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Invited Editorial

A spring in your step: some is good, more is not always better

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WHEN HUMANS AND OTHER ANIMALS run and hop, they operate with muscle efficiencies nearly twice those observed during cycling (2, 4). This "free energy" is due to the storage and return of elastic energy in muscles and tendons during the stretch-shorten cycles of landing and takeoff (1). If spring-like tendons and muscles can save substantial energy, could artificial springs added to the legs further reduce the metabolic cost of locomotion?

Researchers Grabowski and Herr asked just such a question in an article appearing in this issue of the *Journal of Applied Physiology* (4a). These authors might be on to something: amputee runners with energy-storing prostheses may be on the verge of outcompeting those with intact limbs (Fig. 1, *left*), as evidenced by the recent world-class performances of sprinter and double-amputee Oscar Pistorius. And for intact runners, tuning the stiffness of an elastic track underfoot results in record times for the mile (6).

Before adding elastic exoskeletons to the legs of volunteers, Grabowski and Herr (4a) measured the metabolic cost of hopping in place without any assistance. Surprisingly, this had never been documented. Perhaps more surprising was their finding that 20% less oxygen was consumed at hopping frequencies much higher than the preferred frequency. Whereas runners will chose a step frequency that minimizes the metabolic cost, people prefer to hop in place at ~2 Hz (7) despite this new study projecting a metabolic minimum close to 3 Hz.

Perhaps these new metabolic data can finally put to rest the mystery of the preferred hopping frequency. It has long puzzled biomechanists that subjects prefer to hop at slower frequencies despite less mechanical work and smaller center of mass fluctuations required for faster hopping. One possible explanation applied to this problem was Kram's cost of generating force hypothesis (3, 5). The theory was that the short ground contact times at high hopping frequencies required muscular force to be generated too quickly, leading to a greater metabolic cost.

Given these new data revealing that metabolic cost is actually lower at faster hopping rates, we may have to return to the explanation offered by the original report documenting the preferred hopping frequency. Melville-Jones and Watt (7) suggested that the long-latency stretch reflex leads to an enhancement of muscle force at precisely the right time to assist the takeoff phase when hopping at ~2 Hz but is unhelpful at faster or slower frequencies. This neural explanation is reinforced by the fact that we choose nearly the same frequency whether hopping on one leg or two (3, 7), despite requiring only half the muscle force per leg in the latter condition. Thus, we may choose to hop at a frequency tuned to our stretch

Fig. 1. *Left*: amputee runner with an energy-storing prosthesis. *Right*: individual using Alexander Böck's jumping stilts.

reflexes, opting for the simpler neural control paradigm at the expense of greater caloric consumption.

So can a springy exoskeleton reduce this metabolic cost, regardless of the frequency chosen by the hopping subject? Grabowski and Herr (4a) found that adding springs in parallel with the leg reduced the metabolic cost of hopping by nearly one third. These exoskeletons more than pulled their own weight: the exoskeletons weighed ~10% body mass and thus should have increased the metabolic cost by about as much (although the exoskeleton weight was largely self-supporting during stance).

The authors tested two different stiffness exoskeletons. Counterintuitively, the softer spring that supported a smaller proportion of body weight actually reduced the metabolic cost to a much greater extent. Although this at first seems like an additional challenge to Kram's cost of generating force hypothesis (5), most likely the explanation concerns the ability to overpower the spring to maintain balance. Too stiff an exoskeleton will leave the subject with little control over the hopping movement, and they will simply bounce at the natural frequency (plus aerial time) of the spring.

These results suggest that springs placed in parallel with the legs have to be less stiff than the legs during the required task, leaving some room for the biological legs to fine tune the stiffness to match the task. This could explain why benefits from the stiffer exoskeleton were only observed at a hopping frequency higher than that for which it was designed. As subjects hopped at the faster frequency, their legs contributed more of the total stiffness and permitted greater control over the force generated during the contact phase. While the optimum stiffness exoskeletons for both hopping and running still need to be determined, this study is off to an excellent start by

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showing that a randomly chosen soft spring exoskeleton can save an impressive 28% of the energy required to hop in place.

The authors used springs that decreased stiffness with increasing compression, especially the softer springs associated with the greatest metabolic savings. This exoskeletal design would seem to provide relatively greater contributions during landing and takeoff, with less support during the peak force occurring at midstance. The slight nonlinearity of these exoskeletal springs suggests the need for future studies examining the trade offs between balance and weight support at different parts of the stance phase. One might speculate that the opposite type of nonlinear spring, where stiffness increases with compression, might permit subjects to make fine adjustments during landing and takeoff while supporting a greater portion of body weight at midstance.

The potential applications of exoskeletal leg springs extend far beyond those popularized by Alexander Böck's jumping stilts (Fig. 1, *right*). Future exoskeletons may provide partial weight support for individuals with neuromuscular disorders and aid in the rehabilitation of locomotion after injury or disease. Exoskeletons may also be useful in industrial settings. For instance, Honda has developed robotic exoskeletal legs designed to reduce fatigue during standing and squatting by supporting a portion of body weight. In contrast to robotic legs, the passive spring exoskeletons in the present study are remarkably simple and require no power supply or control circuitry.

Exoskeletons should also continue to improve our understanding of the neural and mechanical control of movement. Powered exoskeletons and boots have shed light on the functions of the stretch reflex (9) and propulsive muscles during walking (8). And, as demonstrated in the present study, the ability to add springs in parallel with the leg should lead to further discoveries regarding the trade offs between mechanical stability and metabolic cost during locomotion.

Continued research on elastic exoskeletons will also improve running prostheses, building on the success of the carbon fiber "blades" used by amputee runners to achieve near-world record times. Like McMahon's tuned elastic track (6), exoskeletons may also help to increase performance of the intact athlete, either through training or perhaps even in a new type of competition. It is inspiring to think that we all may need these exoskeletons to keep pace with amputees in the near future.

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