reversed; the downward movement of the body must be halted, then work must be done to propel it upward for the start of the next step. The mechanical cost of transport can be calculated from this work. To imitate human walking, assume a speed of 1.3 m/s, a leg length of 0.9 m, and an angle α of 25° (see the figure). With these values, the mechanical cost of transport is 0.02, even lower than the value actually observed for humans.



Principles of walking. The diagrams represent walking by a biped whose legs remain straight while the foot is on the ground. (**A**) shows successive stages of a step. (**B**), (**C**), and (**D**) show forces on the feet at the instant when the left (leading) foot hits the ground. In (B), the foot hits the ground before any muscle becomes active. In (C), the right foot pushes on the ground at the instant the left foot lands, making the resultant force on the body vertical. In (D), a torque at the hips has a similar effect.

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A first step toward the design of a new, simpler type of walking robot was taken by McGeer (*6*). He built a more sophisticated version of a familiar toy that walks passively down slopes, powered by gravity. As expected (since the toys work well), his robot walked down slopes with a stable gait. In contrast to the earlier powered robots, with their complex control mechanisms, here was a robot that walked stably without any control system. McGeer's work suggested the possibility of much simpler powered robots than had previously been made. However, as a model of bipedal walking, McGeer's model was perhaps a cheat. Instead of two legs it had four that were symmetrically arranged so that it was, in effect, two-dimensional. Kuo (*7*) showed that an equivalent three-dimensional biped would rock from side to side in an unstable way.

McGeer's walker was powered by the gravitational potential energy it lost as it walked downhill. Thus, the cost of transport was (potential energy loss)/(body weight × distance traveled), which is equal to the gradient. By this measure, it proved more economical energy-wise than conventional robots. It was not, however, as economical as the theoretical minimum calculated above, for a surprisingly subtle reason (*6*, *8*). In the figure, (B) represents McGeer's robot at the instant when its foot hits the ground. The force of the impact on this foot reduces the horizontal component of the body's velocity, as well as eliminating the vertical component. More kinetic energy is lost and has to be replaced than predicted by the simple theory in which only the vertical component is affected. As a consequence of this, the mechanical cost of transport is $4\cos\alpha$ times the cost predicted by the simple theory. Using the same values of speed, leg length, and angle α as before, it is 0.07 instead of 0.02. This penalty can be avoided in powered robots if the impulse on the body (the time integral of force) can be kept vertical. One possibility is an upward, forward push with the foot that is about to be lifted, simultaneous with or just before the landing of the other foot (see the figure, C).

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Another is torque applied at the hip joints, making the forces on the feet vertical (see the figure, D).

One of the new robots described by Collins *et al*. (*1*), the Cornell biped, has been designed to work like the robot in part (C) of the figure. It has a torso, arms with shoulder joints but no elbows, and legs with hip joints, knees, and ankles. An electric motor in the ankle makes one foot push on the ground, just before the other lands. This is remarkably effective, giving a mechanical cost of transport of only 0.055. This cost is approximately equal to the human value, and far better than the estimated mechanical cost of 1.6 for the robot Asimo, in which all joints are motorized and controlled. The hip joints have no motors, but a passive linkage ensures that the torso bisects the angle between the two thighs, and so is kept upright. Other passive linkages make each arm swing in phase with the opposite leg. The knees have no motors, but latches keep them straight while the foot is on the ground. Only the ankles are motorized. This astonishingly simple machine walks like a human and is remarkably economical with regard to energy expenditure.

The second of the new robots described by Collins and co-workers, the Delft biped, was not designed specifically for energy economy, but nevertheless achieves a mechanical cost of transport of only 0.08. It is powered by pneumatic actuators at the hips (see the figure, D). It has no other muscles but, like the Cornell biped, does have controlled latches at the knees. Clever ankle design, based on the principle of skateboard suspensions, improves lateral stability. The third new robot from the Massachusetts Institute of Technology group is based like the others on ramp-walking toys. It has motors only at the ankles. Its special feature is that it learns to control its own walking. Typically, the learning process takes about 10 min or 600 steps, and it can adapt to uneven terrain and different surfaces.

These new robots are important for three reasons. They give us new insight into human walking. They point a possible way to the design of more lifelike artificial legs for amputees. And they bring renewed excitement to the design of humanoid robots. They show us that bipedal robots far simpler than their predecessors work as effectively and far more economically, and can even be designed to teach themselves to walk.

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GEOLOGY

The Calibration of Ediacaran Time

Alan J. Kaufman

Early animals? A pile of three-dimensionally preserved casts of the soft-bodied Ediacaran organism *Ernietta* from ~545 million-year-old sediments in the Nama Group of southern Namibia. The scale bar corresponds to 15 cm.

CREDIT: A. J. KAUFMAN

More than a century ago, the last great geological period was formally ratified by an international committee. This was the final rocky step in the subdivision of deep time based on the evolutionary progression of animal fossils. However, recent years have seen the identification of an older and tumultuous new interval, the Ediacaran Period, during which Earth's earliest soft-bodied organisms emerged in the oceans. This interval was recently ratified (*1*), underscoring advances in the absolute dating (*2*–*6*) and worldwide correlation of geological strata that were deposited in isolated basins before true animals exploded onto the scene in the succeeding Cambrian Period.

On page 95 of this issue, Condon *et al.* (*7*) present precise age constraints for the Ediacaran Period. The authors have analyzed volcanic dust in two key depositional layers in the Doushantuo Formation of southern China. Their radiometric dates provide important insights into the rates of geological and evolutionary processes. The first layer, with an age of about 635 million years, is at the base of the new interval, whereas the second, at about 550 million years, may constrain the age of an environmental disaster (*8*–*10*) that is closely associated with the rapid diversification of the Ediacara biota (see the figure) that lend their name to the new Period.

Convention previously focused on the evolutionary first appearance of a specific fossil or assemblage to define the beginning of new geological periods. In contrast, the beginning of the Ediacaran period is defined by the base of a marine carbonate rock, which formed in southern Australia in the aftermath of a distinctive and potentially global ice age (*11*, *12*). Equivalent glacial rocks occur immediately beneath similar carbonates at the base of the Doushantuo Formation.

In the area studied by Condon *et al.*, the new ages constrain the Doushantuo Formation, which represents most of the Ediacaran Period, to some 85 million years—a remarkably long interval for only about 100 m of rock. This observation begs the question: How much time may be missing in Ediacaran strata from southern China?

In the absence of dates between the two radiometric tie points, one must consider two possibilities: Either the sediments accumulated continuously, albeit slowly (some two orders of magnitude more slowly than in similar environments of the same age), or there are breaks in time (hiatuses or unconformities) hidden within the poorly exposed layers. On the basis of limited physical data, Condon *et al.* suggest the presence of two such unconformities in their study area near the Yangtze Gorges. The duration of these stratigraphic breaks with respect to the environmental anomaly—reflecting a dramatic change in the cycling of carbon on Earth's surface—and subsequent biological innovations form the cornerstone of their conclusions, and deserve closer examination.

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