METABOLIC COST OF GENERATING FORCE DURING HUMAN LEG SWINGING

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INTRODUCTION

When people walk at a particular speed, they choose a step frequency that is the least metabolically demanding [1]. This optimal selection of preferred step frequency can be attributed to determinants such as the cost of stance leg push-off during step to step transitions [2] and the cost of swinging the legs quickly. Sharp increase in metabolic cost during one-legged isolated leg swinging has been seen [3]. We hypothesized two potential causes to the cost of leg swinging: *work hypothesis* and *force/time hypothesis* [3]. According to the work hypothesis, the metabolic cost would increase proportionally to the positive mechanical work performed on the leg, which is assumed to be continuously fueled by the muscles. With the force/time hypothesis, the muscles are generating short bursts of forces, which result in a metabolic cost that is proportional to the force but inversely proportional to the duration of the bursts. Force/time hypothesis has been shown to better predict the preferred speed-step frequency relationship than the work hypothesis [4].

The purpose of this study is to test the force/time hypothesis on the metabolic cost of fast leg swinging. In order to isolate the effect of the work hypothesis, we maintained a constant rate of positive mechanical work over all swing frequencies. If the metabolic rate increases in spite of constant positive work rate, then we can conclude that work hypothesis has little contribution to the increase of metabolic cost at high frequency leg swinging.

METHODS

We measured the mechanics and metabolics of swinging a single human leg, using a frame inside which subjects stood on one leg and swung the other leg at prescribed amplitudes and frequencies (Figure 1). The amplitude was set at 50 degrees at the lowest frequency of 0.75 Hz and decreased with higher frequency, in order to assure a constant rate of positive mechanical work. We measured ground reaction forces, swing leg angle, and oxygen consumption rate, which we used to estimate the metabolic rate.

Six male subjects (aged 29.8 ± 4.9 yrs., mean ± s.d.) consented and participated in this study. They performed single-leg swings at five different frequencies ranging from 0.75 Hz to 1.08 Hz. Each frequency trial lasted six minutes, and the last three minutes were used for analysis in order to ensure steady state metabolic rate.

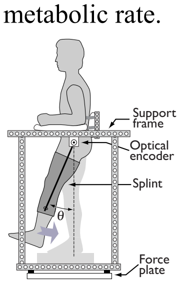

Figure 1: The apparatus consisted of a metal frame with back and arm rests for support, and a raised block for single-leg standing. The subject was securely strapped inside, and the leg angle was measured by an optical encoder at the hip. The whole frame was place on top of a force plate.

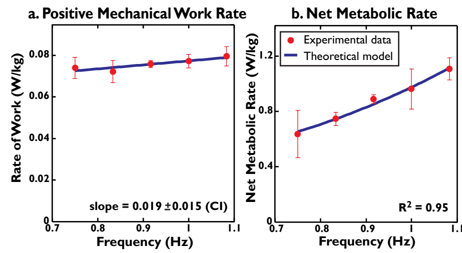

Figure 2: **a.** Positive mechanical work rate remained nearly constant. **b.** Metabolic rate increased with frequency to the 2.5th power, as predicted by the force/time hypothesis.

We created a theoretical model that consisted of a simple pendulum representing the swing leg, with the equations of motion

$$\ddot{\theta} + \omega_n^2 \theta = T\,,$$

where ω_n is the pendular natural frequency and T is the hip torque. Assuming a sinusoidal motion with amplitude A and frequency $\omega \triangleq 2\pi f$,

$$\theta(t) = A\cos\omega t\,.$$

In leg swinging, force/time cost is defined as a cost proportional to hip torque amplitude and inversely proportional to swing period [3]. With a constant positive work rate, the force/time hypothesis yields a metabolic rate prediction of

$$\dot{E} \propto f^{2.5}\,.$$

RESULTS AND DISCUSSION

The metabolic rate increased substantially by 74.3% from 0.75 Hz to 1.08 Hz, despite the nearly constant positive mechanical work rate (Figure 2). Moreover, the metabolic rate increased with frequency to the power of 2.5, as predicted by our force/time model ($R^2 = 0.95$). The rate of positive work had a slope of 0.019 ± 0.015 (95% confidence interval) W/kg. If the work hypothesis was to hold, the cost would amount to a mechanical to metabolic efficiency of 1.5%. Assuming a typical efficiency of about 21% in isolated muscles [5], the result suggests a weak link between mechanical and metabolic work.

CONCLUSIONS

We isolated the effect of muscular work by keeping the positive work rate constant. There was a substantial increase in metabolic rate. This strongly suggests that the work hypothesis alone does not explain the increase in metabolic cost during high frequency leg swinging. Instead, the increase is better explained by the force/time hypothesis, which credits the cost to muscles generating short bursts of force.

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