THE SPRING-MASS MODEL FOR WALKING

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INTRODUCTION

In general, two different models are employed when addressing animal and human locomotion on a simple mechanical level: the *inverted pendulum model for walking*, where the body is reduced to a point mass m at the center of mass (COM) vaulting over a rigid stance leg of length ℓ_0, and the *spring-mass model for running* or hopping, where the rigid stance leg is substituted by a compressing spring of rest length ℓ_0 and stiffness k.

The spring-mass model reproduces salient features of the characteristic ground reaction force (GRF) pattern observed in running, which renders it ideal to explain experimental observations, predict functional dependencies, and formulate biological control hypotheses.

By contrast, the inverted pendulum model suffers from GRF patterns inconsistent with experimental observations. Consequently, experiments also demonstrate that instead of vaulting over rigid legs (characterized as 'compass gait'), the COM experiences much less vertical excursion necessitating significant stance limb compressions, which at high speeds are even comparable to those observed in running [e.g. 1].

Motivated by these experimental findings, we here ask in how far the characteristic GRF patterns of walking can be explained by purely elastic leg behavior.

MODEL

To address this question we extend the planar spring-mass model for running [2] by a second idealized leg spring and investigate a single walking step characterized by two subsequent apices (**Fig. 1**).

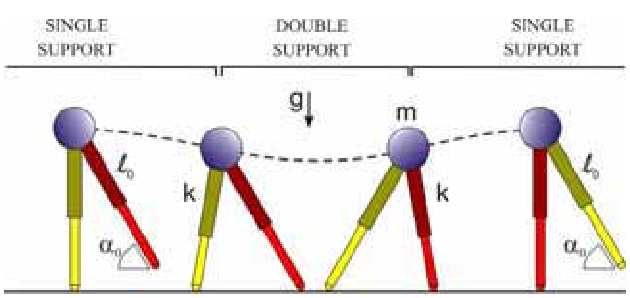

Fig. 1: Two-legged spring-mass walking model.

Starting in single support, the stance leg compresses due to the acting gravitational force (gravitational acceleration: g). The swing leg, however, remains in a fixed leg orientation (angle of attack α_0) until it touches the ground initiating the double support phase. During this phase, the COM is redirected upwardly since both spring forces together exceed the counteracting gravitational force. Maintaining forward progression, the rear leg-spring relaxes and eventually reaches its rest length initiating the subsequent single support phase.

RESULTS AND DISCUSSION

By scanning the model's behavior throughout the parameter space (angle of attack, spring stiffness, and system energy), we find that (i), similar to spring-mass running [2], the extended model describes self-stable and robust periodic locomotion if the parameters are properly chosen. (ii) Furthermore, the resulting steady state trajectories yield GRF patterns similar to those observed in animal and human locomotion (**Fig. 2**) suggesting leg compliance to be an essential feature not only in running but also during walking.

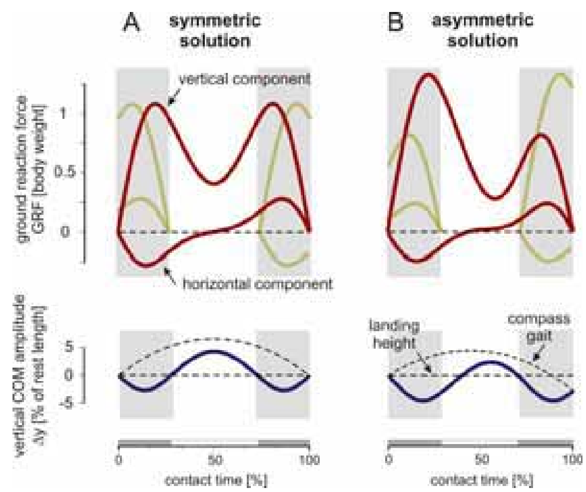

Fig. 2: Steady-state patterns of GRF and vertical COM amplitude in spring-mass walking. Dependent on the actual parameters, (**A**) symmetric and (**B**) asymmetric steady-state trajectories can be observed.

CONCLUSIONS

The bipedal model put forth in this study is probably the simplest mechanical model describing GRF patterns similar to those observed in walking. In comparison to the inverted pendulum model it establishes two new qualities. First, it emphasizes the importance of the double support. Second, it incorporates the experimentally observed motion along the leg axis as an additional degree of freedom. Moreover, as a direct derivative of the spring-mass model for running, the bipedal model allows to describe the two fundamental gait patterns within a single framework unifying the investigation of legged locomotion on the mechanical level from walking to the walk-run transition to running.

REFERENCES

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2. Seyfarth A, et al. *J Biomech* **35**, 649-655, 2002.

ACKNOWLEDGEMENTS

This research is supported by an Emmy-Noether Grant of the German Science Foundation (SE1042/1-4) to AS.