Walking, Skipping, and Running Produced From a Single Bipedal Model

Shawn M. O'Connor and Arthur D. Kuo

University of Michigan, Ann Arbor, MI, USA
E-mail: smoconno@umich.edu

INTRODUCTION

Human gaits such as walking and running have traditionally been treated as distinct paradigms with different dynamics. In walking, the legs are thought to act as coupled pendulums, whereas in running they compress and extend like springs. Here we show that walking, running, and even skipping can be produced entirely by the dynamic modes of a remarkably simple model which combines pendulum and spring-like behavior.

METHODS

The simple locomotion model is comprised of a single point mass at the pelvis, two axially-compliant legs with very light point mass feet, and a torsion spring acting between the legs (Figure 1). The model is a simplification of a passive bipedal running model (McGeer 1990) with the added capability of double support. We developed walking simulations that integrated equations of motion for the model and also handled discrete events such as heel-strike. We then searched for periodic gaits by varying the model parameters and initial conditions in a Newton method search.

After non-dimensionalizing the governing variables, the model has only two physical parameters: the axial and torsional leg stiffness. Gait parameters, such as the time of ground contact and step frequency, are set by tuning the two stiffness parameters and by selecting appropriate initial conditions for the simulation.

The speed and type of gait depend on physical parameters as well as the mechanical energy of the body center of mass and axial springs, which is set by the initial conditions of the model states. The model has 3 degrees of freedom during single support, and thus the model energy and movement can be divided up into three modes: inverted pendulum, pendulum, and spring-mass, which correspond to the three model states: stance angle, θ, swing angle, ϕ, and variable stance leg length, L.

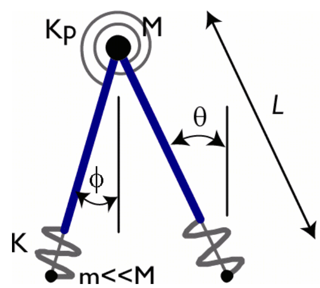

Figure 1: A two-dimensional elastic dynamic locomotion model with two stiffness parameters.

In order to compare different gaits, we developed a metric, named spring fraction, *SF*, that quantifies the maximum amount of energy stored in the axial stance leg spring as a fraction of the total system energy. This metric provides a basic measure of the amount of spring-mass behavior present in each gait.

$$SF = \left[0.5 \cdot K \cdot (1-L)^2\right] / E_{total}$$

RESULTS AND DISCUSSION

After adding compliant legs to our simple model, we found that the motion of both legs for an entire stride can be generated completely passively. A variety of human-like gaits may be produced with one simple model, without enforcing ground reaction force patterns or prescribing motions. Examples of these gaits are shown in Figure 2 and directly compared with corresponding sample human data. The maximum fraction of energy stored in the stance spring for each of these gaits is then compared in Table 1.

Table 1. Comparison of the maximum elastic energy stored among bipedal gaits.

	Normal Walking	Fast Walking	Skipping	Running
Speed	1.25 m/s	1.50 m/s	1.79 m/s	2.2 m/s
SF	0.029	0.034	0.100	0.137

When walking, the model's compliant legs produce ground reaction forces and perform work on the body similar to humans. As the model walks faster and takes longer steps, more energy is stored in the stance spring and the vertical motion of the center of mass is increasingly affected by spring-mass mechanics. With increasing speed, the stance leg spring eventually stores enough energy such that the leg rebounds at mid-step and leaves the ground, producing a skipping gait. The model therefore smoothly transitions to skipping as walking speed is increased. Running can be produced with the same model parameters as for walking or skipping, but started with different initial conditions. Therefore, the distribution of system energy largely distinguishes walking and running gaits, with significantly larger amounts of energy stored in the stance spring during running, even at equivalent speeds.

Although the model parameters affect features of gait such as step frequency and contact time, the most significant difference between the demonstrated gaits lies in how the energy of the system is distributed between pendular and spring-like modes.

SUMMARY/CONCLUSIONS

We have shown that the dynamics of a variety of gaits are the result of the combination of pendulum and spring-like behavior in a simple locomotion model.

REFERENCES

McGeer, T. (1990). *Proc. R Soc. London B*, **240**, 107-134.

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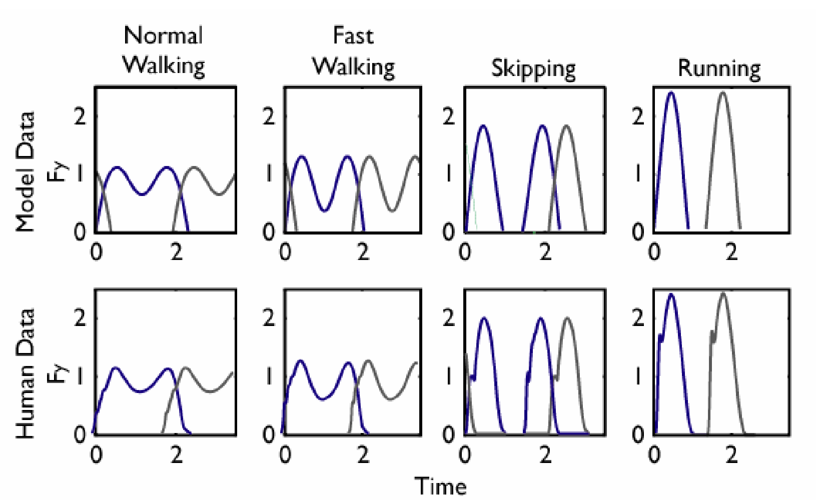

Figure 2: The simple elastic locomotion model reproduces the vertical ground reaction forces (Fy), measured in units of body weight, seen in a variety of human gaits. Time is in dimensionless units, normalized by leg length and the gravitational constant.