

PERSON-TO-PERSON VARIATION IN GAIT PARAMETERS CORRELATES WITH PERSON-TO-PERSON VARIATION IN METABOLIC COST

John E.A. Bertram¹, Andy Ruina², Anindya Chatterjee³

¹ Nutrition, Food & Exercise Sciences, Florida State University, Tallahassee, FL, USA

² Theoretical and Applied Mechanics, Cornell University, Ithaca, NY, USA

³ Mechanical Engineering, Indian Institute of Science, Bangalore, INDIA

E-mail: jbertram@garnet.acns.fsu.edu

Web: www.tam.cornell.edu/~ruina/hplab

INTRODUCTION

A common qualitative explanation for various features of gait is that animals tend to minimize energy usage. But different people walk in different ways. Could it be that these individual differences in coordination patterns are correlated with individual differences in individual energy use patterns?

A person constrained to walk at a given speed v on a treadmill chooses a particular step frequency f and step length $d = v/f$. Testing over a range of speeds generates a speed-frequency (v - f) relationship. Since $v = fd$ and since the “normal” v - f relationship reflects the most economical manner of walking, why shouldn't the variables v , f and d be interchangeable resulting in a single relationship that minimizes cost for a variety of situations? However, we previously found that subjects walking under different constraint circumstances – a range of fixed metronome beats or a range of spaced markers – produce v - f relations distinct from the standard constrained v relation (Bertram and Ruina).

The data in this paper show 1) that constrained optimization of metabolic cost per unit distance reasonably predicts three distinct frequency-velocity (f - v) curves for an individual, and 2) that the differences between individuals in their metabolic costs correlate with differences in their f - v curves.

Reviewing Bertram and Ruina, multiple speed-frequency relations are predicted if gait variables are chosen to optimize an underlying objective function, say metabolic cost of transport. In Fig. 1 schematic contours of constant metabolic cost are shown as a

function of f and v . Each contour has a lower cost than the one outside it.

A line perpendicular to the v axis indicates a set speed (i.e. a subject on a treadmill). At this v , minimum cost occurs if the subject picks the frequency and step length combination where the constant v line grazes a cost contour (point A). The v - f relationship for constrained speeds is the locus of such points, one for each constrained v .

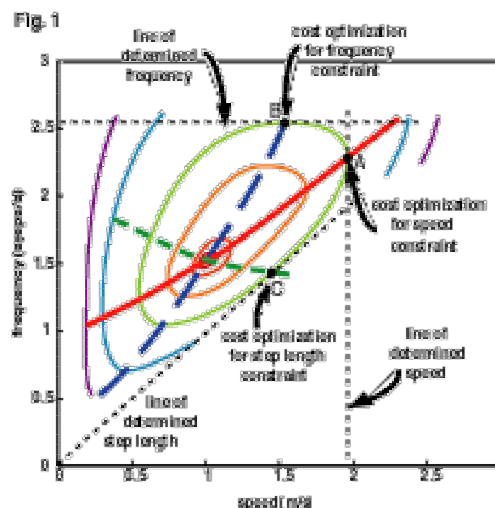


Figure 1: How constrained optimization predicts gait variable selection.

Optimization for a constant f will be determined in like manner (point B), except that a horizontal line will indicate the constraint. With a bowl shaped cost function, it is only at the global minimum that the constrained v and f curves cross.

Because $d=v/v$ constant step length is a line emanating from the origin. Cost is minimized for constant d walking where this line is tangent to a constant cost contour (point C).

Three different v - f curves are thus predicted, one for each kind of constrained task.

TESTING THE HYPOTHESIS

To test this prediction we measure both oxygen consumption and preferred constrained v - f curves for several individuals.

Part 1. Measurement of the cost surface. Subjects walked on a treadmill at eight speeds and step frequencies. Some combinations of low frequency and high speed were not possible; so a total of 49 O_2 consumption measurements were made. Oxygen data were taken using a metabolic testing system (TrueMax 2400, Parvo Medics, Salt Lake City, UT).

Measurements were taken on three different days with v and f mixed so that effort varied. Oxygen consumption was taken as the average over the last two minutes of a six-minute collection. Subjects rested for one minute before beginning a new v - f combination.

Part 2. Measurement of walking behavior We constrained, one at a time, speed, step frequency, or step length and measured the freely chosen values for the other two variables. Subjects were told simply to walk in a comfortable manner under the imposed conditions. Twelve subjects were tested.

ANALYSIS

Fig. 2

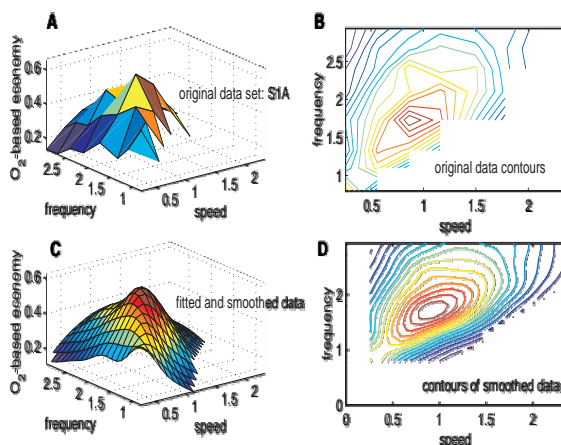


Figure 2: Metabolic economy of walking and the cost contours generated from it. A and B: Raw measures, C and D: smoothed data.

The 49 raw data points provide a rough characterization of the cost surface which we plot reciprocally as economy (Fig. 2A) and which generates the rough contours (2B). Note, both cost and reciprocal cost have the same contours.

We use a smoothing and interpolating algorithm that compromises between smoothness and passing through the data points to get plot (2C) which has the smooth contours of (2D).

RESULTS

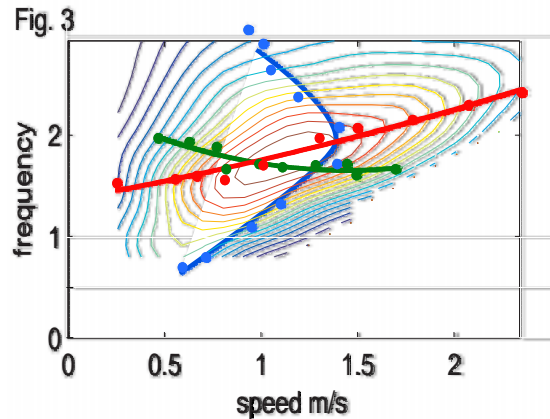


Figure 3: a plot of v - f curves overlaid on the cost contours for one of the subjects. The red plot is constrained speed (treadmill), blue is constrained frequency (metronome) and green is constrained step length (tape markers).

The predictions from the contours, based on constrained optimization, agree reasonably with the actual behavior of the subjects.

Differences between the contours and the behavior suggest that other factors also contribute to the choice of walking behavior. For example the data generally suggest that the underlying objective function punishes slowness as well as metabolic cost. Nonetheless, the idea of a task as a constrained optimization of something close to metabolic cost of transport correctly predicts trends that distinguish tasks and that distinguish the individuals from each other.

REFERENCES

Bertram, JEA, Ruina, A., *J. of Theor. Biology* (in press).