INTRODUCTION

Humans prefer to walk at the combination of step length and frequency that minimizes metabolic cost for a given speed (Elftman, 1966). We previously hypothesized that the optimum combination is largely determined by trade-offs between two costs. The first cost is for step-to-step transitions, associated with work needed to redirect the body center of mass (COM) from the pendular arc described by the stance leg. The second cost, for forced leg motion, is associated with work and force necessary to move the legs back and forth relative to the torso. Step-to-step transitions were shown to increase sharply with step length. Here we show that the cost of leg motion increases sharply with step frequency. Trade-offs between the two hypothesized costs determine optimum step length and the corresponding metabolic cost.

The optimum step length hypothesis is based on a simple model of passive dynamic walking, modified to walk on level ground (Kuo, 2001). In the passive model, energy dissipation only occurs when the COM is redirected from one pendular arc to the next. We powered this model by applying a push-off impulse, and found that step-to-step transition work was minimized by pushing off just prior to heelstrike (Fig. 1A). We also found that forcing the legs with spring-like actuation can reduce step-to-step transition costs. However, there is presumably a metabolic cost to forcing leg motion, even if no net work is performed over the step (Fig. 1B). We proposed metabolic rates $\dot{E}$ for step-to-step transitions and leg motion, roughly proportional to $l^4 \cdot f^3$ and $l \cdot f^4$, respectively, where $l$ is step length and $f$ is step frequency. The minimum of the summed costs yields optimum $l$ and $\dot{E}$.

Each of these hypothesized costs can be tested by measuring $\dot{E}$ under conditions that highlight particular contributions. For example, we previously evaluated step-to-step transitions by asking subjects to walk with increasing $l$ but constant $f$. We found that rate of work performed on the COM increased with $l^4$, and $\dot{E}$ also increased proportionally (Donelan et al., 2003). Below we describe an experiment to measure the cost of leg motion by increasing $f$ with constant $l$.

METHODS

Eleven healthy subjects (7 male, 4 female; mass 67.2 ± 7.0 kg; leg length 0.93 ± 0.07 m).

Figure 1: Trade-offs in metabolic cost of walking. (A) Net metabolic rate increases sharply with step length $l$, keeping step frequency $f$ fixed (Donelan et al., 2001). (B) Minimum metabolic rate (min) at a given speed is observed to occur at intermediate step length, implying that another cost increases sharply with $f$. We hypothesize that a cost of forced leg motion produces the appropriate trade-off (Kuo, 2001).

TRADE-OFFS IN THE DETERMINATION OF OPTIMUM STEP LENGTH IN HUMAN WALKING

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m; mean ± s.d.) provided informed consent and then familiarized themselves for 10 min. walking on a treadmill at 1.0 m/s, after which we measured their preferred step length $l^*$ and step frequency $f^*$ at that speed. We then measured their net metabolic rate (subtracting the cost of quiet standing) at seven speeds $v$ ranging from 0.8 to 1.8 m/s, with constant $f^*$ and increasing $f^*$ ($v = l^* f$). The constraint was enforced with a metronome. At constant step length, the cost of forced leg motion is hypothesized to dominate step-to-step transitions, with metabolic rate $\dot{E}$ proportional to $l^4$. We also recorded net metabolic rate and preferred step length at the same speeds, allowing subjects to freely select gait. Both sets of conditions were applied in random order.

RESULTS AND DISCUSSION
We found that metabolic rate increased sharply with $f$ when $l$ was kept fixed. Consistent with the forced leg motion hypothesis, $l^4 f^4$ fit these data well (Fig. 2A; $R^2 = 0.92$. Adding together the predicted costs of step-to-step transitions and forced leg motion yielded a curve for each speed, whose minimum was designed to roughly match the preferred step lengths we observed (Fig. 2B). A more significant test is whether $\dot{E}$ at those step lengths was also predicted. We found good agreement, $R^2 = 0.94$, but only with the addition of a relatively constant offset of about 1.4 W/kg (seen in Fig. 1B and 2B). At a speed of 1.2 m/s, the proportions of overall cost were 32% for step-to-step transitions, 12% for forced leg motion, and 56% for the offset.

Trade-offs between step-to-step transitions and forced leg motion offer a plausible explanation for the optimum step length in human walking. The metabolic cost of step-to-step transitions is explained by the work needed to redirect the COM, predicted by a simple walking model. However, what governs the cost of walking at increasing step frequencies (Fig. 2A) is less clear. Given that metabolic rate also increases sharply in isolated leg swinging without walking (Doke et al. 2003), it appears that the cost of increasing step frequencies is indeed for forcing the leg to move quickly. This cost might not only be for work but also for generation of force (yielding the $f^4$ relationship); series elasticity might also reduce the muscle fiber work needed to move the legs (Kuo, 2001). These latter predictions have yet to be addressed experimentally. Finally, we do not explain the relatively constant offset, which might be for supporting body weight or for controlling the limbs.

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