Scale-Dependent Modeling Framework of Motor Control

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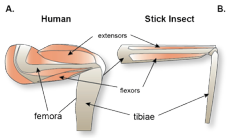
How does size affect control of a limb movement?



C.

Linear Equation of Motion (Sum of Forces)	$F = m\ddot{x} + c\dot{x} + k_{lin}x$
	$r \times F$
Rotary Equation of Motion (Sum of Moments)	$M = J\ddot{\theta} + c_r\dot{\theta} + (k_{lin} + k_{rot})\theta$
	$\int M\, d\theta$
Rotary Work-Energy Equation (Sum of Work)	$W = \frac{1}{2}J\dot{\theta}^2 + \int c_r\dot{\theta}^2\, dt + \frac{1}{2}(k_{lin} + k_{rot})\theta^2$

D.

Linear Motion Parameter	Scales with	Rotary Analogue	Scales with
x (distance)	L	θ (angle)	L^0
m (mass)	L^3	J (mom. of iner.)	L^5
c (damping)	L	c_r (damping)	L^3
k_{lin} (stiffness)	L	k_{rot} (stiffness)	L^3
		k_{grav} (stiffness)	L^4
		r (moment arm)	L

General limb model to model motion across all size ranges and speeds

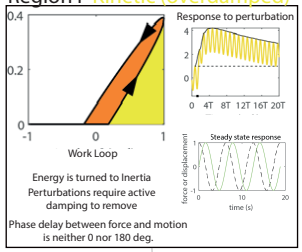
Fundamental Equation of Motion of a Limb

$$\boldsymbol{F} = m\,\ddot{x} + c\,\dot{x} + Kx$$

Quantify Relative Energy:
Kinetic (yellow),
Viscous (orange),
and Elastic ("Quasi static": red)

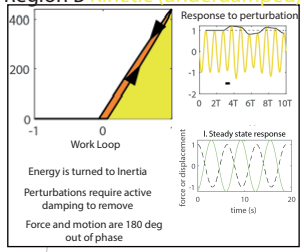
These ratios are independent of actuator force

Region F Kinetic (overdamped)



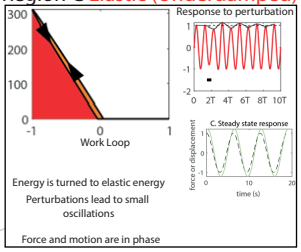
Energy is turned to Inertia
Perturbations require active damping to remove
Phase delay between force and motion is neither 0 nor 180 deg.

Region B Kinetic (underdamped)

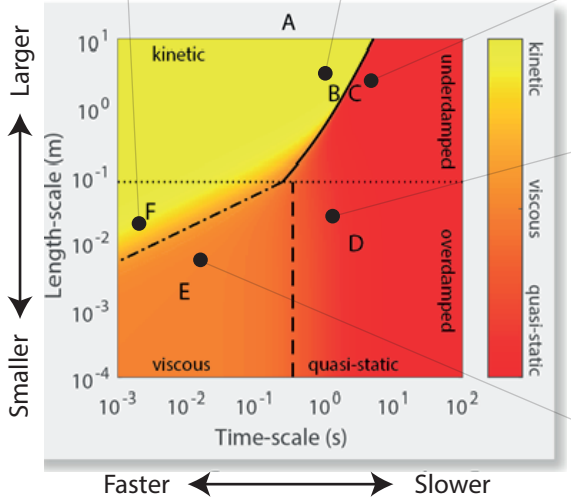


Energy is turned to Inertia
Perturbations require active damping to remove
Force and motion are 180 deg out of phase

Region C Elastic (Underdamped)

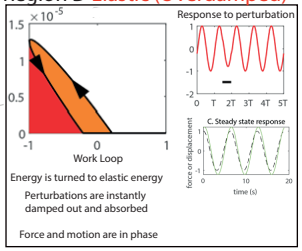


Energy is turned to elastic energy
Perturbations lead to small oscillations
Force and motion are in phase



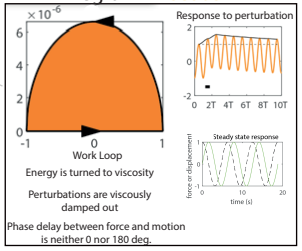
As a function of limb size and length, there are 5 different regions of movement: each dominated by a different kind of Energy

Region D Elastic (Overdamped)



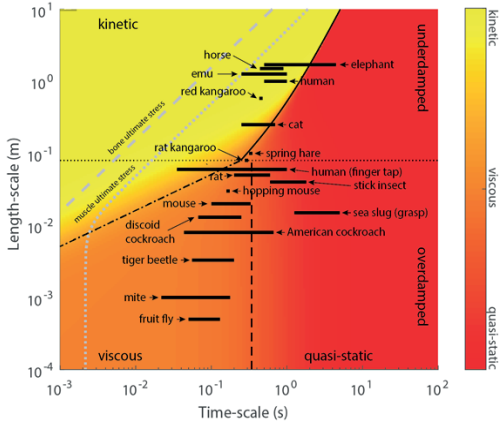
Energy is turned to elastic energy
Perturbations are instantly damped out and absorbed
Force and motion are in phase

Region E Viscous



Energy is turned to viscosity
Perturbations are viscously damped out
Phase delay between force and motion is neither 0 nor 180 deg.

Limb swings in Nature



Appendage swinging across the animal kingdom occupies all five regions. Each region defines a different set of control problems for the limb.