Energy optimality in novel locomotion tasks: experiments, theory, and simple models

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***Abstract*—Experiments over the last fifty years have shown that aspects of human locomotion can be predicted using energy optimality, at least approximately. Here, we describe how theoretical predictions from energy optimality can predict outcomes in novel tasks: sideways walking, reaching a destination by a time-deadline using a mixture of walking and running, and walking in non-straight-line paths (circles and other complex paths). Next, we will discuss current work with complex muscle-driven models in explaining human metabolic data and the reliability of these predictions.**

Energy optimality is a potential predictive theory for human locomotion and there is about fifty years of experimental evidence, at least partly in favor of this hypothesis. In this talk, we will briefly review the evidence for energy optimality, describe three human behavioral experiments and corresponding theory for novel locomotion patterns, such as walking sideways, using walk-run mixtures to reach a destination on a deadline, and walking in non-straight-line curves. We will discuss the goodness of match between experiment and theory in these novel tasks, and then discuss energy optimality in more complex muscle-driven models.

I. Optimality of walk-run-rest mixtures

We asked subjects (with no intentional practice) to travel a given distance overground (i.e., not on a treadmill) in a given amount of time. They could use any mixture of walking and running. The subjects mostly walked when given a lot of time and mostly ran when given very little time. Most interestingly they used a mixture of walking and running for intermediate amounts of time. This walk-run mixture is energy optimal, arising from the non-convexity of lower envelope of the walking and running energy cost curves. (Work with Leroy Long [3] and Nicholas Baker.)

II. Sideways walking

We asked subjects to walk sideways at their "comfortable" sideways walking speed. Then, we measured the energy cost of sideways walking at various speeds on a treadmill and determined the optimal speed for each person. Remarkably, we found that the distribution of preferred speeds and the optimal speeds for the 10 subjects had almost the same mean, differing only by 0.03 m/s. However, individuals were further away from the best fit of their optimal speeds – one reason could be the remarkable flatness of the energetic landscape, so that every subject was within 2.5% of their optimal energy cost (and most within 1%), despite greater variation in speed. (Work with Matthew Handford [2].)

III. Not walking in a straight line

We measured the energy cost of humans walking in circles. We found that for a given tangential speed, the cost increases with decreasing radius, as predicted by simple point-mass models. Further, using the empirically derived energy cost as a quasi-steady model of human energy costs, we can predict that humans would prefer to slow down at the higher curvatures when walking along complex curves. The quasi-steady approximation allows us to perform trajectory optimization calculations, which have classically used minimum jerk or other similar cost functions, explaining human paths qualitatively. (Work with Geoff Brown [1].)

IV. Energy optimality in muscle-driven models

We consider simple and planar muscle-driven models of humans walking, such as considered by Mombaur, Todorov, van den Bogert, Miller, Pandy, Anderson, and many other colleagues. We minimize simple models of metabolic cost and compare them to steady state human experiments. We find, perhaps not surprisingly, that while the kinematics are easier to predict, it can be more challenging to predict kinetics, especially given the flatness of the energy landscape with respect to these variables. We will discuss uniqueness of optima and motions within a given range of energies around the putative optimum.

V. Discussion

An open question is whether human coordination is predicted only on average by energy optimality, or if small individual differences in behavior can be explained by energy optimality as having origins in corresponding small differences in the individual's physiology. Answering this question may require better experimental energetics, better muscle models, better individual characterization, and better optimizations.

References

[1] G. Brown and M. Srinivasan. Curvilinear locomotion. In *World Congress of Biomechanics*, 2014.

[2] M. L. Handford and M. Srinivasan. Sideways walking: preferred is slow, slow is optimal, and optimal is expensive. *Biol. Lett.*, 2014.

[3] L. L. Long and M. Srinivasan. Walking, running, and resting under time, distance, and average speed constraints: optimality of walk-run-rest mixtures. *J R Soc Interface*, 10:20120980, 2013.