Our ultimate goal is to obtain the simplest general model for legged locomotion. To this end, we began with the inverted pendulum (IP) and spring-loaded inverted pendulum (SLIP) as our starting point. One limitation of the IP and SLIP models is that the tension force can only act along the leg. Tangential forces cannot be modeled by IP and SLIP.

I will demonstrate (in my talk) that one limitation of IP and SLIP resulting from this inability to model tangential forces is that IP and SLIP cannot model slow locomotion. It is very difficult to model locomotion below Froude number of 0.2, which is only slightly below Froude numbers at which a human being walks normally.

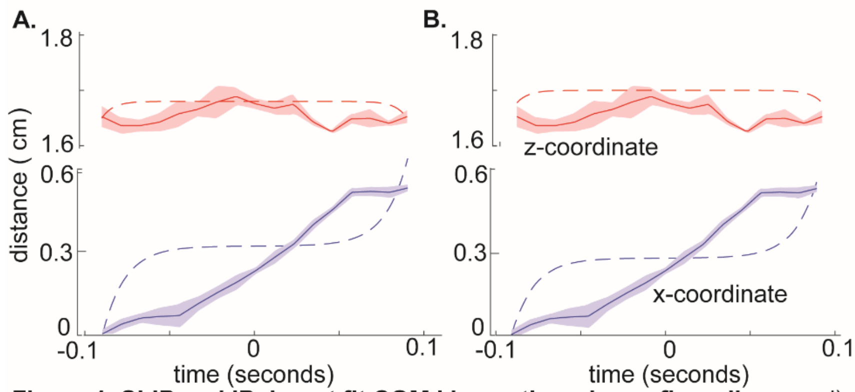

Figure 1. SLIP and IP do not fit COM kinematics when a fly walks. panel). **A**. The best fit to IP (dotted line) is a poor fit to the actual COM motion (solid line) during a single step. The shaded area represents experimental uncertainty. **B**. SLIP is a poor fit to the COM motion.

We tested the prediction that IP and SLIP are not appropriate as models for a fly's locomotion by collecting kinematic data from *Drosophila*, which is known as a slow walker. Indeed, SLIP and IP cannot fit the kinematics of a fly's center of mass (COM) (Figure 1). Essentially, SLIP and IP do not work because the natural time constants associated with a fly-sized pendulum is much shorter than the experimentally observed stance duration. For instance, for the IP model, assuming that the height of a fly's COM is 1mm, the gravitational timescale is 30 ms—a factor of ~4 shorter than the shortest stance duration we observed.

To walk slowly, animals have to lengthen their stance duration beyond what is possible under the conditions modeled by SLIP or IP. One method to slow stance is to apply tangential forces to counteract gravitational forces and brake the body's fall from its vertical mid-stance position. We propose a new model - **a**ngular SLIP or aSLIP (Figure 2) - which employ springs to generate forces that opposes the motion of the leg away from the vertical mid-stance position. In this model, there are no tangential forces when the leg is vertical. But as soon as the leg falls from its vertical position, restorative spring forces pull the leg towards the vertical. Thus the spring forces are always counter to gravitational forces. The aSLIP model is an excellent model for the COM kinematics of a fly (Figure 2).

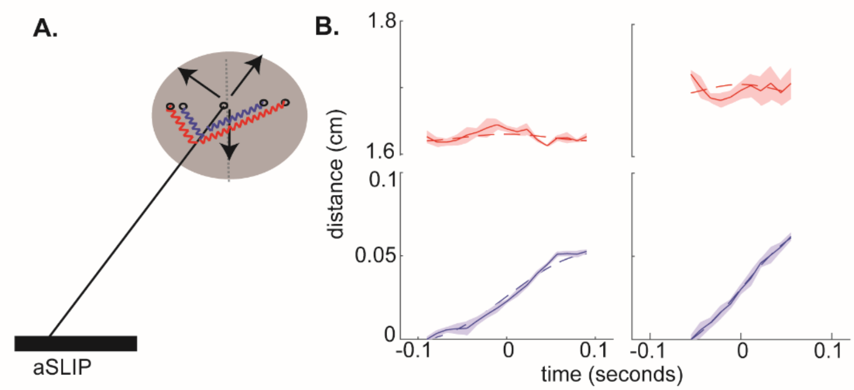

Figure 2. aSLIP is an excellent model for COM movement of a fly. A. aSLIP model - schematic **B**. best fits of this model to two steps. The two steps were selected to demonstrate two different stance durations.

It is instructive to consider the small angle approximation of aSLIP.

$$\ddot{\psi} = \left(\frac{g}{Q} - \frac{k_a}{mQ^2}\right)\psi \qquad (1)$$

Eqn 1 is identical to the equation for the IP model except that the gravitational constant g is replaced by the effective gravity (g_{eff}).

$$g_{eff} \approx g\left(1 - \frac{k_a}{mgQ}\right) < g$$

As k_a/R (a measure of the angular muscular force) approaches mg (the gravitational force), the effective gravitational acceleration becomes small, and thereby the stance duration becomes long. Essentially, by tuning the angular spring constant, an animal can walk as slowly as it wants.

We found that aSLIP was superior to all other models we investigated. (Figure 3).

We also performed a dimensionless analysis of the SLIP and aSLIP models. This analysis demonstrated that unless one allows large fluctuations in speed and COM height, SLIP cannot accommodate slow locomotion beyond a Froude of 0.2. In contrast, by tuning the angular spring, one can locomote at Fr ~0 using the aSLIP model. (Figure 4)

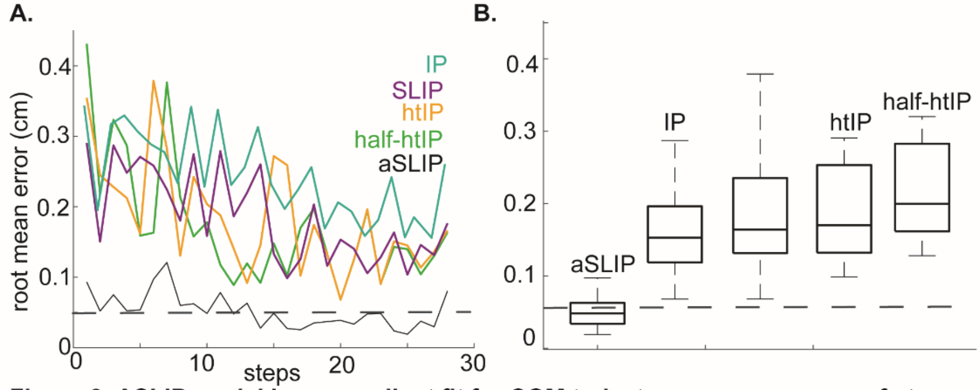

Figure 3. ASLIP model is an excellent fit for COM trajectory across a range of stance durations. **A**. Root mean error for the best fit to each of the five models to our data. Dotted line shows the average experimental error. htIP and half-htIP are modifications to IP in which tangential forces are modeled by torques at the hip. **B**. Boxplot showing summary data. aSLIP is significantly better.

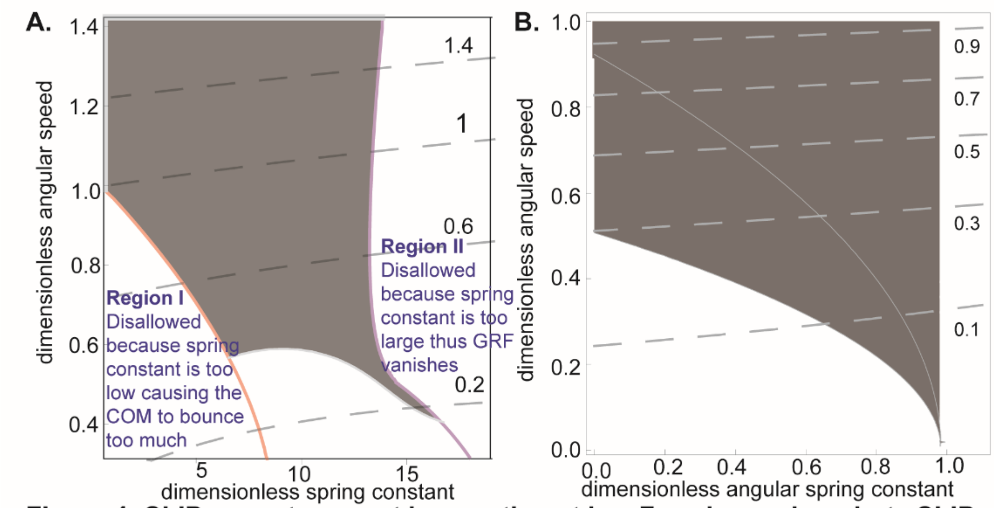

Figure 4: SLIP cannot support locomotion at low Froude numbers but aSLIP can. A. The SLIP locomotor space constructed at a fixed step length of 25 degrees. The allowed region is shaded. Dotted lines represent constant Froude numbers. **B**. Locomotor space for aSLIP shows that low Froude numbers are allowed. By increasing the spring constant, one can travel at low Froude numbers.

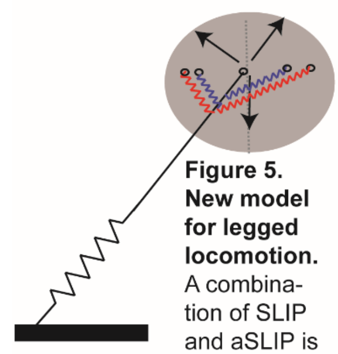

Figure 5. New model for legged locomotion. A combination of SLIP and aSLIP is necessary.

We propose that a combined aSLIP and SLIP model would be able to model locomotion at the entire range of speeds encountered during locomotion. (Figure 5).

Link to video: http://online.kitp.ucsb.edu/online/smell-c15/bhandawat/