WALKING DOWNHILL: THE TRADE-OFF BETWEEN ENERGETICS AND STABILITY

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INTRODUCTION

Humans tend to choose walking patterns that minimize energetic cost [1], but must also maintain stability. We used model simulations and experiments to investigate the potential trade-off between energetic economy and stability during downhill walking, a context in which gravitational potential energy will reduce the need for active powering but may also contribute to instability.

One method of keeping energetic cost low is to take advantage of the body's passive mechanics, as evidenced by the development of dynamic walkers. These simple devices can walk with low energetic demand when powered by a downhill slope or push-off impulses [2, 3] and can produce typical human kinematics by actuating the swing leg with passive springs [4]. In comparison to human walking, however, these devices are quite unstable.

We hypothesized that when walking downhill, humans prefer to increase stability rather than minimize energetic cost by behaving like a dynamic walker. In simulations of a dynamic walking model, we anticipated that increased slope would decrease the required actuation and decrease stability. Similarly, we expected that instructing subjects to walk more like dynamic walkers would decrease both energetic cost and stability.

METHODS

Model Simulations
Our dynamic walking model is actively powered by push-off impulses, with the hip and knee joints actuated by bi-articular springs (Fig. 1A) [4]. For a range of downhill slopes, we quantified the push-off and spring stiffness values that produced gait limit cycles (at 1.25 m/s), the stride period, and the model stability (using the gait sensitivity norm metric [5]).

Experimental Procedure
Twelve subjects walked on a treadmill for 6 minutes at 1.25 m/s. The treadmill was set to one of four slopes (0, 0.05, 0.10, and 0.15 grade decline), and subjects were instructed either to walk normally (*normal* walking) or to allow gravity to assist their walking and use as little muscle activity as possible (*relaxed* walking). One *normal* and one *relaxed* walking trial were performed at each slope.

Metabolic cost and foot-ground contact data were collected. All data were analyzed during the last 3 minutes of each trial to ensure subjects reached a steady state. Paired 2-way ANOVAs ($p<0.05$) were performed to determine if metabolic cost, average stride period, or stride period variability were significantly influenced by slope or walking strategy (i.e. *normal* or *relaxed*).

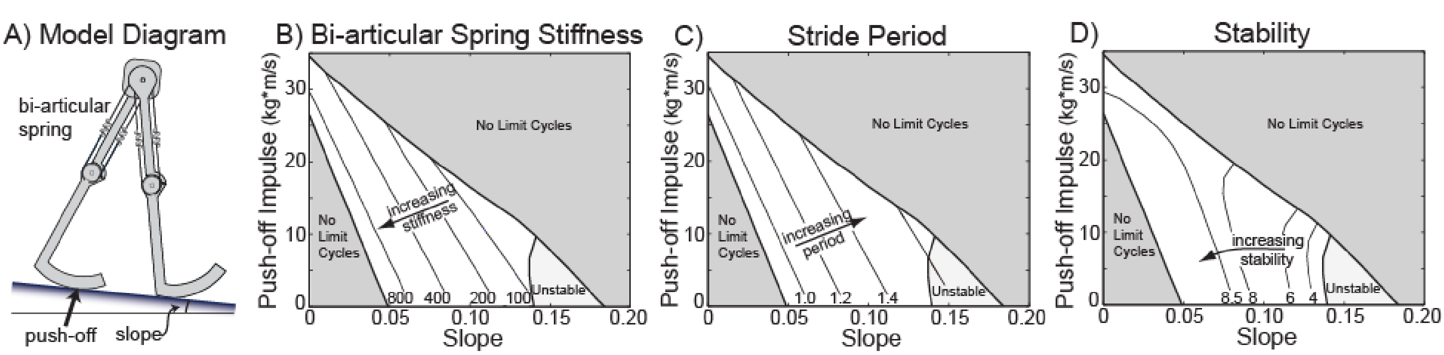

Figure 1. A dynamic walking model (A) was able to walk down a range of slopes. Steeper slopes allowed a decrease in push-off impulse and spring stiffness (B), increased stride period (C), and decreased stability (D).

RESULTS AND DISCUSSION

As hypothesized, subjects did not prefer the energetically optimal gait when walking downhill. Subjects were able to voluntarily reduce energetic cost by walking more like our simple model, but this was accompanied by decreased stability.

In our dynamic walking model, steeper slopes required less push-off and weaker springs (Fig. 1B). The decreased spring stiffness at steeper slopes caused an increase in stride period (Fig. 1C) and a decrease in stability (Fig. 1D).

Experimentally, walking using a *relaxed* strategy decreased energetic cost by 16% at the steeper slopes (Fig. 2A). The *relaxed* strategy increased stride period (Fig. 2B) and stride period variability (Fig. 2C), a measure associated with instability [6].

While the dynamic walking model was able to walk down a range of slopes, it did not predict the *normal* gait strategy used by human subjects. The model predicted that steeper slopes would reduce the required actuation (both push-off impulse and spring stiffness) and increase stride period. In contrast, the experimentally measured energetic cost of walking reached a plateau at a relatively shallow slope (~0.05), and stride period actually decreased at steeper slopes.

The discrepancy between our model predictions and *normal* walking behavior may be explained by the decrease in model stability at steeper slopes. In order to maintain stability, humans may prefer a gait strategy that requires more active control and is thus more energetically costly.

The importance of stability in determining the preferred gait pattern is supported by the *relaxed* walking data. Simply by changing their gait strategy to behave more like a dynamic walker, subjects were able to voluntarily reduce the energetic cost of walking. Despite the improvement in energetic economy, this gait is likely not preferred because of the decrease in stability, as evidenced by increased stride period variability [6].

CONCLUSIONS

When walking downhill, humans prefer a gait strategy that increases stability rather than minimizing energetic cost. This may partially explain the increased cost of locomotion in older adults and patients with gait disorders. While some of the increased energetic cost may be due to changes in cardiovascular or muscular properties, an additional portion may be attributable to the goal of ensuring stability. Additionally, the development of assistive devices may require the assurance of stability as an important first step in encouraging subjects to prefer a gait with reduced energetic cost.

REFERENCES

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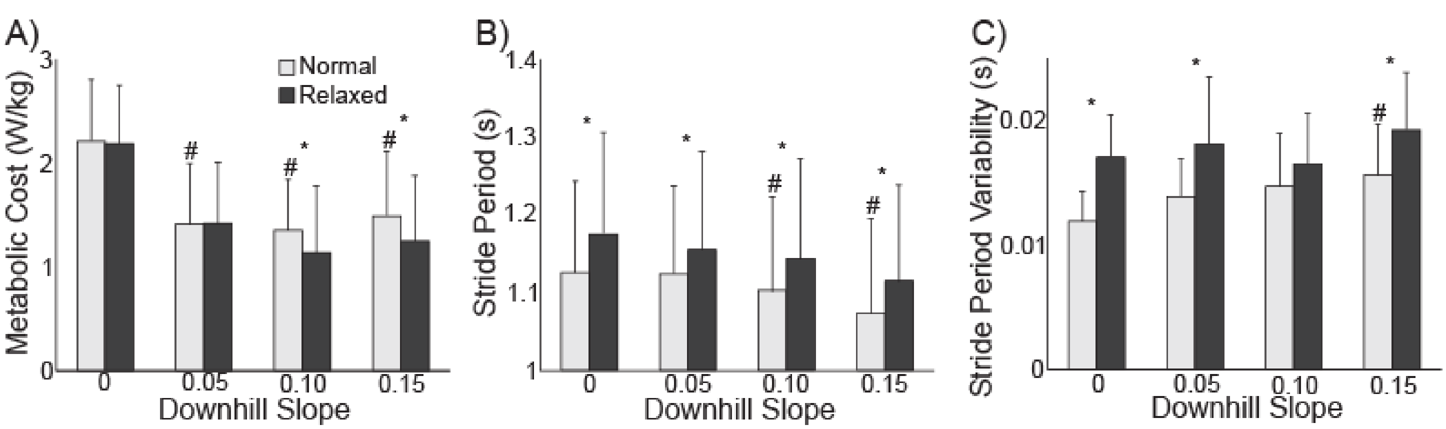

Figure 2. Walking using the relaxed strategy decreased energetic cost at the steeper slopes (A), increased stride period (B), and increased stride period variability (C). #Significantly different from walking on level ground. *Normal and relaxed values are significantly different.