Pack Weight and the Science of Walking

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Backpackers walk. Some backpackers walk a lot. Along with carrying our houses on our backs it’s what defines us, although most of us walk without thinking about it, at least until sore knees or blisters draw our attention to it or we notice that the backpacker walking in front of us has great legs.

However, while painless walking may be easy to take for granted, it is by no means easy to do. It requires an incredibly complex series of interactions between most of the bones, muscles, tendons and joints of the trunk and lower limbs. These interactions result in relocations of body mass that sequentially and repetitively destabilize and re-stabilize the body’s axial balance while realigning its structural support. When properly coordinated by the nervous system, the net effect of these interactions is to maintain the body’s upright posture while moving it forward in space.

Each individual interaction influences each other interaction, and each interaction varies in response to the external conditions that exist at the moment the interaction occurs. For backpackers, the most important external conditions are the slope of the walking surface, surface traction and regularity, wind speed, pack weight, and the relationship of these conditions to each other and to the direction of travel.

While backpackers can accommodate various combinations of moderate conditions, an extreme of any one condition can make it impossible to successfully complete a crucial interaction, and at that point we either stop walking or we fall. We can prepare for extremes of terrain, weather and surface, and we can plan our routes in order to reduce the probability of encountering those extremes, but we have no direct control over them. On the other hand, we can control how much weight we carry.

The Importance of the Body’s Center of Gravity

The body’s center of gravity (COG) is located at the point where the body’s mass (or weight) is balanced in three dimensions. In other words, the COG is at the point where the mass above the point is equal to the mass below the point, the mass in front of the point is equal to the mass behind the point, and the mass to one side of the point is equal to the mass on its opposite side. When standing still, unclothed and without a pack, that point is on the axis (or midline) of the trunk and is roughly in line with the hip joints.

Walking can be thought of as controlled falling. To begin walking we push off with one foot while leaning forward slightly, forcing our COG forward of its base of support. Then, in order to avoid falling, we lift the other foot and swing it forward, seeking a new base of support. If we can plant the leading foot and successfully establish a new base of support, we then pivot the leg above it under a now moving COG. At the same time we swing the other foot forward into a position where it, in turn, can provide a new base of support.

To continue walking we repeatedly stride underneath a moving COG, first with one leg and then the other. Throughout the stride cycle (or gait cycle) the COG remains pretty much in the horizontal plane of the hip joints, although it does move side-to-side over first one leg and then the other as the leg becomes the body's primary supporting member. It also rises about two inches above the walking surface as each leg pivots underneath it.

The speed with which the COG moves forward in space varies during the gait cycle. When pushing off at the beginning of a stride we force the COG to speed up, and when planting the leading foot we force it to slow down. The COG attains its greatest speed as it falls from its peak in the gait cycle, immediately before we plant the leading foot.

Weight carried in a backpack has two major effects on the COG. First, assuming that the pack is firmly affixed to the back and that the pack load is balanced from side-to-side and cannot shift, the COG will move upward and to the rear relative to its "unloaded" position.[1] How much upward and to the rear will depend upon the weight of the load and its top-to-bottom and front-to-back distribution in the pack.

Second, because pack weight increases the total weight of the body and all that the body is carrying (i.e., the system weight), it also increases the momentum of the body mass, which is expressed through the COG. The increase in momentum is directly proportional to the increase in system weight.

As indicated above, walking requires that we get our COG moving forward. So, in order to walk, backpackers must compensate for the rearward shift in the COG caused by the weight of the pack, and we do so by leaning forward from the waist. When leaning forward we pivot the trunk around our hip joints. As a result, most of the movement associated with a slight to moderate forward lean (i.e., when the angle of the trunk is between zero and forty-five degrees) is horizontal. Because unloaded walking requires a small amount of forward lean at the beginning of each stride, this act of adjustment is familiar and easily accommodated.

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[1] If the load is not balanced from side-to-side the COG will move upward, to the rear and to one side of its "unloaded" location, depending on which side of the pack is heavier. If the load can shift or the pack is not firmly affixed to the back each stride will result in the COG moving up and down, backwards and forwards and from side to side relative to its "loaded and unmoving " position. All of these conditions will make the act of walking more energy consuming, if not downright dangerous, especially if the load is heavy.

However, backpackers can adjust very little for the upward shift in the COG. While leaning forward eventually lowers the COG (i.e., when the angle of the trunk is between forty-five and ninety degrees), the more we lean the more we run the risk of a gravity-powered face plant. At the very least a lot of forward lean makes walking a slow and uncomfortable process.

Re-distributing the pack load is not a complete solution. While it is always better to carry heavy items close to the body, and therefore horizontally closer to the COG, changes in vertical load distribution have mixed results. If heavy items are carried high in the pack then we won't need to lean forward as much to adjust for the rearward shift in the COG, but its upward shift will be greater. If heavy items are carried low in the pack then the upward shift in the COG will be less, but more lean will be required to adjust for its rearward shift.

Overall, reducing the weight of the load is a substantially more effective way of moderating the load's effect on the location of the COG. Reducing the weight of the load is the only way to reduce its effect on the momentum of the COG.

That is not to say that individuals cannot accommodate the combined effects of a "heavier and higher" COG to an amazing extent. Foot soldiers and Sherpa porters regularly carry as much as 100% of their bodyweight in their packs, and in many cultures women walk with staggering loads balanced on their heads. Even inexperienced backpackers can make instantaneous changes in their posture and gait and set out with fifty or sixty pound packs, and we've all encountered a hearty soul laboring up the side of a mountain with as much as eighty pounds on his or her back. Maybe that's where those great legs come from.

So, what's the point?

The aforementioned feats of strength and balance are made possible by the fact that human beings are not born knowing how to walk. We don't even try for the first nine months or so, and then we spend the next six to eight years learning and practicing the basics while accommodating our particular physiological limitations and the constraints of our environments. Consequently, we are used to learning to accommodate in the act of walking.

However, learning is not the only issue in successfully carrying heavy loads. For porters and foot soldiers it is a job requirement. For those amazing women who carry food and water on their heads it is a matter of survival. As a result, all of those individuals spend a good deal of time doing it, and over time they condition their bodies to its demands. Their muscles and bones get stronger and their coordination and dynamic sense of balance improves.

On the other hand, recreational backpackers carry weight on their backs for fun, and most do it too infrequently to benefit from a conditioning effect. Therefore, backpackers who carry heavy loads are more likely to suffer from a variety of immediate and long-term problems.

Problems Associated with Carrying Heavy Packs

As any veteran of carrying a heavy pack can attest, falling is the most immediate problem, because a heavy pack raises the COG and a “higher” COG makes balancing more difficult. When standing still, we can compensate for a “higher” COG by moving our feet apart and broadening our base of support, but walking requires a constantly changing and limited base of support. At the point in the gait cycle known as the “single stance phase,” the base of support can be as small as the ball and toes of a single foot.

Further, a heavy pack results in a “heavier” COG, and not only is more force needed to get a “heavier” COG moving, more force is needed to slow it down. When walking we either slow the forward motion of the COG with each foot plant, we walk faster, or the COG moves beyond its base of support and we fall. Likewise, we must slow the side-to-side motion of the COG as it moves over the supporting leg during each stride, or it moves beyond its base of support and, again, we fall.

Forcing muscles to repeatedly overcome the momentum of the COG results in muscle fatigue. Muscle fatigue results in a loss of muscle strength, and a loss of muscle strength results in a loss of control over a moving COG. That is why we are more likely to fall at the end of long day, a long climb or a long hike. And, despite how well conditioned we are, a “heavier” COG results in greater muscle fatigue. Ask any Sherpa or Navy Seal.

Finally, when walking on level ground we have only a fraction of a second in the course of each stride to change our minds about where we want to plant the leading foot, and our ability to do so depends partly on being able to alter the trajectory of the COG as it descends from its peak in the gait cycle. The heavier the pack, the greater the momentum of the COG, and the greater is both the force and the time required to alter its trajectory.

Since backpackers regularly seek out places where the surface is irregular and the traction poor, even a tiny delay in altering the trajectory of the COG can result in an insecure foot plant, and down we go. This particular problem is complicated by the fact that backpackers who carry heavy loads often wear heavy boots. A heavy boot greatly increases the momentum of the leading foot, and therefore increases the time it takes to change either its trajectory or its orientation.

On an ascending slope the descent of the COG from its peak in the gait cycle is shortened. Therefore, if we’re maintaining our pace, we have marginally less time to change our minds about where our heel strikes the ground. However, because the COG has had less time to gather speed as it falls from its peak in the gait cycle, and because we usually walk slower when going uphill, planting the leading foot may actually be less problematic than on level ground.

On the other hand, a downhill slope lengthens the descent of the COG from its peak in the gait cycle. While this does give us marginally more time to change where and how we plant the leading foot, it also gives the COG time to gather speed. Because most backpackers are not used to slowing a "heavier" COG as it falls, it is likely that it will be moving faster when the leading foot strikes the ground.

As your high school physics teacher pointed out, force equals weight times acceleration, so the force with which the leading foot strikes the ground (i.e., the ground reaction force) will be greater than it would had only the "weight" of the COG increased. In fact, when stepping off a log or a rock, this force may be equal to six or seven times the weight of you and your pack. Therefore, an insecure foot plant (i.e., one that allows the ground reaction force to be translated into a sliding motion), is more likely to result in a fall, especially on an irregular or slippery surface.

Other problems that can result from carrying heavy loads are both immediate and long term. A muscle that's not strong enough to overcome the momentum of the COG can burst or tear, and, as indicated above, a fatigued muscle loses strength. Perhaps more seriously, an overstretched tendon will pull loose from its attachment point on a bone, a bone forced beyond its bending point will break, and a misaligned joint subjected to too much pressure will shear (i.e., slip side-to-side). Even an aligned joint subjected to excessive pressure will fail when its shock-absorbing pad of cartilage ruptures.

It would be bad enough if an increase in pack weight increased in a linear fashion the probability that these problems will occur, but the stress on muscles, tendons, bones and joints increases at an increasing rate as the angle of a joint gets more acute.

For example, in order to better absorb the shock of impact when the leading foot strikes the ground, it is natural to have the knee slightly bent at impact and let the thigh muscles act as shock absorbers. When walking on level ground without a pack a "normal" knee joint is bent about two degrees at the moment of impact, and a knee joint bent at two degrees is subjected to a compressive force that's equal to about half the weight of the body.[2]

Following impact, the joint continues to bend another thirteen degrees while slowing the descent of the COG to its lowest point in the gait cycle. A knee joint bent at fifteen degrees is subjected to a compressive force that's about one-and-one-half times the weight of the body.

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[2] The compressive force on a bent knee is the force exerted by the kneecap trying to keep the joint from coming apart. This force is supplied by muscles contracting against the resistance of bones, and is directed over the kneecap through tendons.

Add the weight of a pack and the longer it will take to slow the momentum of the COG as it descends to its lowest point in the gait cycle, and the more the knee will be forced to bend after impact. The heavier the pack, the more the knee will be forced to bend. If the angle of the knee reaches twenty degrees it will be subjected to a compressive force of about twice the system weight. And that's while walking on level ground.

Step up on a rock or a log or step down off a ledge and it's not unusual to bend the knee ninety degrees or more. A knee bent at ninety degrees will be subjected to a compressive force equal to three to four times the system weight. More than ninety degrees and that force can reach six to eight times the system weight. Multiply that by the weight of you, your clothing and your fully loaded pack and think about a steep and rocky trail. Scary, huh?

Fortunately, however, the most common weight-induced injury is neither severe nor life threatening, just painful and tedious to remedy. Unconditioned skin that is forced to move against a surface while under pressure will eventually blister, especially when moist. All backpackers subject the skin on the soles and margins of their feet and between their toes to greater pressure than normal, and the heavier the pack, the greater the pressure. Since most backpackers who carry heavy loads also wear hot, heavy boots that they don't wear often…well, you get the idea, and if you carry heavy loads you've probably gotten blisters, too.

And those toenails, those black toenails that result when the weight of a heavy pack repeatedly crams them into the toe of the boot. What a relief when they finally fall off.

Pack Weight and the Backpacker's Choice of Footwear

While each "heavyweight" backpacker has his or her particular reasons for doing so, I feel safe in suggesting that at least one of the following reasons applies when a "heavyweight" chooses to wear heavy boots.

The first reason is probably unconscious. Wearing heavy boots at the extent of the lowest limbs lowers the body's COG and compensates somewhat for the COG-raising effect of a heavy pack. Second, wearing boots is traditional and universally accepted. If you're going backpacking, you wear boots. In fact, boots have become as commercially symbolic of the backpacking experience as the backpack itself. Third, there are the related issues of traction and cushioning. Fourth, many backpackers indicate that their ankles need support when carrying a heavy pack. Finally, a boot offers protection from the intrusion of sharp or hard objects.

I'll deal with the last two issues here, and save a discussion of other footwear issues for a rainy evening in a shelter.

A heavy pack subjects the ankle to greatly increased forces. Those forces can cause a misaligned ankle to deform to one side or the other, resulting in a debilitating sprain, if nothing else. A boot with a collar that surrounds the ankle can provide it with sufficient support to prevent it from deforming to the point of injury. However, unless a boot provides rigid side-to-side support (e.g., the support provided by a hinged plastic ski boot), its ability to support the ankle depends on compression of the ankle collar. If the collar is laced tightly enough to compress the ankle and stop it from deforming, it will also eliminate other joint movement. This results in substantial deterioration in the function of the joint.

The ankle, while its movements are small in comparison to the knee, serves a number of important functions in helping us get from here to there. First, the ankle helps absorb the force with which the heel strikes the ground, smoothing the transition of the leg from its swing-through phase to its weight-bearing phase. Second, the ankle allows us to pivot the leg above it while keeping the foot flat on the ground, making full use of the foot as a base of support. Third, the ankle allows us to use our calf muscles in toeing-off. Fourth, the ankle allows us to lift the toe of the foot so that it clears the ground during the leg's swing-through phase. Finally, it allows us to adjust rapidly to changes in the front-to-back and side-to-side slope of the walking surface, helping us to maintain our balance.

In a tribute to the designer of the leg, it's possible to walk with both ankles completely immobilized, although there are costs for doing so. Immobilized ankles require about 4.5% more energy per step, or 9% for a completed gait cycle, and they make losing our balance or stubbing a toe on the leg's swing-through phase more likely. Have you ever walked behind a boot wearer and noticed how often he or she stumbled when stubbing the toe of one boot on the ground as it swung forward? I have, and I've also fallen when I couldn't get the sole of my boot flat on a canted surface.

In addition, while compression of an ankle collar can protect the ankle from a sudden side-to-side force, that force will have to be absorbed further up the leg. In a slip or fall the "lucky" heavy boot wearer will sprain a knee or pull a hip or back muscle. I say "lucky" because there's worse that can happen. The knee or hip can dislocate, and there's always the dreaded "top-of-boot-break." I know of one solo backpacker who suffered a "top-of-boot-break" in a talus field and sheltered for two days under a boulder waiting for someone to find her.

While most of us will live long enough to get rescued, and while we will usually recover well enough from breaks and sprains to be able to continue backpacking, such injuries can really take the fun out of a hike. And while they don't happen often, they usually happen in a setting where medical help is not immediately available. If they also result in a fall where other injuries occur they can be life threatening. In preparation for them, many backpackers carry extensive first aide kits and supplies, making a heavy pack even heavier.

In reference to those less serious collisions with hard or sharp objects, I've already discussed how a heavy pack and heavy boots limit your ability to precisely "target" the place where you plant your leading foot. How many side and top-of-foot collisions result from poor lead foot "targeting?" Frankly, I don't know, but it is my experience that wearing trail shoes or running shoes while carrying less than a total of twenty-five pounds has resulted in far fewer side and top-of-foot collisions than when I wore heavy boots and carried fifty pounds.[3]

"But wait," as they say in the infomercials, "there's more!"

Due to the force required to get a weight carried on the end of the leg to start and stop moving, a shoe or a boot takes more of a backpacker's energy than an equal amount of weight carried in a pack. In fact, walking in a shoe or boot takes about seven times the energy it takes to carry the same shoe or boot. Add this to the extra energy it takes to walk with both ankles immobilized by compressed boot collars and you could be talking about a ten-fold penalty. For a four pound pair of boots this can mean an absolute energy increase over walking barefoot of about 40%, and that's on level ground.

Expended energy must eventually be renewed, so even a desert backpacker wearing heavy boots will have to carry more food than if he or she were wearing lighter footwear, and it takes additional energy to go up and down hills. No wonder that the eight-pound, load monster pack manufacturer was overheard to say to his banker, "The more you carry, the more you need to carry."

Pack Weight and Energy Expenditure

The physical work that backpackers do when carrying a pack results mainly from the force of gravity. We do work when we lift weight off the ground, and when we carry a pack on anything but perfectly level ground we do two types of lifting.

I've already discussed the first type of lifting – the "average" unloaded walker lifts her COG off the ground about two inches with every step. If she moves forward twenty-four inches with every step, then in a surface mile she will take 2,640 steps. If the walker weighs one hundred pounds, then she will do one hundred foot-pounds of work with every six

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[3] O.K., so you get your pack weight down to twenty pounds and you're considering giving up your six pound mountaineering boots for two pound trail runners. Still worried about that protruding ankle and all those nasty rocks? Wear a crew type sock and roll it down to form a partial cushion around the ankle joint. If the sock has a high percentage of moisture transporting fibers (e.g., Coolmax), such a collar will also make a reasonably effective sweat sump.

steps, or 44,000 foot-pounds of work every mile.[4] Strap a twenty-pound pack on that walker and she will do 52,800 foot-pounds of work covering the same mile. Increase the load by twenty pounds and the work required will be 61,600 foot-pounds.

The second type of lifting that backpackers do occurs when ascending a slope. Let's say our one hundred pound backpacker carries a forty-pound pack up a continuous mile-long slope that gains one hundred feet in elevation. The increased work imposed by lifting one hundred and forty pounds one hundred feet will be 14,000 foot-pounds. Therefore, the total work required of our backpacker will be something less than 75,600 foot-pounds. I say less because a continuously ascending slope will account for some of the distance that the backpacker has to lift her COG with each step.[5]

More realistically, let's say that our backpacker climbs a total of three thousand feet during the course of a ten-mile day in mountainous terrain. Carrying a forty-pound pack she will have done about 1,000,000 foot-pounds of work by the end of the day (i.e., the work involved in walking ten miles with a forty-pound pack plus the work involved in lifting 140 pounds three-thousand feet). However, had our backpacker been carrying a twenty-pound pack she would have done about 900,000 foot-pounds of work. That's a difference of 100,000 foot-pounds, or the work it would take to lift a fully loaded tractor-trailer truck one foot off the ground. Quick, add that to your resume.

"Very cute," you say, "but you haven't mentioned descending. That's the opposite of lifting, and it's certainly easier than going up. Don't we 'heavyweights' reap some benefit there?"

The short answer is "no." Descending any slope is easier than going up it, because we're not actually lifting any weight. However, it's not as easy as walking on level ground, because whatever amount of weight we're carrying is trying to fall down the slope, and we have to stop it from falling with each step. The "braking" that we do with the leg muscles takes energy, and the heavier the pack the greater the energy required. Further, when a descending slope exceeds about six degrees then progressively more energy is required to descend the slope with each additional degree of downward slant.

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[4] One foot-pound of work is the amount of work it takes to lift a one-pound weight one foot off the ground.

[5] The most "efficient" ascending slope, at least as far as total lifting goes, will be one that eliminates most of the two-inch descent of the COG during each step. For our hypothetical backpacker that will be an 8% slope, or one that rises about two inches for every twenty-four inches traveled. Over a surface mile a continuous 8% slope amounts to an elevation gain of about 440 feet.

So, descending three thousand feet with a heavy pack doesn't negate any of the energy cost of ascending three thousand feet with the same pack. The descent actually requires more energy than if we had climbed three thousand feet and then walked the rest of the distance on level ground. That's why I didn't use a "slope efficiency" correction in my estimate of the amount of work a backpacker will do in climbing three thousand feet. It's also why I think the practice of considering only net elevation gain when planning a route is misleading.

Pack Weight and Length of Stride, Pace and Mileage

You'll remember that I said that even an inexperienced backpacker can instantaneously adapt his or her posture and gait and set off with a fifty or sixty pound pack. What gait adaptation was I talking about?

When walking, a backpacker's neuromuscular system "automatically" attempts to find the combination of stride length and frequency that requires the least amount of energy to continue moving forward, given the combined effects of slope, surface traction and regularity, wind speed and pack weight. That's why we shorten our stride and slow our speed when we're going uphill – it minimizes the energy required to take a step. That's also the reason why we shorten our stride and slow our speed when walking on a sandy or slippery surface. Not only does a shorter stride and slower speed give us more control over our balance, it also allows us to minimize the amount of energy that's expended with each tiny slip of the foot.

Basically, our neuromuscular system does the same thing in response to carrying weight, because when we shorten our stride we decrease the distance that we must lift the COG with each step. To prove this to yourself, stand next to a washable wall. Then step forward three feet and stop as soon as you plant your leading foot. Make a pencil mark at eye level. Then, return to your standing position, step forward two feet and make another eye-level mark. The vertical distance between the two-foot mark and the three-foot mark is the amount of lifting you will avoid by shortening your stride length from three feet to two feet. Of course, on the trail you won't shorten your stride that much, and the amount you shorten it will vary according to other conditions. However, the energy savings per step will be proportional to the amount you shorten it.

"Wait a minute," you say, "if I shorten my stride I'm going to have to take more steps to cover the same distance, and I'll end up expending the same amount of energy." That's roughly true, but the "automatic" mechanism that controls stride length doesn't factor in how far we're going to go today, only how much energy will be required for us to take the next step. If we concentrate, we can override the "automatic" mechanism for a while, but sooner or later it will have its way with us, especially when we're tired.

Because stride length and pace are strongly related, the net result is that we slow down when carrying weight. The more weight we carry the slower we walk, and the less distance we can cover in a day. This won't matter if we're planning to do three miles on Friday and then camp for the rest of the weekend, but it will appreciably shorten the distance we can expect to cover in a day if we're trying to walk a long way.

Ask “Flyin' Brian” Robinson, who at the age of forty walked 7,400 miles in three hundred days in completing backpacking's first “Calendar Triple Crown.” [6] Brian packed thirteen to nineteen pounds during his long trek, and he'll tell you that the weight of his pack played an important role in his success.

However, while you may not be interested in duplicating Brian's amazing feat (pun intended), your safety, your enjoyment and your ability to venture further can only be enhanced by a carefully thought-through reduction in the weight of what you're packing.

Give it a try.

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[6] Between January 1st and October 27th of 2001 Brian walked the entire lengths of the Appalachian Trail, the Pacific Crest Trail and the Continental Divide Trail. You can learn more about Brian's Triple Crown at http://royrobinson.homestead.com/Triple_Crown.html.

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