Is the Leg Most Spring-Like at the Preferred Hopping and Running Frequencies?

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INTRODUCTION

Humans strongly prefer particular frequencies during hopping and running. Furthermore, the metabolic cost of running at this preferred stride frequency (PSF) is near its minimum (Cavanagh, 1982). It is possible that metabolic cost is minimized at the PSF because elastic energy storage and return provides most of the mechanical work. If this is true, it would make sense that the overall leg would behave more like a spring at the PSF than at other stride frequencies. Based on this idea, we hypothesized that a spring-mass model most accurately predicts the COM motion during hopping in place and running when subjects use their PSF. In the model, the mass of the body is represented by a point mass, and the mechanical behavior of the leg is modeled as a linear spring. This model has been successfully used to represent bouncing gaits in a wide variety of animals (Farley et al., 1993), including hopping in place and running in humans.

METHODS

Eleven males ran (2.5 m/s) and ten males hopped in place on two legs at a range of stride frequencies that were above, below, and at their PSF. We measured ground reaction force (GRF).

For each trial, leg stiffness was calculated using two methods: from the slope of the leg force-leg compression curve during stance and using a spring-mass simulation (Matlab). We calculated leg compression by twice integrating the COM accelerations, calculated from the GRF. For the second method, we ran a simulation of a spring-mass model using initial conditions from each trial (leg length, body mass, leg angle at touchdown, COM velocity at touchdown). The simulation error was calculated as the average absolute difference between subject data and the simulation's prediction for COM displacement over the ground contact phase. For each trial, we found the spring stiffness that minimized this error ('optimal' leg stiffness for that trial). Finally, we compared this 'optimal' leg stiffness value to the value calculated from the leg's force-compression curve for the stance leg.

RESULTS AND DISCUSSION

The leg stiffness values that optimized the spring-mass model trajectory predictions were, on average, within 0.6 kN/m of values calculated from the leg's force-compression curve for both hopping and running. The finding that two very different methods give similar leg stiffness values lends further support to the idea that the leg behaves like a spring during hopping and running.

Contrary to our hypothesis, the spring-mass model did not predict COM motion most accurately at the PSF for hopping and running (Fig. 1). Rather, its predictions improved continuously as frequency increased and were remarkably accurate at moderate and high frequencies. This observation suggests that the stance leg did indeed behave more like a spring at the PSF than at lower stride frequencies but behaved less like a spring at the PSF than at higher stride frequencies.

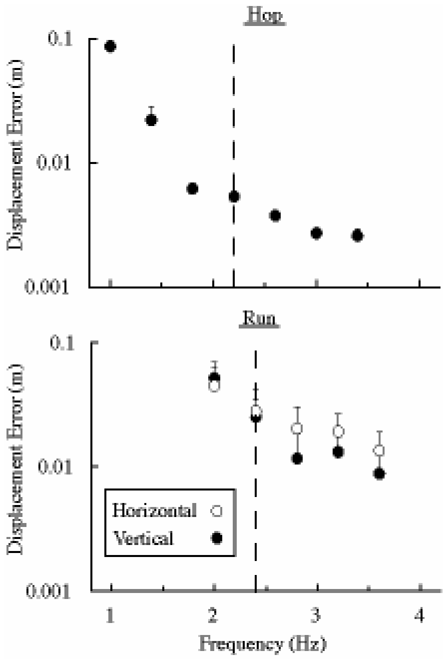

Figure 1: Vertical dashed lines show the average PSF. Frequency is step frequency for running. For running, the figure shows horizontal and vertical errors, while the text uses total error which is the vector sum of the two components. Error values are larger for running than for hopping because COM displacements are larger for running.

The spring-mass model did predict COM motion more accurately at the PSF than at lower frequencies for both hopping and running. The model's predictions differed the most from subject data at the lowest frequency for both hopping (8.7 cm) and running (6.9 cm). In contrast, at the PSF, the average error was lower for hopping (0.5 cm) and running (3.8 cm). This observation suggests that the leg behaved more like a spring at the PSF than at lower frequencies, which might indicate greater storage and return of mechanical energy.

Contrary to our hypothesis, the model predicted COM motions with 40-60% less error at the highest frequency (0.3 cm for hopping and 1.6 cm for running) than at the PSF. This observation suggests that the stance legs behaved more like springs at higher frequencies than at the PSF. Consequently, spring-like behavior of the leg does not explain why runners consume less metabolic energy at the PSF than at higher frequencies.

It is possible that the metabolic cost increases at frequencies higher than the PSF because stance time becomes shorter. Shorter stance times require the use of faster muscle fibers which are metabolically more expensive for force generation (Kram, 1990). Thus, shorter stance times might explain why metabolic cost increases above the PSF.

SUMMARY/CONCLUSIONS

Despite its simplicity, a spring-mass model predicts COM motions in human hopping and running remarkably well. Surprisingly, the body coordinates the actions of many muscle-tendon units to make the overall stance leg behave like a spring at the PSF and higher frequencies. It is likely that the energetic cost of running is minimized at the PSF due to an optimal combination of high elastic energy storage/return and a low cost of generating force.

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