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Load Lugging Locomotion: Lessons from Indigenous People, Rhino Beetles, and Wallabies

Rodger Kram

Associate Professor
Dept. of Kinesiology and Applied Physiology
University of Colorado, 354 UCB
Boulder, CO 80309-0354, U.S.A.
rodger.kram@colorado.edu
<http://stripe.colorado.edu/~kram/Home.html>

Summary

Two fundamental mechanisms underlie walking and running. Walking involves an inverted pendulum-like exchange of kinetic and gravitational potential energy. Running involves spring-like exchange between kinetic and gravitational potential energy with elastic energy stored in the tendons. People are better able to utilize the inverted pendulum mechanism when loads are carried on the head and this method allows small loads to be carried for free. However, there is not a clear link between the mechanical work performed in walking and the metabolic cost. Rhinoceros beetles are able to carry enormous loads very cheaply but how they do so is not clear. People can use external springs to carry loads more comfortably, but not more cheaply. But kangaroos and wallabies can use internal springs to save energy during their hopping gait and to carry loads in their pouches. These examples can inspire novel means of improved human load carriage.

Introduction

We can learn a great deal about the biomechanics and energetics of load carriage from indigenous people and animals in nature. Many indigenous people carry staggering loads and in some cases with remarkable economy of effort. Animals ranging from ants to wallabies carry loads cheaper than predicted by conventional theories. Studying this anthropological and zoological diversity has revealed mechanisms and movement patterns that can stimulate creative load carrying equipment designs and techniques. But, before I can introduce examples of these unique mechanisms of load carriage, it is important to explain the basic mechanisms of normal, unloaded walking.

Discussion

Walking fundamentally involves an inverted pendulum-like mechanism (Figure 1) that conserves mechanical energy (Cavagna et al. 1977). At the beginning of the stance phase of walking the center of mass of the body is low but the forward velocity of the center of mass is at its maximum. Thus, the gravitational potential energy (mgh) is at first relatively small while the kinetic energy ($1/2 mv^2$) is great. As the body arcs up over the rigid support leg to its highest point, the body slows and the kinetic energy is converted into gravitational potential energy. During the second half of the stance phase, the body falls and velocity increases. The gravitational potential energy is converted back into kinetic energy during this second half. Thus, kinetic and gravitational potential energies are exchanged and the muscles need not do all of the work to lift and accelerate the center of mass during each step (W_{com}). The degree to which this energy exchange takes place has been quantified as a “per cent recovery”. Most humans appear to recover about 65% of the energy from step to step in walking and this presumably minimizes the metabolic cost of walking.

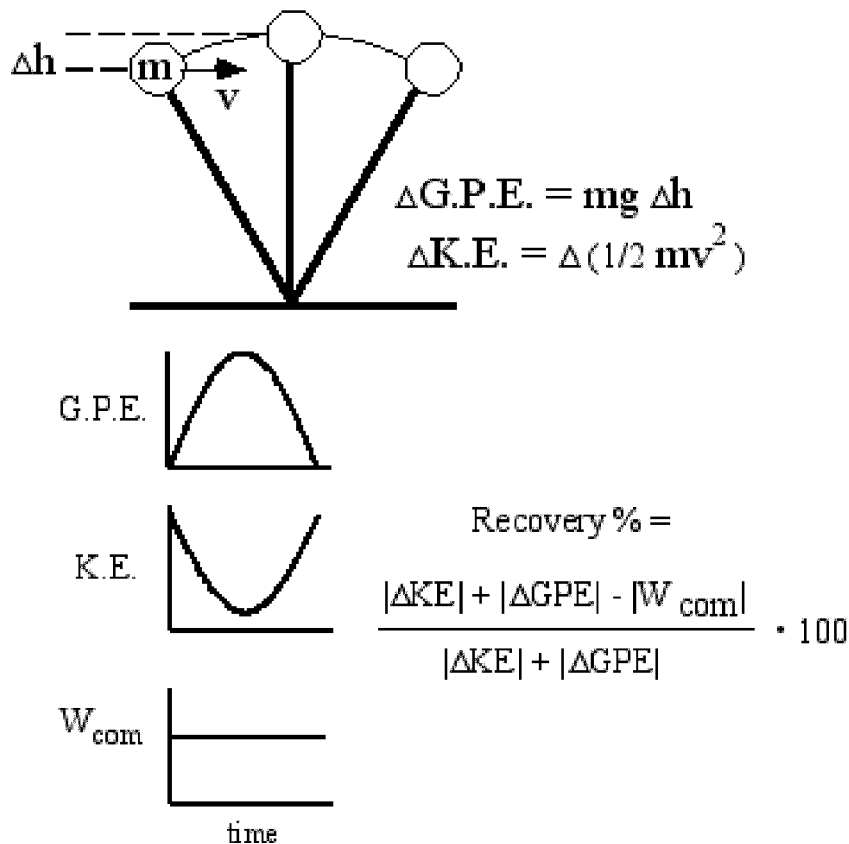


Figure 1. Walking, likened to an inverted pendulum-like mechanism

Inverted pendulum-like recovery of mechanical energy seems to be best perfected by people who carry loads perched on top of their head. This method of load carriage is common in many parts of the world but the techniques used by African women have been best studied. One advantage of head load carrying is that the load is directly in line with the body's center of mass and thus no compensating torque must be exerted. Maloiy et al. (1986) were the first to show that head load carriage is remarkably economical. They found that experienced head load carriers could carry up to 20% of their body mass on their heads with no measurable increase in metabolic energy consumption! After some years of speculation about the mechanism, Heglund et al. (1995) demonstrated that trained head load carriers are able to recover a greater percentage (up to 75%) of the mechanical energy fluctuations within a step and thus reduce the work input required. This certainly could explain part of their remarkable energetics.

However, recent research in my laboratory indicates that the link between mechanical work performed and metabolic cost of walking is more complicated. Instead of head loads, we studied loads carried symmetrically about the waist. To accomplish this, we wrapped lead strips over a padded hip belt. With this method, the center of mass of the load is also directly in line with the body's center of mass and thus no compensating torques need to be exerted.

We found that moderate symmetric waist loads are not carried for free; the metabolic cost increased directly with the load carried up to 20% of body mass. Like head load carriage, with heavier symmetric waist loads the per cent recovery of mechanical energy increased. Also similarly, the mechanical work performed on the center of mass + load did not increase for loads greater than 20% of body mass. Yet, unlike the head load carriers, the metabolic energy consumed by the symmetric waist load carriers increased dramatically for heavier loads. Thus, we saw a disconnection between the metabolic cost of locomotion and the external mechanical work performed.

It appears that the metabolic cost of walking is determined by three factors: the cost of performing external work, the cost of generating muscular force to support body weight and the cost of swinging the limbs. But what is the relative cost of these three components?

To try and distinguish the cost of performing external work and the cost of generating force, we studied “negative load carriage”. That is, we examined the mechanics and energetics walking in simulated reduced gravity (Griffin et al., 1999). To simulate reduced gravity, we pulled up on the subjects via a waist-torso harness attached to stretched elastic rubber tubing (Figure 2).

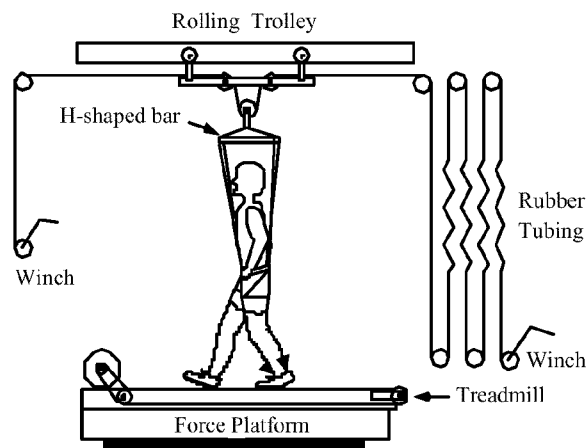


Figure 2. Experimental set-up for simulating reduced gravity

If the cost of generating force is the primary determinant, one might guess that in 50% of Earth gravity, metabolic cost would be 50% of normal. However, Farley & McMahon (1992) showed that the effect of reduced gravity is more modest. We investigated if low gravity walking was not as cheap as expected because of a disabling of the inverted-pendulum mechanism. That was not the case. Subjects adjusted their gait so as to reduce their kinetic energy fluctuations and thus match the reduced gravitational potential energy fluctuations. In other words, they walked with a more constant velocity and they had similar per cent recovery values. As a result, the calculated mechanical work performed decreased directly with the reduced gravity.

Thus, reduced gravity walking is another situation where metabolic cost does not parallel the mechanical work performed. Yet, metabolic cost did not exactly parallel the cost of generating force either.

As impressive as human feats of strength and load carrying can be, they are dwarfed by the abilities of other species. Every child knows that ants can carry many times their own body weight. In natural situations they “only” carry about 2 or 3 times their own body weight on a regular basis (Lighton et al., 1993). The maximum load that ants can carry is about 10 times body weight. The alleged world record holders for load carrying are rhinoceros beetles. The Guinness Book of World Records purports that rhino beetles can carry 850x their own body weight (Matthews, 1992). After reading that, I became very curious to find out if it was true or even possible. I obtained some beetles from Arizona and immediately began my investigation.

So, how much weight can a rhinoceros beetle carry? Unlike ants, beetles do not naturally carry loads but it is easy to attach weights to their exoskeleton using glue and Velcro. I found that these beetles could walk or perhaps more accurately, stagger with up to 80 times their own weight. With greater weights, the beetles were not hurt, but refused to walk. With loads up to a still impressive 30 times their own weight the beetles readily marched along. We know that in humans and other animals, the metabolic rate typically increases in direct or greater proportion to the load being carried (Taylor et al. 1980). If that rule held true for beetles, they would need to have an enormous aerobic capacity to carry 30 times their own weight.

To investigate the energetics of rhinoceros beetle load carriage I walked them with various loads in a treadmill-respirometer chamber (Figure 3) and measured their rates of oxygen consumption (Kram, 1996).



Figure 3. Measuring oxygen consumption of rhinoceros beetles carrying loads

Rather than finding that beetles have enormous aerobic capacities, I found that they instead carry loads with remarkable economy. When walking with a load of 30 times body weight, they increased their metabolic rate to only about 4 times their normal unloaded walking cost! That is, carrying a gram of load was about eight times cheaper than carrying a gram of body mass.

Unfortunately, I have not yet been able to definitively explain this phenomenon. The beetles do not appear to be sliding their abdomens on the ground when they walk with these loads. It may be that they are able to support the weight using non-metabolizing exoskeleton structures. Another possibility is that their muscles are unusually efficient, but this species is not unusually efficient when walking without loads. It seems unlikely that these beetles use the same trick as the African women head-load carriers. The beetles move too slowly for there to be useful exchange of mechanical energies. For now, this mystery remains unsolved. But just imagine if a human could transport 30 times their own weight (~4500 lbs.) with less effort than it takes to jog.

Turning now to running gaits, it is again important to review the fundamental mechanism underlying normal unloaded gait. In contrast to the inverted pendulum of walking, in running the legs do not act like rigid struts but rather like bouncing springs (Farley & Ferris, 1999). At the beginning of the stance phase of running the center of mass of the body is still relatively high and the forward velocity of the center of mass is at its maximum. Thus, the gravitational potential energy (mgh) and the kinetic energy ($1/2 mv^2$) are both great. During the stance phase, the body slows, the leg flexes and the center of mass reaches its lowest point. Accordingly, the gravitational potential energy and kinetic energy reach minimum values at the middle of the stance phase. However, during the first half of stance, both forms of energy are stored as elastic spring energy primarily in the tendons of the leg extensor muscles. During the second half of the stance phase of running, the tendons recoil and the elastic energy is converted back into gravitational and kinetic energy.

Tendons can return as much as 93% of the energy stored in them (Alexander, 1988). Thus, the muscles need not repeatedly perform work to lift and accelerate the center of mass during each step. This dramatically reduces the metabolic cost of running.

Taylor et al. (1980) showed that for a variety of running animals the cost of carrying a load was directly proportional to the load expressed as a percent of the body mass (see Figure 4). These and other experiments led to the idea that the metabolic cost of running is determined not by the mechanical work done but by the magnitude and rate of force generation (Kram & Taylor, 1990). In short, the idea is that during running the muscles act primarily as nearly isometric force generators that allow the tendons to function like springs.

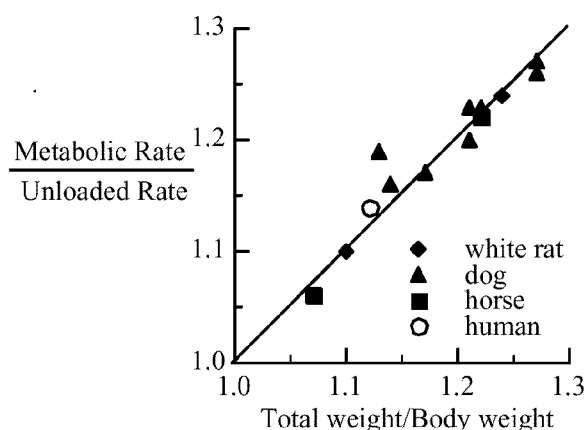


Figure 4. Metabolic cost of load carriage for a variety of running animals (from Taylor et al, 1980)

Hopping marsupials (e.g. wallabies and kangaroos) provide the most intriguing evidence for the importance of springs in locomotion and load carrying. In one of the most dramatic discoveries in the study of locomotion, Dawson and Taylor (1973) discovered that unlike all other species, as red kangaroos hop at progressively faster speeds they consume metabolic energy at the same rate! Even hopping at a 4-minute mile pace, kangaroos are only at about a third of their aerobic capacity (Kram & Dawson, 1998). This phenomenon is also difficult to explain. As kangaroos hop faster they must generate muscular force more rapidly which is generally more expensive. However, it may be that the muscles and tendons of kangaroos are “tuned” to function best at faster hopping speeds. At least one aspect of kangaroo locomotion energetics seems normal: they do consume energy more rapidly when they hop uphill (Kram & Dawson, 1998).

Besides their distinctive bouncy hopping mode of locomotion, the best popularly known feature of kangaroos is the female’s pouch. Young kangaroos (joeys) are carried in the pouch while the mother hops about her business. Baudinette and Biewener (1998) investigated the metabolic cost of carrying weight in the pouch by Tammar wallabies, which are smaller relatives of red kangaroos. They studied female adults hopping on a treadmill while carrying 15% of their body mass in their pouch. Just as Dawson and Taylor found for speed, Baudinette and Biewener found that pouch loads were carried without any additional metabolic cost! This is difficult to explain, but again a tuning argument for musculoskeletal springs seems most plausible.

Running humans can not only tune the spring-like properties of their legs (Ferris et al., 1999) but we can also tune the external springs used to carry loads. People throughout Asia carry loads using springy bamboo or wooden poles slung over the shoulder (Figure 5).

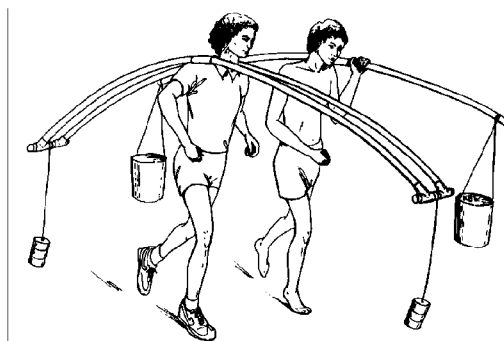


Figure 5. The carriage of loads using springy bamboo or wooden poles

These poles are distinctly different from the rigid yokes used by oxen. The yoke for oxen is designed to be rigid so as to maximize the transmission of force from the animal to the implement. For human load carriage, the goal is the opposite. To maximize comfort, the pole should act as a suspension system that reduces the peak forces experienced by the shoulder. Thus, a springy pole used by a human to carry loads is ideally very compliant, with a low natural frequency of vibration. The natural frequency of vibration for a spring-mass system is equal to the square root of k/m where k is the spring stiffness and m is the mass supported by the spring. A springy carrying pole should have a natural frequency of less than one third of the excitation or driving frequency. When a person jogs, they have a step frequency of about 3Hz. That is, their shoulder oscillates vertically (driving the vibration of the spring-mass system) about 3 times per second. Thus, according to engineering theory, a springy carrying pole should have a natural frequency of less than 1Hz.

My empirical measurements of the biomechanics of pole carrying bear out this theory (Kram, 1991). When a person jogs, the peak vertical ground reaction force is about 2.5 times their own body weight. Thus, if a load is rigidly attached to the body, it would slam on the shoulders with ~2.5 times its weight with every step. However, with a properly tuned carrying pole, I found that the force exerted by the load on the shoulder was quite steady and moderate. The force fluctuations were less than 10% of those expected with a rigidly attached load.

Of course, I was also curious to see if a springy pole allows loads to be carried cheaply, akin to the kangaroo and wallaby findings. Unfortunately, I found no energetic savings during springy pole load carrying. The cost of carrying loads was the same as with a normal backpack. However, carrying poles do offer other biomechanical advantages in addition to the peak load reductions. Because the loads are carried symmetrically front to back, they reduce the need to exert torques about the hips to lean forward. Because the loads are suspended from the poles by strings or ropes, the loads are carried with a low center of gravity and thus may be more stable. Finally, poles allow heavy loads to be hoisted by an individual without assistance. The person can crouch down under the pole, slackening the ropes, then stand up straight, and thus don the load without lifting it high in the air. Springy poles used for load carriage are a remarkably simple example of “appropriate technology” that has many ergonomic benefits. Perhaps they can inspire designers to incorporate compliant suspension systems into load carrying systems used by soldiers.

Conclusions

To sum up, elucidating the biomechanical bases for the metabolic costs of walking and running remains a major challenge for biomechanists and physiologists to solve together. In addition to the basic science questions, if we can unravel this enigma it will aid in the optimization of load carrying techniques and equipment. That would be only fair, since practical studies of load carrying have clearly provided insights into normal unloaded locomotion biomechanics and physiology. Studying the load carriage practices of indigenous people and of animals in nature has and will continue to breathe fresh ideas into these fields of inquiry.

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