The Mass-Spring Model of Movement for Cross-Country Skiing

The Problem With What We Know

We have come to know a great deal about how the body works with its skeletal system and muscles. Analysis has isolated each of the muscles in both structure and function and explained how force is produced and the skeleton supported and moved.

This has provided a basic but limited understanding, and not enough to inform us about the principles of whole-body movement. Without additional understanding we are left without the resources we need to both learn ourselves and teach young athletes. As Loney describes the history of our understanding, "We have believed mammals move through their worlds by contracting muscles, which flex and extend joints, which move our legs, which push or pull us down the trail. Think of rowing or cycling, and this model seems to fit. However, research has led us to a markedly different conclusion about running….that we 'bounce' down the trail." (Nensa *Nordic Studies Project*, Spring, 2013) As we do, I will suggest here, in cross-country skiing.

Just the sheer variety of muscle types, for example, each with a somewhat different location and role in stabilizing and moving the body, should suggest we need to look beyond simple flexing and extending in linear directions. The muscles, just for starters, are strap-shaped, two-headed (biceps), three-headed (triceps), four-headed (quadriceps), unipennate (feathered to one side), bipennate (feathered to both sides), segmented, serrated (from Wirhed, *Athletic Ability & the Anatomy of Motion*). They extend across, and criss-cross joints in complex ways. (Think, for example, of the various patterns of taping the trainer uses to stabilize fragile joints.) They work together to set free and define the almost infinite variety of movements of which the human body is capable – walking, running, leaping, twisting, turning, with all four limbs at once.

What We Haven't Reckoned With

Traditional mechanics/physics have described movement in terms of many separate linear and thus simple force-lever relations, from a stable origin/impulse to a stable completion. This is handy, but it tends to make us single out applied power and acceleration and ignore maintenance speed, or pace, which is the essence of endurance sport. Individual movements/positions which we can easily see, describe, and measure are emphasized while ignoring the fundamental dynamic-system principles of animal movement, like watching swimmers from the pool deck without investigating how the body operates to create the strokes we see. First, rarely is a single movement performed without the involvement of the whole body. It is the whole body, in fact, which in its movement determines the nature of the individual peripheral movements. The whole determines the parts then, and it is both more than the sum of the parts and different from the sum of the parts. Secondly, it follows from the first that a given muscle never acts in isolation. Within the dizzying complexity and matrices of muscle tension and release, an agonist system acts in dynamic concert with its antagonist system in a synergetic interaction with gravity, terrain and, above all, movement itself.

Enter Mass-Spring Theory

At the outset it is important to understand that these ideas are not new. Kelso and Holt, writing in 1980 in *Psychology of Motor Behavior and Sport* make that stunningly clear. “That nature might take advantage of the viscous and elastic properties of muscle-joint systems in control and coordination of movement is a view that has just recently gained recognition in this country (eg. Polit & Bizzi , 1978). However, the notion had its birth as long ago as 1947 in Berstein’s proposal (reported in Bernstein 1967) that when muscles acting at a joint are constrained to act as a unit [agonist-antagonist], the linkage is describable as a class of vibratory system whose physical and behavioral characteristics are qualitatively similar to a mass-spring…. [Feldman] extended Bernstein’s intuitions by demonstrating that when subjects were required to hold a steady angle at the elbow joint against a resistance, a change in the load resulted in changes in joint angle that were predictable as the behavior of a non-linear spring.” (p. 408f.)

The spring-like action of muscles was partly explained by Hook’s principle: “The force of a spring is directly proportional to its stretch; in the musculature a similar behavior appears, according to Rack and Westbury.” (1969) (Birklbauer, p.78) We have understood the stretch-shortening cycle for many years now.

But “stretch-shortening” turns out to be a more complex phenomenon than we have understood. “Schmidt (1998) limits the structuring of motor programs not only to point-to-point controls, in which each position of the limbs s represented as code in program, and thus by extension to impulse-timing models. He likewise notes the possibility of very simple and elegant program models which make use of the mechanical relations of the limbs and the physical surroundings/environment. Accordingly, the central nervous system needs only to establish an equilibrium point, in a balance-point or mass spring model, in which the courses of movement are controlled via the mechanical relationships of the moving bodies and the spring-like relationships of the muscles. The causal dynamic conditions throughout the system (ex. the behavior of the muscles as oscillating springs)… make possible a far more simple representation of the movement processes within the nervous system.” (Birklbauer, *Modelle der Motorik*, 2006, p. 77f.)

“Using trials with animals researchers were able to establish that at a stable innervation level a small lengthening of the muscle leads to a similar increase in force. However, at a certain point the muscle, following a self-induced/autogenic recruitment of the alpha motor neurons, begins to actively resist further lengthening. At that point the stiffness of the muscle (relationship of force to length) increases drastically… The muscles length at which the autogenic recruitment of the alpha neurons begins Feldman calls the *tonic stretch reflex threshold*.” (1969) (Birklbauer)

It is at this threshold where the simple stretch-shortening cycle of single muscle elasticity no longer encompasses the complex whole movement picture. A coil spring, for example, helps complete it. It not only stretches and recoils, it compresses/shortens and rebound/lengthens, or launches through ground reaction forces. But it also bends and rotates, rebounding to its initial point of equilibrium at any new location of the center of mass. It applies particularly well to skating on skis, a movement which has remained elusive to compelling explanation, particularly because of skating's rotational aspects. But Phillip Cheetham's explanation of a golf swing gives us some helpful additions. "The equations of motion end up the same for the linear model as the rotational model except that the mass is replaced by moment of inertia, linear speed with rotational speed and linear spring stiffness with torsional spring stiffness." ("Mass Spring System shows a Natural Kinematic Sequence." 2008, pdf., *www.amm3d.com*)

Practical Applications of the Mass-Spring Model

Getting closer to practical application, Farley, Glasheen, McMahon write in *J.exp. Biology* (1993), "Running Springs and Animal Size," the authors conclude: "The spring-mass model we use in this study is the simplest model for describing the mechanics of bouncing gaits. The figure lumps the mass of the whole body at the hip and represents the entire musculoskeletal spring system as a single linear [coil] spring (the 'leg spring'). In reality, the musculoskeletal system consists of a complicated system of muscle, tendon and ligament springs which act across nearly every joint in the body (Alexander, 1988). Because of the difference between the simplicity of the spring-mass model and the complexity of the actual musculoskeletal spring system, it is remarkable how well the model describes and predicts the mechanics of locomotion." (p. 81)("Mass-spring" and "Spring-mass" both appear as terms in the research literature.)

The authors' further conclusions become relevant to skiing technique. The bracket numbering and bold type are mine.

"In the context of this simple spring-mass model we have been able to find **general principles** about how the musculoskeletal spring system operates in trotting, hopping and running animals in each of these bounding gaits, **[1.] the stiffness of the leg spring is nearly the same at all speeds. [2.] The spring system is adjusted to operate at higher speeds by increasing the angle swept by the leg spring while it is in contact with the ground rather than by increasing the stiffness of the leg spring. [3.] Consequently, at higher speeds, the leg spring experiences greater vertical forces, which result in larger compressions of the leg spring. [4.] Furthermore, it sweeps through a greater angle and the center of mass follows a flatter trajectory. [5.] The combination of these effects results in an increased vertical stiffness and a decreased period of ground contact**." (p. 81)

[2] The critical role of the angle swept by the leg spring while it is in contact with the ground, which results in the leg spring experiencing increased vertical stiffness, makes clear that it is the whole body in motion which creates pressure/compression on the ground, not a particular flexion, sharpened individual limb angle or downward push through the foot.

As Whittington notes (2009) “Active modulation of muscle stiffness [is] needed to maintain the constant limb stiffness. However, this energy expenditure would be distributed throughout the gait cycle, not just occurring at the step-to-step transitions.”

Davids, Bennett, and Newell (2009) make a similar point: “Activation levels of flexors and extensors help stabilize joint angles in an attractor [coordination pattern] while the overall movement amplitude helps set joint stiffness for a particular angle.”

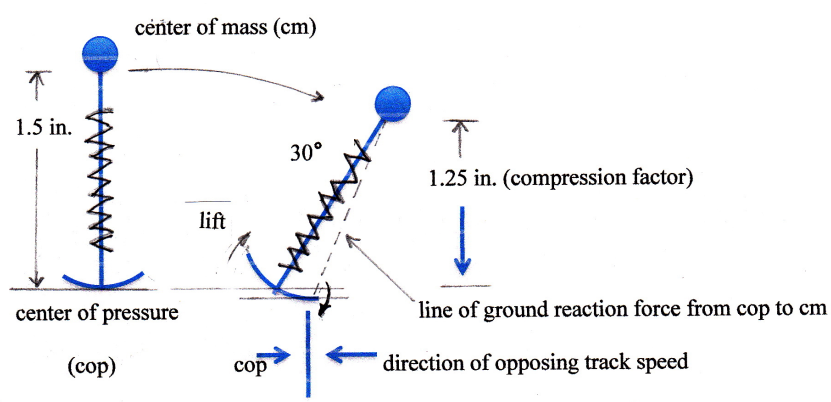
The fact that the stiffness of the leg spring is nearly the same for all speeds [1.] further suggests that no deeper flexion in the leg/ankle is needed to produce greater speed. In fact, studies of counter-movement jumps demonstrated some years ago that deeper flexing of the knees and ankle actually produced less power and speed than letting the legs compress and release naturally, according to their own instinct for self-organization, or, returning to the beginning of the discussion, to their own autogenic recruitment of alpha neurons which initiates optimal muscle/joint stiffness, the key to optimizing vertical ground reaction forces. (Bobbet, Huijing, Van Ingen Schenau, 1987)

[1.] If the stiffness of the leg spring is nearly the same for all speeds, a simple class-room steel marble launcher can become informative.

With a standard spring compression/stiffness, a relatively small increase in launch angle of 6 degrees (from 5 to 11 degrees from vertical) resulted in a steel marble going from 10 to 16 inches. I have run many sequences with a marble launcher, with similarly compelling results, and they do not reckon with the added compression of a forward “sweep” of the body through that change in launch/spring release angle.

Finally, bioengineers have that found the mass-spring model became more accurate yet with the addition of “roller feet.” Roller feet provide the leg spring with a rocker much like our foot as it rocks from the ball of the foot to the toe, a leaf spring that triggers the release into flight, like a triggered catapult. The release is optimally powered by the stored energy in the compressed spring.

The relevant article is: Ben Whittington, Darryl Thelen “A Simple Mass-Spring Model With Roller Feet Can Induce the Ground Reactions Forces Observed in Human Walking,” *Journal of Biomechanical Engineering*, Vol. 131, January, 2009. The figures below are my renditions of figures in the article.

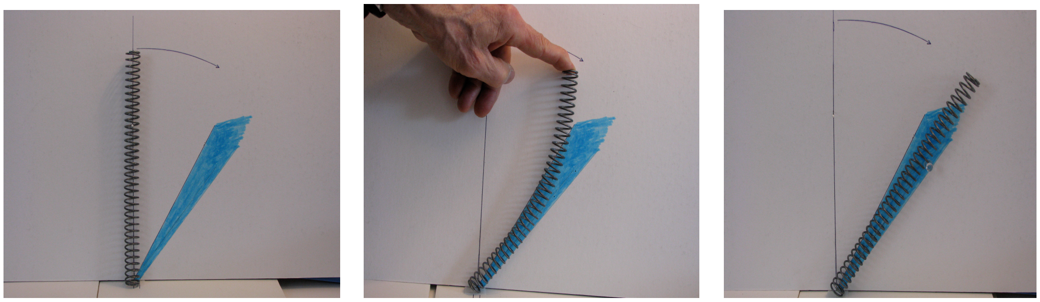


Unlearning Notions of Applied Power

The counter-movement jump studies had already showed that attempting to "strengthen" the body's force against the ground in fact breaks through the essential stiffness threshold, the efficiency of the leg spring(s), squandering both power and speed/time. (Van Ingen Schenau, et al. 1987) The extra flexion increases the energy cost and may feel more powerful, but does not gain speed. In fact, it causes ground reaction forces to "leak" at the joints. You're "over-skiing" and just giving away pressure in your "tires."

We also know of similar compression-release responses from a shock absorber, or from the compression we feel through a dip in the trail. The only difference to the skiing movement is that the dip in the trail causes a compression from the action of the terrain and from the bottom up. In skiing the process is more dynamic and active. It comes more generally from the convex trajectory curve of the body in motion within the varying environment and the natural flexibility and responsiveness of all the body's springs as an single integrated system.

A coil spring, for example, can show how the knees work. Stabilizing one end of the spring held vertically, compress it slightly while moving the top end forward. This, we know, is natural to the body. What happens to the spring happens with our knees: it bends while compressing. If you let it go, a catapult is created which flings the body upward into a flight trajectory, somewhat similar to the manner in which a pole vault bends and flings the vaulter up (or as a spitball flies from a popsicle stick!). The forward swinging leg matches the flex of the spring leg because the space to swing through has been compressed, and flexing instinctively assures that that leg can move itself freely forward to the next necessary support location for the body in motion.



standing sweep/ “fall” / compression launch/lift/ release

Note that the center of pressure at the ground moves from the center of the spring to the forward edge, in a word from center of the foot to the toe. The forward sweep of the body is maintained initially by the balanced “stiffness” of the, knee, ankle joint and the foot rocker. The foot acts then like a leaf spring (like the prosthetic spring legs of handicapped runners), first directing flexed pressure to the ground through the ball-toe progression, then rebounding in synchrony with the released leg/knee spring. (It is interesting that the German word for spring is *Feder* or “feather,” and the word for ankle is *Sprunggelenk*, “spring link.”)

The following photo of the five best lady classical skiers in the world shows this sweep over the point of ground contact with the heel rising naturally before springing away from the ski/ground as a unit with the whole leg. (A YouTube video shows this even more clearly: *Pertsan potku ja liuku*.)

In neither running nor skiing is it productive to keep the heel down or think a sharper ankle/shin angle will result in more power or speed. What happens is that the total leg spring synchrony is compromised and inordinate compression placed on the anterior muscles of the lower leg – among other things an invitation to compartment stress.

Principles of Movement Take Many Forms

Looking for other analogies, it is the force of the curve itself which compresses the rider/motorcycle springs and creates the added friction the tires need to hold onto the track while the rider/machine leans sharply in to ride the turn and not be pitched to the outside. The same principle explains how the curve of the turn itself adds the necessary hold or edge as the alpine skier rides the turn. This sort of gravity-plus compression force is also created, albeit with much greater subtlety, by the convex trajectory of the cross-country skier. But it is enough to trigger adequate ground reaction forces and resulting flight in gliding. Think of how a motorcycle or alpine skier snaps up to vertical when it or he comes out of the turn. That is a spring release or "lift" we see in running and cross-country skiing, one which I have described elsewhere in an article with Jim Galanes on "lift-kicking."

A simple device can also show the extent of compression when the body is considered a "leg-spring." Attach a foot long string or light chain to the top of a stick a foot long. Sweep the top to 30 or 35 degrees from vertical and notice the small section of string now lying on the table. That approximates how much that sweep compressed the leg spring(s). More is not needed to achieve an optimal lift off release. Demonstrations with the marble launcher and simply handling a coil spring are also both simple and compelling, even to youngsters (especially if accompanied by videos of animals). Your "classroom" is complete. And how they think is how fast they'll go.

If greater grip is attempted by either forcing the shin-ankle angle or by keeping the whole foot in ski contact longer, two negative effects tend to result: anterior compression forces break through the natural, and fastest, spring release, and the forward-moving center of pressure does not naturally transfer the forward sweep of the whole body. If the shin-ankle angle is forced, the whole spring lift system is thrown out of coordination. It "sags," and the skier seems to sit, or push the ski like pushing a scooter. This is quite clear if one compares the two figures above (page 4) and notes how the front of the foot rocker penetrates below the line of the ground. That already represents the spring system establishing a positive support point and beginning to roll up, tensing to uncoil, even as the body "falls" forward.

The evolutionary biologist, Daniel Lieberman, tells us about this distinctively human capacity. "The shape of the human foot is created by the shapes of the foot's bones, as well as by many ligaments and muscles that secure the bones in place like cables in a suspension bridge, and which become taut (to varying extents) when the heel comes off the ground." (p. 36) More generally: "Since running uses the legs like springs, some of our most important adaptations for running are literally springs. One key spring is the dome-shaped arch of the foot…. A full and springy arch is not necessary for walking….but its spring-like action helps lower the cost of running by about 17%." (p. 86) (*The Story of the Human Body*, 2013)

As counter-intuitive as it seems, extra down-effort only adds to negative forces by overriding the body's instinctive split-second acceptance of the leg/foot spring release, the trajectory up and forward, staying "on top" of the onrushing track, in a word, gliding.

I had an early hint of the counter-intuitive logic of this principle when I did some force-plate trials with Gould's physics teacher, Nancy Eaton. She attached two force plates to her computer which would graph the impulse curve of any kind of push-off. Trying to release my leg spring most quickly, I still could not avoid pressing down because I was starting from a stand-still. Without already being in the movement itself it was difficult to get the time down to under .2 sec as it is in skiing. She took a turn, having no idea about skiing, and just swung her free leg forward simultaneously with both arms….and produced both greater force and a shorter time than I had. The force-plates trials gave me a demonstration of the force potential of forward body sweep just by itself. It also reminded me of a favorite adage: It's amazing how much you can learn from someone who (apparently) doesn't know anything about your particular sport. Lack of experience may at times make for less biased thinking.

Finally, this is not new stuff; it's old stuff, and I'm embarrassed it has taken me so long to find, study and begin to understand it.

Dick Taylor March, 2014