Steady-state running on uneven ground for the spring-mass model

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Introduction

During running on uneven ground human runners maintain an approximately constant apex height. To achieve such a smooth ride of their Center of Mass (CoM), humans adapt their leg stiffness, angle of attack, and leg length to up and down steps on a running track [1]. Although running mechanics can be modeled with a spring-mass system [2,3], existing control strategies for this model (e.g. [4,5]) cannot describe this observation. Here we show how the model's parameters must be adapted from step to step to run with constant apex height.

Methods

First, we compute the model's steady-state solutions for different relative apex heights y_0/L_0, angles of attack α, dimensionless spring stiffnesses K, and dimensionless running speeds (Froude numbers), (Fig.1). Second, as the relative apex height equals the vertical distance to the ground, for each step, we change α and K such that the absolute apex height remains constant. For this parameter change, we used the planes that belong to different Froude numbers in the (α, K, y_0/L_0)-space (Fig.1). Finally, to limit the leg stress, we pick only those combinations of α and K that minimize the leg force in constant apex height running (Fig.2).

Results

Our numerical analysis shows that steady-state solutions are limited to certain regions in the parameter space (Fig.1). Moreover, considering only biologically relevant, maximum leg forces, the possible parameters are further constrained (Fig.2). Nevertheless, the remaining parameters that we can choose from suffice to reproduce constant apex height running with the spring-mass model (Fig.3).

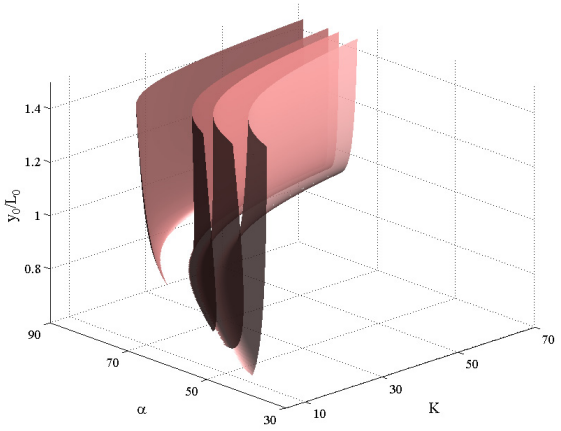

Fig.1: Steady-state solutions for the spring-mass model in running for four dimensionless speeds $F = v^2 / (g\ L_0) = [0.41, 1.63, 2.25, 5.0]$ (left to right).

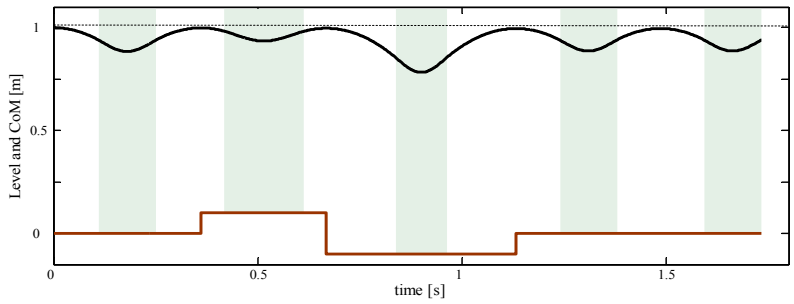

Fig.3: Example of the CoM trajectory of a spring-mass model for F=2.25 (black curved line). The level is varied in height (brown line). For every step the parameters of the model are adapted to achieve a constant absolute apex height. The light blue marked areas are the contact phases.

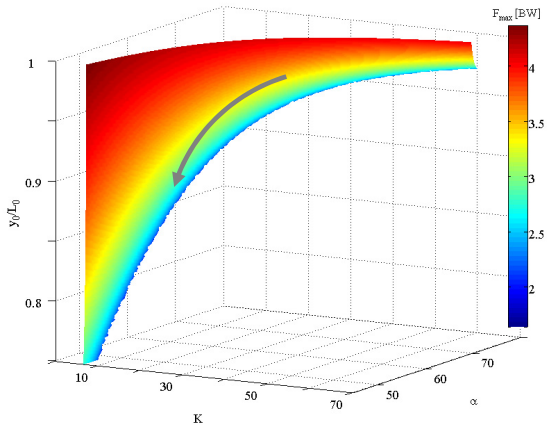

Fig.2 (right): For the model's steady-state solutions at F=2.25 (running at about 5ms^{-1}), the maximum leg force in body weight (BW) is color coded. The arrow marks a possible path for the adaptation.

Discussion

Despite the limited parameter choices, human running on uneven ground can be described with the spring-mass model. In addition, our dimensionless approach allow us to directly compare the model to running animals and humans of different sizes, and to apply the model to derive controllers that ensure smooth running for legged robots.

Acknowledgement:
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