

# Damping And Size: Insights And Biological Inspiration

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## Abstract

We present scaling arguments verifying that as an animal's size decreases, the relative friction and viscosity (damping ratio) of their limbs increases. These intuitive predictions are supported by data from other studies, our experiments on the death head cockroach (*Blaberus Discoidalis*), and our modeling results, all of which we briefly describe. High damping has implications for control, favoring the use of simple feed-forward strategies; we show evidence that this is actual control mechanism which cockroaches use. Additionally, high damping ratios and the presence of Coulomb friction lead to a preference for running over walking, which is also observed. For the joints we studied, the majority of the damping was apparently due to the mechanics of the joint itself, and not to the soft tissues.

## 1. Introduction

Relative to their size, cockroaches are among the fastest land animals [1]. In addition, there is a growing body of knowledge regarding their kinematics and biomechanics. Thus, they are attractive design targets for biomimetic locomotive robots [2].

Most biomimetic walking and running robots fall far short of the dynamic capabilities of their biological relatives. One reason is that the robots are typically built on larger length scales than the animals that inspire their design, and the dynamical characteristics and control strategies of the animals are not preserved.

In this paper, we propose a particular model for the scaling of damping in small insects, summarize our results of ongoing laboratory damping measurements in cockroaches, suggest how these phenomena are relevant to control, and briefly test some of our hypotheses with observations and data from the animals.

## 2. Scaling Theory

During legged locomotion, a leg can be in one of two phases: swing phase or stance phase. During swing phase, the leg moves forward relative to the body, and is commonly thought to act like a pendulum [3]. During stance phase, the leg is thought to behave more or less like an inverted pendulum as it supports the body. (We say "more or less" because for running gaits, a pogo stick is a more appropriate analogy than a pendulum, but the pogo stick is a combination of an inverted pendulum and a spring.) The dynamic behaviors of these two cases will be different because in stance phase, the body is considered to be part of the pendulum, while in swing phase, the body is not considered to be part of the pendulum. In a sense, we will test the extent to which these pendulum assumptions are valid.

Using pendulum-like models, studies over the past thirty or so years have established scaling rules which have mostly dealt with the effects of animal size on limb shape and gait characteristics [4, 5]. In humans and large animals, we are accustomed to the notion that the limbs are underdamped when they move as pendula; that is, friction and viscous effects (which we refer to collectively as "damping") play a minor role in the limb dynamics during one step, both in swing and stance phases. In cockroaches and smaller animals, however, damping may not be negligible, especially during the swing phase.

We use a simple second-order mechanical model, shown in Figure 1, to quantify how damping should increase as length scales decrease. Consider a system with a single cylindrical limb connected to the body at a hinge joint. The limb has mass  $m$ , density  $\rho$ , length  $L$ , diameter  $d$ , and angular position  $\theta$  (positive counter-clockwise), and we could include the effects of gravity  $g$ , depending on how the joint is oriented with respect to gravity (neglect  $g$  for sprawled postures, include  $g$  for upright postures). A single muscle actuates the

limb; this muscle is modeled as an ideal force generator which produces a force  $f(t)$ . This muscle and its (presumably relaxed) component on the opposite side of the joint have some stiffness and viscosity which can be collected into a spring and damper acting in parallel. Because muscle tissue consists of sarcomeres in series and in parallel, the spring and damper are assumed to have stiffness and viscosity proportional to the limb cross-sectional area  $A$  and inversely proportional to the limb length. The net stiffness will be proportional to the muscle elastic modulus  $E$ , and the damping will be proportional to the viscosity  $\gamma$ ;  $E$  and  $\gamma$  are material constants which are invariant to length scale. We may include the damping torque of the joint itself, which we assume is equal to the product  $C\dot{\theta}$ , where  $C$  is proportional to the amount of surface area contact at the joint  $C = \hat{C}A$  (assuming that the joint surface area scales with  $A$ ). When considering the limb as an inverted pendulum, we also need to know the effective mass  $M$  of the body, which for simplicity will be concentrated at the body center of mass.

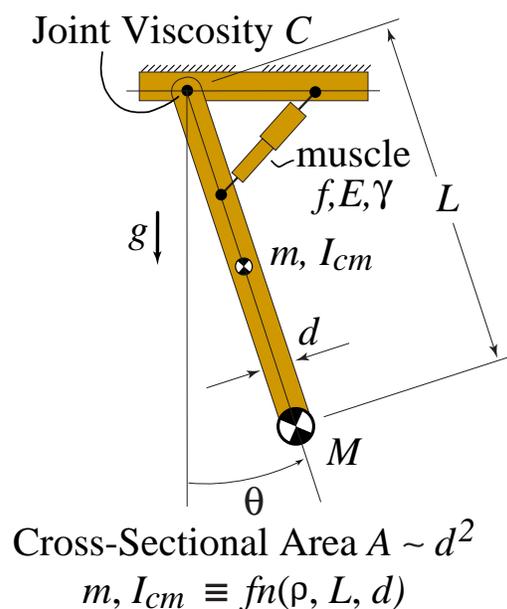


Figure 1: Theoretical pendulum model used to predict scaling of damping ratio. For the stance phase, it would be more correct to present an inverted pendulum, but for consistency and familiarity we only use one orientation. Moreover, the scaling of the damping ratio does not change with the pendulum orientation.

The general dynamics of the system (both swing and stance phase) are described by an equation of the form

$$J\ddot{\theta} + B\dot{\theta} + K\theta = rf(t), \quad (1)$$

where  $J$  is an inertia term,  $K$  is a stiffness term, and

$B$  is a damping term. The actual scaling relationship will depend on whether it is the swing phase or stance phase under consideration, as well as several other assumptions, the most important of which is the relative scaling of lengths and diameters. These assumptions affect the constants  $J$ ,  $K$ , and  $B$  (which in turn are functions of  $m$ ,  $\rho$ ,  $L$ ,  $d$ ,  $\hat{C}$ ,  $A$ , etc.) in Equation 1, and hence the damping. The details of the calculations can be found in a full-length paper in preparation [6].

We are interested in the damping ratio  $\zeta$ ,

$$\zeta = \frac{B}{2\sqrt{JK}}, \quad (2)$$

which describes the significance of the damping over short time scales. If  $\zeta > 1$ , the damping dominates the dynamics and the system is said to be *overdamped*, whereas if  $\zeta < 1$ , the damping is negligible and the system is said to be *underdamped*. If  $\zeta \approx 1$ , the system is *critically damped*; critical damping is associated with fast return to equilibrium. In general, higher  $\zeta$  suggests that more energy is lost during voluntary motions, while if  $\zeta = 0$ , no energy is lost. The value of  $\zeta$  also has implications for control, as we will address below.

## 2.1. Swing Leg

We first restrict our attention to the behavior of the swing leg. Independent of the assumptions, we find the general rule that damping ratio increases as leg length (or length scale) decreases. The leading terms in the series expansions for  $\zeta$  as a function of  $L$  about  $L = 0$  are shown in Table 1, for a number of different scaling laws. These include isometric scaling ( $d \sim L$ ) and elastic similarity ( $d \sim L^{3/2}$ ) [7], with and without joint viscosity  $C$ .

## 2.2. Stance Leg

Now we consider the behavior of the stance leg, during which the body is considered to be part of the pendulum, now inverted and hinged at the ground (we neglect the limb mass  $m$  and assume that the body mass  $M$  is attached at the top end of the pendulum). Since damping is assumed to be insensitive to limb orientation, Equation 1 and Figure 1 still apply if we fix the foot on the ground and swing the leg upside down (in order to simplify the experiments described later). In the stance phase, the scaling predictions differ more, depending on the assumptions used. For most of the assumptions, damping ratio increases as leg length decreases, as shown in Table 2.

Assume	$g \neq 0$	$g = 0$
$d \sim L, C = 0$	$\zeta \sim L^{-1}$	$\zeta \sim L^{-1}$
$d \sim L^{3/2}, C = 0$	$\zeta \sim L^{-1/2}$	$\zeta \sim L^{-1/2}$
$d \sim L, C \neq 0$	$\zeta \sim L^{-2}$	$\zeta \sim L^{-2}$
$d \sim L^{3/2}, C \neq 0$	$\zeta \sim L^{-5/2}$	$\zeta \sim L^{-5/2}$

Table 1: Leading-term scaling results for the damping ratio  $\zeta$  during swing phase as a function of limb length  $L$  as  $L \rightarrow 0$ . Assumptions are as follows:  $g \neq 0$  represents upright posture, while  $g = 0$  if gravity is neglected (sprawled posture).  $C = 0$  neglects joint viscosity, while  $C \neq 0$  includes a joint viscosity term proportional to surface area and joint angular velocity.  $d \sim L$  assumes geometric scaling of limb thickness, while  $d \sim L^{3/2}$  assumes elastic similarity as proposed by McMahon [7]. Regardless of the assumptions used,  $\zeta$  increases with decreasing  $L$ , suggesting that damping is more dominant at smaller length scales.

Assume	$g \neq 0$	$g = 0$
$d \sim L, C = 0$	$\zeta \sim L^{-1}$	$\zeta \sim L^{-1}$
$d \sim L^{3/2}, C = 0$	$\zeta \sim L^{1/2}$	$\zeta \sim Const.$
$d \sim L, C \neq 0$	$\zeta \sim L^{-2}$	$\zeta \sim L^{-2}$
$d \sim L^{3/2}, C \neq 0$	$\zeta \sim L^{-3/2}$	$\zeta \sim L^{-2}$

Table 2: Leading-term scaling results for the damping ratio  $\zeta$  during stance phase as a function of limb length  $L$  as  $L \rightarrow 0$ . See the caption of Table 1 for an explanation of the assumptions. For most of the assumptions, and for the most reasonable assumption of joint viscosity and elastic similarity, stance phase  $\zeta$  increases with decreasing  $L$ .

### 2.3. Comments On Scaling Results

The scaling results shown in Tables 1 and 2 demonstrate that, for both isometric and elastic scaling assumptions, the length scale decreases as the damping ratio increases. Insects operate at much smaller length scales than humans, and so the higher damping ratio should be evident. It is of course expected that at very small length scales, other forces which are not modeled in Equation 1 might become relevant, such as more complicated viscoelasticity, plastic-like bulk deformation effects, sliding friction, etc. It is also important to note that comparing scaling as  $L \rightarrow 0$  is not the same as comparing actual scaling exponents for small but finite  $L$ . In the former case, the leading term dominates the scaling, but in the latter case, the relative contributions of the terms in the series depend on the particular values of the length-independent constants ( $\hat{C}$ ,  $E$ , and  $\gamma$ , for instance). By themselves, our results should not be used to compare assumptions about scaling as much as to indicate that at small length scales, damping plays an increasingly dominant role in the dynamics of small animals.

## 3. Measurements From Cockroach Legs

There are little data on how damping scales with size, in part because controlled (e.g., muscle activation) and uncontrolled (e.g., viscous) effects are usually not separated in the motor control literature. In humans, Reiner and Edrich [8] estimated the passive joint moments of the lower extremities and found that damping was negligible for most purposes. At the smaller scale of the human finger, Hajian and Howe [9] found damping ratios at the human finger joint to be of order(1); they also found that the ratios differed by a factor of about 2, depending on whether or not the joint was extending or flexing. Esteki and Mansour [10] also studied the properties of a finger joint and applied a nonlinear viscoelastic model to characterize the passive joint moment. They claimed that joint friction is relatively insensitive to joint speed in human fingers. We estimated the passive damping properties of cockroach legs, with the expectation that they would exhibit greater damping than seen in human limbs. We also wanted to determine the accuracy of a damping model of the form of Equation 1.

### 3.1. Method

To estimate passive damping parameters of cockroach muscles and joints (for eventual use in dynamic simulations), we performed some simple pendular experiments. We separated the femur-tibia segments from the rest of the body and fixed the femur. In some experiments, we removed relevant muscles and internal tissue in order to isolate the effects of the joint itself, as opposed to the effects of the muscles and apodemes. We then applied perturbations to the tibia and filmed the time response as it returned to a resting position, mainly due to gravity. We added different masses (between one-tenth of body mass and body mass) to the tibia and repeated the procedure several times. Results were compared with numerical simulations having different dissipation laws. More sophisticated experiments are planned, and more complete details will be given in a full-length paper [6].

### 3.2. Results

Motivated by the familiar damped oscillator model (Equation 1 with  $f(t) = 0$ ), and similar studies, we attempted to fit our results to this model (assuming a viscous torque proportional to  $\dot{\theta}$ ).

### Poor Model Fit For Swing Phase

For the unloaded trials (which represent swing phase) there appear to be some effects which are difficult to model if  $M = 0$  but negligible if  $M > 0.1 \times$  (body mass). The effects appear in trials with and without muscle and seem to dependent on the direction of the initial perturbation. Possible explanations for these complicating effects are: (1) effects of the joint membrane itself, or (2) residual effects of the elastic apodeme (which is not removed when the muscle is removed). Figure 2 shows an example data set from a swing-phase experiment with muscles removed.

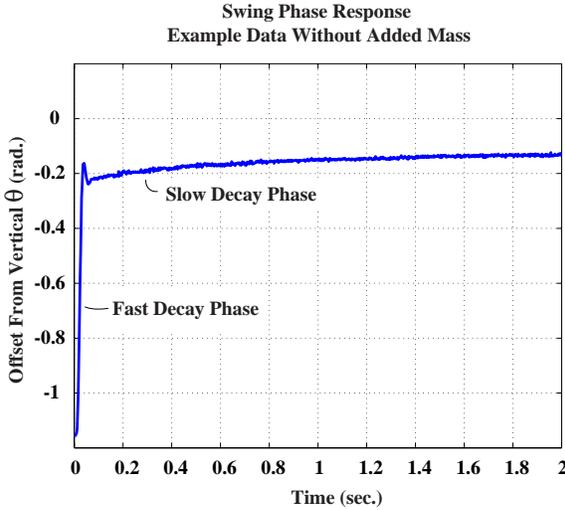


Figure 2: Example results from a perturbation experiment with no added mass and muscles removed. The plot has a fast-response phase and a slow-response phase, and is not well-characterized by a simple spring-dashpot model. However, the model can be used to characterize each phase independently, and the model results from the slow-response phase only are consistent with the results from the experiments with added mass. The fast response may be caused by some residual elasticity in the joint membrane or possibly the elastic apodeme, which remains in the joint after the muscle tissue is removed. This effect becomes negligible when we add mass to the swing limb; the smallest increment of added mass was about one-tenth of body mass.

### Model Works Well For Stance Phase

For trials with added mass, a linear damping component models the passive limb motions reasonably well (RMS errors of less than 5%, see Table 3) Adding a Coulomb or quasi-Coulomb component (so that frictional torque is approximately proportional to  $B_1 \dot{\theta} \pm B_2$ ) would give an even better fit, although the con-

stant term is not considered in the scaling law derivation for  $\zeta$  in Section 2.. We say “quasi-Coulomb” and “approximately proportional” because a true Coulomb term is discontinuous at  $\dot{\theta} = 0$  and can be problematic for numerical simulations. High-order roots or arctangent functions are smooth Coulomb-like functions that are more practical from a numerical standpoint [24].

Although we could include Coulomb-like terms in our model, we still discuss the damping ratio as if the damping were linear because the linear term accounts reasonably well for the majority of the damping, and because the damping ratio is a convenient concept. The values of  $B$  (i.e.  $B_1$  with  $B_2 = 0$ ) which yielded good agreement with the experiments were between  $1e - 7$  and  $5e - 7$   $\text{kg}\cdot\text{m}^2/\text{s}$ . Figure 3 shows example simulations, overlaid on top of data for cases with and without added mass.

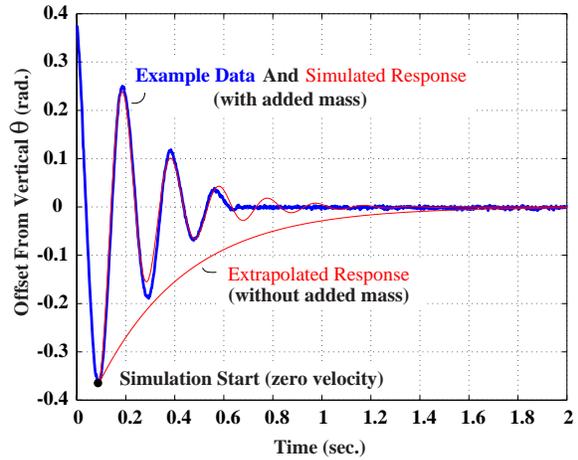


Figure 3: Example results from a perturbation experiment with added mass. Damping was assumed to be proportional to angular velocity; we chose a damping constant  $B$  which minimized the total RMS error between simulation and experiment. The extrapolated response results from a simulation with the same damping constant but no extra mass, intending to simulate the unloaded swing-phase response shown in Figure 2. The extrapolated response suggests that the leg is overdamped during swing phase, but there are complicating factors implied by Figure 2. The parameters from the simulations are as follows:  $m = 1.3e - 5\text{kg}$ ,  $L = 0.0113\text{m}$ ,  $I_{cm} = 2.0e - 10\text{kg}\cdot\text{m}^2$ ,  $M = 0$  or  $2.71e - 4\text{kg}$ ,  $g = 9.81\text{m/s}^2$ ,  $B = 2.17e - 7\text{kg}\cdot\text{m}^2/\text{s}$ ,  $\theta_0 = -0.367\text{rad}$ .

### Damping Ratios For Swing And Stance

Preliminary results from a best-fit  $B$  with no Coulomb-like terms are shown in Table 3. Although we could not directly model the swing phase, we extrapolated the damping ratio by assuming that the damping co-

efficient  $B$  was independent of added mass. We then simulated the limb response with no added mass using the same  $B$ , as shown in Figure 3. The no-mass simulations were consistent with the slow decay phase of the no-mass experiments (see Figure 2).

Case	$\zeta$	RMSE, %
Stance w/ muscle	$0.19 \pm 0.01$	$1.6 \pm 0.5$
Stance w/o muscle	$0.13 \pm 0.01$	$3.6 \pm 0.6$
Swing w/ muscle	$6.53 \pm 0.11$	NA
Swing w/o muscle	$5.92 \pm 0.41$	NA

Table 3: Best-fit results for damping assumed proportional to  $\theta$  with and without muscles. RMS error is expressed as percentage of maximum angular displacement per trial. For each case, we performed 2-4 experiments. The added masses during stance phase produce leg forces comparable to individual leg forces measured during the stance phase of running. The swing phase damping ratios are extrapolated from the results of the stance phase, assuming similar frictional characteristics with no added mass. Because an accurate model for the swing phase would probably need to include extra springs, dampers, etc., we were not able to effectively model the swinging limb response using Equation 1.

#### *Effect Of Muscle Tissue Removal*

Removal of muscle tissue (but not the apodeme) lowered the damping ratio by about 30 % for the stance (weighted) case and by about 10% for the swing (unweighted) case.

## 4. Discussion

Our preliminary results support the theoretical and intuitive predictions of higher damping in cockroach limbs than in larger mammals. During stance phase, cockroach limbs are underdamped, while during swing phase, they are overdamped. Because removal of the muscle tissues did not dramatically decrease the damping ratio, we conclude that joint damping is primarily due to the internal friction and viscosity associated with the joint, and secondarily to the viscosity of the muscles and surrounding tissues.

### 4.1. Implications For Control

Higher damping ratios are associated with decreased energetic efficiency, and thus might be deemed undesirable. However, higher damping ratios have several potentially-interesting control implications.

- **Preference For Running Over Walking**

As relative damping increases, walking motions become less “free.” This is because the exchange between potential and kinetic energy (which characterizes walking) has a cost proportional to the amount of joint friction (and is further reduced by the horizontal orientation of the limbs). As the damping increases, the effectiveness of the pendular mechanism is compromised, and a new locomotion strategy (running) emerges. The transition between walking and running appears to be modulated by their relative energetic costs [11]. Insects and other animals with relatively high damping and sprawled postures should have a walk-to-run transition that occurs at a lower speed. (A rough analogy is the observation that people have a lower transition speed when moving in deep water, although this analogy will break down under careful scrutiny [24].) Likewise, insects should prefer lower stride frequencies than might be predicted from size-related scaling arguments, due to the high-swing-velocity penalty. Lastly, the presence of speed-independent damping (Coulomb friction) mentioned in Section 3 implies a preference for short, quick bursts of force to minimize frictional energy loss [24].

- **Motor Command Is A Velocity Command**

In an underdamped environment, muscle activation is like a force or torque command; the limb exhibits poor stability and requires additional (feedback) control to return to equilibrium and minimize oscillation following a perturbation [12, 13]. An overdamped or critically damped environment is like a first-order system, since there is no overshoot when returning to equilibrium. Applied forces or torques are analogous to constant limb velocities which quickly decay to zero if removed. When coupled with some sensing of time or position, velocity control is analogous to position control. This implies that small animals should be able to successfully locomote in a dynamically stable fashion using feedforward commands with relatively little feedback. Larger animals, however, would exhibit greater sensitivity to perturbations and therefore presumably require some feedback to minimize leg oscillations that might upset the dynamic stability of gait.

### 4.2. Observations From Cockroaches

- **Preference For Running Over Walking**

Cockroach data from Full and Tu [14] support this hypothesis. Energy traces of kinetic and po-

tential energy are nearly in phase, in contrast to the out-of-phase patterns which are seen in walking. They were unable to find evidence of walking gaits at any speed. Cockroaches and other small animals prefer to run intermittently than to walk [15]. Although Alexander [16] suggests that gait transitions occur at equivalent Froude numbers (squared nondimensional velocities), cockroaches do not follow this trend. Specifically, walk-run transitions in humans and similarly sized animals occur at Froude numbers of about 0.5 [16]. Although the walk-run transition was not measured in cockroaches, they are observed to use running gaits down to Froude numbers of 0.027 (0.08 m/s). One possible reason for the discrepancy with the Alexander study is that Alexander's conclusions may not apply to animals with overdamped swing limbs.

- **Motor Command Is A Velocity Command**

There is some reason to believe that cockroaches rely primarily on feedforward strategies. Unpublished experiments on cockroaches with a "Rapid Impulsive Perturbation" system [17] suggest that limb angles in cockroaches do not change significantly in response to impulsive perturbations, even relatively large ones which noticeably disrupt the animal's posture and velocity while it is running. Other researchers have also found evidence that insect limbs appear to follow a predetermined kinematic pattern [18], possibly using position control [19] or velocity control [20]. Moreover, hindlimb muscle EMG measurements during steady state cockroach running are nearly identical as compared to those taken while maneuvering over large obstacles [21]. Lastly, simple horizontal-plane models by Schmitt and Holmes [22] and Kubow and Full [23] demonstrate the plausibility of passive and/or feedforward strategies producing dynamically-stable planar gaits with no feedback.

#### 4.3. Generalizability Of Scaling Ideas

The scaling results presented here may be roughly interpreted in a larger, less specific context that is "part of the common folklore of physics and engineering" [24]. Many processes can be approximately modeled by the damped oscillator of Equation 1. In these processes, the damping component  $B$  is often assumed to be proportional to some characteristic surface area, while the inertia term  $J$  might be proportional to a characteristic mass. In this case, the importance of the damping (as compared to the inertia) at different

length scales would follow a surface area to volume power law ( $\text{length}^{-1/3}$ ) [25]. Generally speaking then, for many phenomena, one would expect the relevance of damping to increase in any observations or applications at very small length scales.

This argument extends across various disciplines; for instance, in fluid dynamics, the Reynolds number ( $Re$ ) is a well-known measure of the relative importance of dynamic forces as compared to viscous forces (low  $Re$  signifies relatively higher viscous forces).  $Re$  is proportional to  $(\text{length}) \times (\text{velocity})$ . Thus, it is common knowledge in fluid mechanics that as length scale decreases,  $Re$  decreases, and viscous forces tend to dominate.

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