

# Predicting steady and transient locomotor dynamics based on the principle of minimizing energy cost

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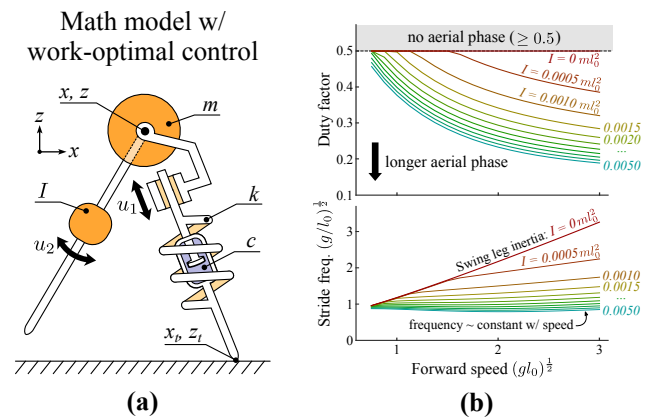
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Animals must seamlessly integrate mechanics and sensorimotor control to achieve agile and stable locomotion in complex environments. While the underlying mechanisms of animal musculoskeletal and sensorimotor systems are complex, locomotor dynamics are relatively simple and consistent across animals with very different body size and morphology. Striding bipedal animals (humans and ground birds) use walking and running gaits that look qualitatively similar in whole-body dynamics, limb trajectory and ground reaction forces. This observation suggests that many aspects of locomotor dynamics arise from the fundamental physics of locomotion on legs.

My research team use comparative biomechanics experiments and reduced-order models as methods to investigate bipedal locomotion. Many of our recent studies have focused on locomotion over simple terrain features, such as obstacles and single downward steps [e.g., 1,2]. Recently, we have also observed self-selected locomotor dynamics of ostriches in an open field, to observe gait-speed and gait-transition dynamics in freely moving animals [3]. The goal of these studies is to gain insight into locomotor control strategies by comparing steady and transient locomotor behaviors, investigating potential trade-offs among factors such as stability, robustness and economy.

While many aspects of animal locomotion can be explained based on the principle of minimizing energy cost, other factors such as stability or musculoskeletal force limits are often invoked to explain deviations between observed behavior and predictions of idealized models. An alternative explanation for such deviations between data and models is that the specific model assumptions and simplifications need to be reconsidered. In our ongoing research, we are using reduced-order models to test the hypothesis that transient locomotor dynamics can be predicted based on the principle of minimizing energy cost, without the need to invoke other factors such as explicit force constraints or limit cycle stability [4]. We are currently using a reduced-order model of a biped (Fig. 1) that includes swing-leg inertia and stance-leg energy dissipation, with trajectory optimisation to minimise mechanical cost of transport.

We will use this model to predict the following locomotor behaviors, and then compare model predictions to observed animal locomotion data: 1) speed-gait patterns



**Figure 1:** (a) A simple actuated model of running with swing-leg inertia and stance-leg dissipation, and (b) properties of energy-optimal running gaits for the model at various speeds (trajectory optimisation minimising mechanical cost of transport). While inertia-free swing results in gaits without aerial phases, increasing swing inertia leads to energy optimal gaits with longer aerial phases. Including swing inertia results in relatively constant stride frequency with running speed, consistent with biological observations.

and specific stride frequency, stride length and duty factors trends with speed, 2) obstacle and pothole negotiation strategies, 3) locomotion over consistently or transiently altered substrate compliance and dissipation, and 4) gait transition dynamics, specifically testing for a cost-minimizing explanation for empirically observed gait transition hysteresis [3].

## References

- [1] Birn-Jeffery, Hubicki, Blum, Renjewski, Hurst and Daley (2014) Don't break a leg: Running birds from quail to ostrich prioritise leg safety and economy in uneven terrain. *J Exp Bio*, 217, 3786-3796.
- [2] Blum, Vejdani, Birn-Jeffery, Hubicki, Hurst, and Daley (2014) Swing-Leg Trajectory of Running Guinea Fowl Suggests Task-Level Priority of Force Regulation Rather than Disturbance Rejection. *PLOS ONE* 9(6): e100399.
- [3] Daley, Channon, Nolan, Hall (2016) Preferred gait and walk-run transition speeds in ostriches measured using GPS-IMU sensors. *J Exp Bio*, 219: 3301-3308.
- [4] Hubicki, Jones, Daley, and Hurst (2015). Do limit cycles matter in the long run? Stable orbits and sliding-mass dynamics emerge in task-optimal locomotion. *IEEE International Conference on Robotics and Automation (ICRA)*, 5113-5120.