Realistic gait transitions: experiment and theory

Leroy Long†, and Manoj Srinivasan‡

Mechanical and Aerospace Engineering, The Ohio State University, Columbus, Ohio, 43210, USA

†*long.914@osu.edu*, ‡*srinivasan.88@osu.edu*

1 One line summary

Humans that wish to travel from A to B, run when they have very little time, walk when they have a lot of time, and use a mixture of walking and running when they have an intermediate amount of time – this behavior, which we establish using human subject experiments, is consistent, at least qualitatively, with energy optimality under time and distance constraints.

2 Introduction

Imagine you wish to go from the bus stop to your office and you have very little time before your next appointment. You would likely run. If you had a lot of time, you would probably just walk. If there was an intermediate amount of time, what do you think you would do? Perhaps you would walk for a while, and perhaps feel like you are getting late, so then run for while. That is, it seems consistent with common experience (at least ours) that we use a mixture of walking and running.

We perform an experiment that confirms this common experience quantitatively, by observing overground (non-treadmill) human gait under conditions in which both distance and time are constrained. As was pointed out earlier in a now-obscure math paper, using a mixture of walking and running at these intermediate time durations is consistent with energetic optimality, arising from the non-convexity of the overall energy landscape [2].

We believe that our experiment is perhaps a more ecological version of the numerous classic treadmill-based gait transition experiments that have been performed over the last 30 years, described briefly as follows.

3 Previous gait transition experiments and theory

The classic gait transition experiment is on a treadmill, and has the following set-up. e.g., [4, 1, 5, 3]. A person walks on a treadmill, and the belt is set at some slow speed. The belt speed is increased slowly, either in a series of steps or with a constant acceleration. At some speed, the person switches to a run, and continues to run as the speed increases further. Then, the belt speed is reduced slowly, until the person switches back to walking. Thus, humans walk at slow speeds and run at high speeds, and change gaits at a narrow range of speeds on a treadmill. The treadmill walk-to-run transition speed is very slightly different from the treadmill run-to-walk transition, and both these speeds are close to but slightly different from the speed at which walking and running metabolic cost curves intersect. More recently, researchers have performed overground gait transition experiments, in which they ask a subject to gradually increase the speed while they walk and break into a run when they feel it appropriate.

4 Our experiment

About 15 subjects had to travel a given distance D (about 120 m), with markers A and B placed at the two ends. They had to travel this distance in a given amount of time T; we used about 15 different values for T for each subject, corresponding to average speeds from 0.9 to 3.5 m/s. For each trial, a subject was given a stop watch that counted down to zero from T, and the subject was asked to either reach B exactly when the count-down reached zero or before the count-down reached zero. The fraction of walking as a function of average speed required D/T is shown in figure 1.

For a couple of subjects each, we performed small variants of the experiment, using longer distances, repeated trials providing practice, etc. These appeared to have the same qualitative behavior. There is plenty of subject-to-subject variability, which is also anticipated by the theory below.

5 Theoretical interpretation

Past theories of gait transition have been based on energy optimality, linear stability of a presumed ad hoc controller for locomotion, stability of the gait choice based on an imagined dynamics using metabolic energy as a potential energy landscape, muscles reaching force-velocity limits, joints reaching stress limits (with safety factors), etc. It is not clear if any above but energetics can explain mixtures of walking and running.

Our interpretation is based on energy minimization [2]. In particular, it can be shown that given cost curves as in Figure 2, the mixture region is determined by where the lower common tangent touches the two cost curves. [1]. The result follows from essentially the definition of convexity, in particular, a property called Jensen's inequality. The result is also known as the "common tangent construction" in physics and material science in the context of physical phase transitions.

[1] The result requires at least a slight curvature to the running cost curve and some quantitative details depend sensitively on this curvature

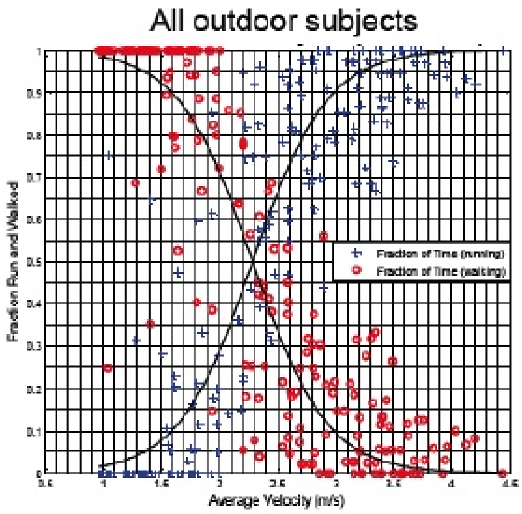

Figure 1: The fraction of time spent walking (red circles) or running (blue dots) is plotted as a function of average speed required (D/T). We see that for low speeds, people mostly walk (the red dots are close to 1) and for intermediate speeds, the red dots indicate a mixture of walking and running.

Similar results can be obtained for mixtures of walking and standing, etc.

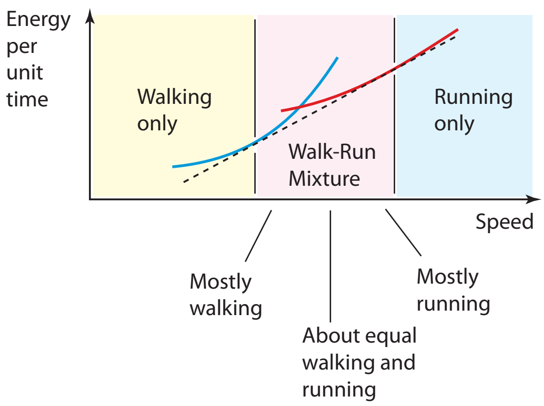

Figure 2: Given walking and running cost curves shaped as above, the walk-run mixture is predicted in the region where the common tangent is below either cost curve. This result assumes no switching cost, which modifies the result slightly.

6 Ecological implications

Children while walking with a parent often trail behind walking slowly, and occasionally overtake the parent running fast, sometimes to a parent's frustration. This could be because the parent walks at a speed that is in the mixture region of the child. Also, perhaps one could speculate that children holding a parent's hand either drags behind or tugs the parent forward because of an impulse to alternately walk slower and run faster. Similarly when adult animals migrate with juveniles, it may be observed that the juveniles use a mixture of gaits. Also possibly applicable to a person walking a dog, but perhaps on a long enough leash, a dog is probably too distracted by olfactory stimuli …

The theory applies to long treadmills which allow movement forward and back, thus not having a strict speed constraint; we predict that people at a range of intermediate speeds are likely to use a mixture of walking and running. Similarly, some animals on treadmills coast on the treadmill back, and then run forward to the forward end – using a mixture of running and standing, also consistent with the theory for appropriate cost curves. An airport moving walkway is just a long treadmill, and one expects mixtures of walking and standing, both when the goal is to hold average position and when the goal is to reach the other end under a time constraint. Mixtures of walking and running are also found in ultra-marathoners, not-quite-fit marathoners and runners, but it may be that their reason is fatigue-related than a pure energy minimization.

Further implications are discussed in an article in preparation.

7 Acknowledgments

Thanks to A. Ruina, who discussed the theory of optimality of mixture strategies in a biomechanics course at Cornell. The journal article in preparation on this work has over 35 citations at this point, including work by many conference attendees. We apologize for not being able to include this past work in this short abstract without being selective.

Key Words: gait transition, behavioral experiments, theory, children trailing their parents.

Format: This topic would be good for a 15 minute talk or a 5 minute lightning talk or a poster.

References

[1] A. Beuter and R. Lefebvre. Un modèle théorique de transition de phase dans la locomotion humaine. *Can J Appl Sport Sci*, 13:247–253, 1988.

[2] J. E. Drummond. The mathematics of scout's pace. *The Mathematical Gazette*, 70:185–190, 1986.

[3] A. Hreljac. Preferred and energetically optimal gait transition speeds in human locomotion. *Med. Sci. Sports Exerc.*, 25:1158–1162, 1993.

[4] R. Margaria, P. Cerretelli, P. Aghemo, and G. Sassi. Energy cost of running. *Journal of Applied Physiology*, 18:367–370, 1963.

[5] A. Thorstensson and H. Robertson. Adaptations to changing speed in human locomotion: speed of transition between walking and running. *Acta. Physiol. Scand.*, 131:211–214, 1987.