The cause of energetic cost differences in walking and running: optimization modeling and speed-gravity experiments

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Introduction

Humans use two main gaits: walking at slower and running at faster speeds. Energetic cost of walking is highly sensitive to speed while running cost is relatively insensitive[1]. Conversely, the energetic cost of human running is sensitive to gravity changes while that for walking is relatively insensitive[2]. These differences might suggest that fundamentally different mechanisms are at work in each gait, however these effects have not currently been satisfactorily explained. Optimization with a minimally constrained bipedal model predicts energetic differences of walking and running for both speed and gravity reduction that parallel empirical measurements, even though the same parameters and cost function are used for both gaits. Both gaits appear to employ similar energy minimization strategies, primarily influenced by the balance between: (i) the cost of stance-leg work to reduce foot-ground collision loss and redirect the center of mass motion from downward to upward during substrate contact, and (ii) the cost of swing-leg work to accelerate and then decelerate the leg motion at the start and end of swing phase to regulate the step length and frequency. Energetic cost differences between the gaits arise from limits to the energy minimization strategies available in each. Collision-based costs in walking determine that walking cost is highly sensitive to speed, but not much to gravity. The near vertical position of the leg at contact in running means that collision costs are relatively insensitive to speed changes while the non-contact phase provides an advantage in reduced gravity. These predictions are tested against human subject response to simulated reduced gravity using a unique harness.

Methods

Model

The model has been described in detail previously[2]. Briefly, it includes a torso, flat feet, and telescoping legs equipped with rotational hip, ankle joints and representative human mass. All joints are powered. The stance-leg telescoping actuator can only apply extensional forces. Each hip-motor applies torque between the torso and the corresponding leg. Trajectory optimization in MATLAB using SNOPT[3] finds the optimal gaits for which the cost of transport (COT) is minimized, subject to a given gait speed and gravity level. COT (the objective function) is calculated from $COT=E_{step}/(m\ L_{step})$, where m is the total body mass, L_{step} is the step length chosen by the optimization, and E_{step} is the energetic cost of each step. E_{step} is calculated using a work-based cost model in which the energy expended by each actuator is related to its positive and negative mechanical work via its work efficiency constants.

Experiment

Two specific simulated reduced gravity studies were conducted to evaluate the predictive capacity of the optimization model. One used indirect calorimetry to measure metabolic energy and involved eight subjects walking and running at two gravity levels over a broad range of speed. The other looked in detail at step length changes in both gaits as gravity is reduced and involved 16 subjects.

Results and discussion

The objective is to compare the mechanical energy optimization of a physically realistic bipedal model to that of human subjects in circumstances that are beyond normal experience. This rigorously tests the predictive capacity of the model. Verification of the model provides strong evidence that the factors determining the optimization strategy are likely also influencing the behaviour of the human motor control system.

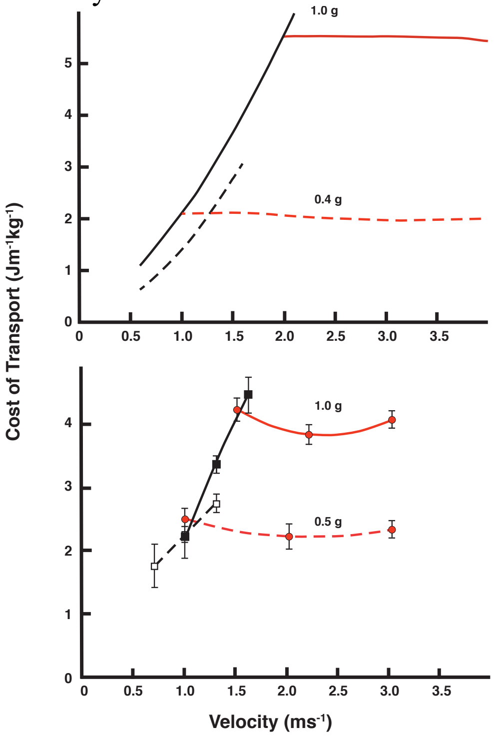

Fig. 1. Comparison of optimization model prediction of transport cost of walking (black) and running (red) over a range of speeds and two gravity levels (above) with the empirical cost of a subject walking and running under similar conditions (below).

In Fig. 1 COT of the model compares favourably with an example subject (all subjects responded similarly). Two features are evident in both the model and the subject: walking cost is remarkably insensitive to reduced gravity but is highly sensitive to speed (regardless of gravity level) while running is very sensitive to gravity level but remarkably insensitive to speed changes. Post hoc analysis of the model indicates that in running collision losses remain fairly constant as gravity declines, but the flight phase of the gait increases without cost. In walking a slight increase in step length is allowed in reduced gravity (Fig. 2), for a given average speed, because speed variations during stance are decreased allowing a lower speed at foot contact.

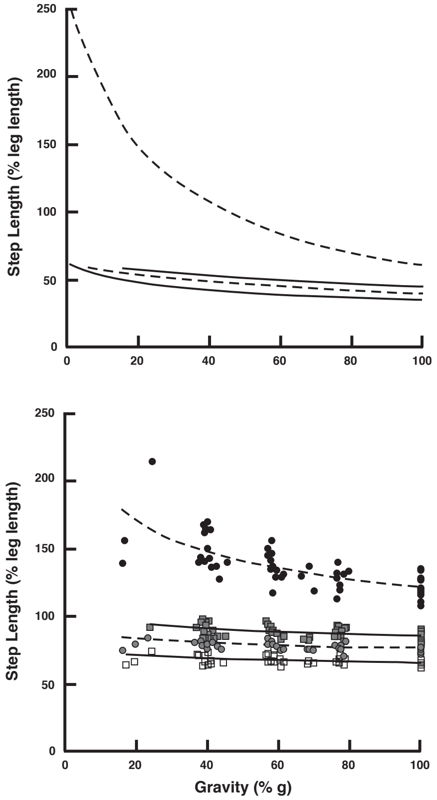

Fig. 2. Optimization model prediction of step length changes due to decrease in gravity (above: run top dashed line, and three walking speeds). Empirical measure of spontaneous step length changes using gravity simulation harness (below). Regression of step length vs. gravity for all walking curves significantly different from zero slope ($p < 0.5$).

References

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