ELASTIC ENERGY AND OPTIMAL STRIDE FREQUENCY IN RUNNING:
THE EFFECTS OF UPHILL AND DOWNHILL

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INTRODUCTION

Each runner strongly prefers a stride frequency that is close to the ‘optimal’ stride frequency that minimizes metabolic cost (Cavanagh and Williams, 1982). We investigated the role of elastic energy recovery in determining the optimal stride frequency during level and hill running.

Because we expected less useful elastic energy storage and recovery in hill running, we hypothesized that altering stride frequency would change metabolic cost less during hill than level running. Further, we hypothesized that increased metabolic cost would cause runners to prefer stride frequencies closer to optimal on an uphill vs. on the level. Finally, we hypothesized that increased impact forces would lead runners to choose stride frequencies faster than optimal on a downhill.

METHODS

We measured metabolic rate and normal and parallel ground reaction forces as ten male subjects ran at 2.8 m/s on a force treadmill on the level, at 3° uphill, and 3° downhill. Each subject performed seven 7-minute trials on each slope: a standing trial, a trial to determine preferred stride frequency (PSF), and five trials using a metronome to set stride frequency. Net cost of transport (J/kg/m) was determined for minutes 4-6 by subtracting resting metabolic rate, and dividing by speed. From thirty seconds of force data, a Matlab program calculated kinetic and potential energy of the center of mass (CoM) from the force data over the course of a step. These data were used to analyze the maximum CoM energy that can be stored elastically and then returned on each slope. An ANOVA tested for significant changes across slope and stride frequency (p≤.05).

RESULTS

As expected, stride frequency and slope affected metabolic cost, but for all slopes, metabolic cost depended on stride frequency similarly (p=0.38). Additionally, runners tended to prefer approximately the optimal stride frequency regardless of slope. PSF mean (SEM) values were 1.44 (0.02), 1.47 (0.03), and 1.43 Hz (0.02) for the level, uphill and downhill, respectively.

![Figure 1. Normalized metabolic cost versus and normalized stride frequency for level, 3° uphill and 3° downhill. Error bars = SEM.](image)

CoM fluctuation patterns changed distinctly with slope and stride frequency (Figures 2 and 3). From these data, we can infer possibilities for elastic energy storage. Based on the energy fluctuations of the CoM, the maximum CoM energy that can be stored elastically and...
then used to lift and accelerate the CoM later in stance is reduced during hill running. The CoM energy fluctuates asymmetrically during hill running (Figure 2). This asymmetry indicates that in uphill running, less energy can be stored elastically than is needed to increase the CoM energy during the second half of stance. Correspondingly, during downhill running, more CoM energy can be stored than is needed later in stance. This indicates that some dissipation of elastic energy must occur. Varied stride frequencies show symmetrical patterns with more CoM energy per stride available for elastic storage and return at slower stride frequencies than faster ones.

![Figure 2. Fluctuations of total CoM energy over a step for a representative subject for 3° downhill, level, and 3° uphill at PSF. Circle indicates end of contact time.](image)

**DISCUSSION**

We reject our hypothesis that reduced elastic energy storage leads to shallower stride frequency vs. cost curves in hill running.

It is possible that elastic energy storage/return was not sufficiently impaired on the slopes used to lead to a shallower stride frequency vs. cost curve. However, calculations from the CoM data showed that the maximum possible amount of useful elastic return was reduced by an average of 19%. This suggests that other factors also influence the optimal stride frequency. Possibilities include change in internal work and the increased cost of producing force as a function of contact time (Kram and Taylor, 1990).

We reject our hypotheses that runners choose stride frequencies closer to optimal uphill and faster than optimal downhill. Runners were as likely to use the optimal stride frequency on hills as on the level. The fact that runners used the optimal stride frequency downhill indicates that minimizing metabolic cost outweighs avoidance of high impact forces.

![Figure 3. Fluctuations of total CoM energy over a step for the same subject for 85, 100, and 115% PSF during level running.](image)

**SUMMARY**

The relationship between stride frequency and metabolic cost does not change from level to hill running, suggesting that factors other than elastic energy storage are also influencing the stride frequency vs. metabolic cost curve.

**REFERENCES**
