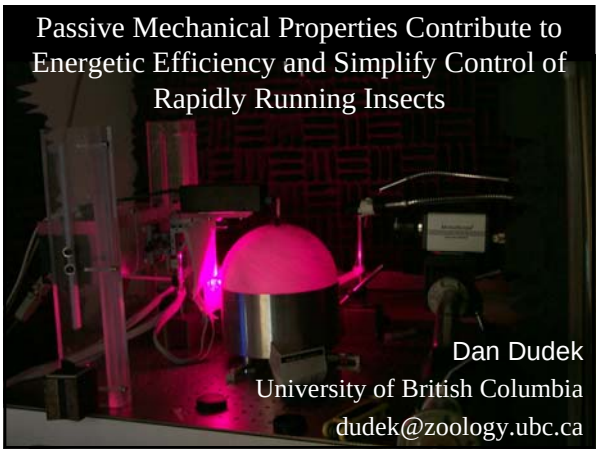
Passive Mechanical Properties Contribute to Energetic Efficiency and Simplify Control of Rapidly Running Insects



Dan Dudek
University of British Columbia
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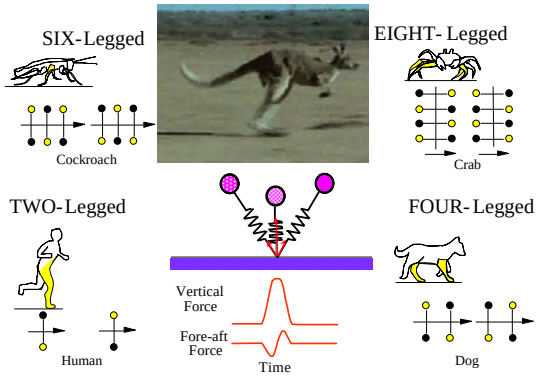
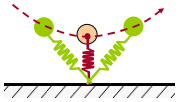
Road Map

- Introduction
- Passive Properties of Isolated Limbs
  - Dynamic Oscillations
  - Impulse Perturbations
- Properties in Active Animals
  - Single Leg in Swing
  - Support Tripod in Stance
- Conclusions

Spring-Mass Systems

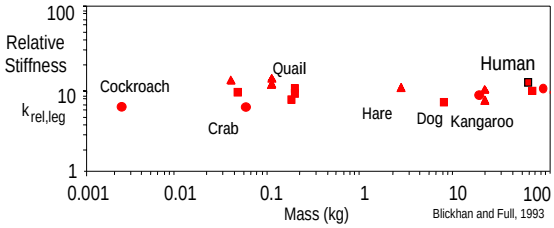


Virtual Leg Stiffness



$$k_{rel} = \frac{\frac{F}{mg}}{\frac{\Delta x}{x}}$$

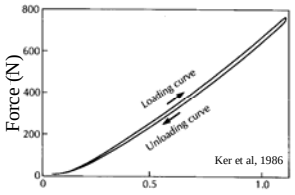
TROTTERS
RUNNERS
HOPPERS



Benefits of Bouncing

1. Storage and return of elastic strain energy can increase efficiency
2. Simplify control via passive self-stabilization

Resilient Structures in Vertebrates



Wallaby tendon: 93% resilient

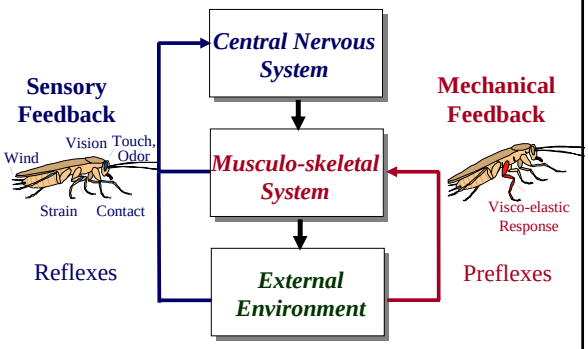
Mechanical Efficiency Increases 37%

Insect Resilience

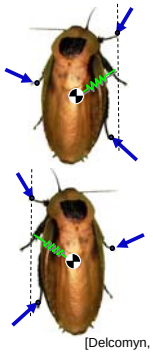
Locust Tibia
95% Resilient
(Katz & Gosline, 1994)

Energy Returned to Locust <10 % of kinetic energy of jump

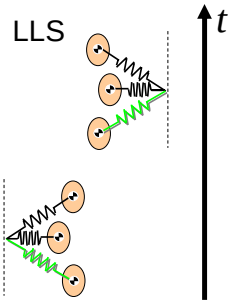
Feedback



Lateral Leg Spring 'Template'



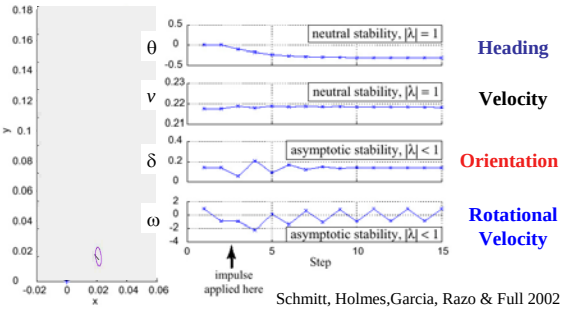
3 Legs Acting as One



[Delcomyn, '71] [Kubow and Full '98] [J. Schmitt & P. Holmes, 2000]

Self-Stabilization

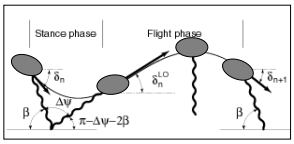
Passive, mechanical self-stabilizing without "neural reflexes"



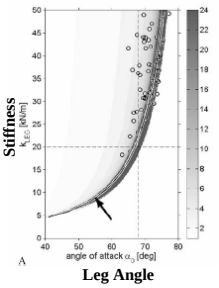
Schmitt, Holmes,Garcia, Razo & Full 2002

Stability in the Sagittal Plane

Self-stabilized Running in the Sagittal Plane for 3 DOF Pogo Stick!



Ghigliazza, Altendorfer, Holmes & Koditschek 2002



Seyfarth, Geyer, Gunther and Blickhan 2002

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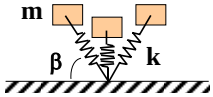
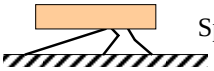
Sagittal Plane Model

ORGANISM

Spring Loaded Inverted Pendulum



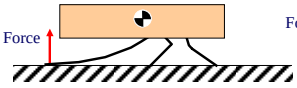
Multi-Leg



Leg Springs ?

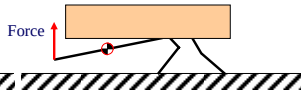
Leg Function

Stance



- Leg in contact with ground
- Forces act on large mass
- Energy storage and return advantageous

Swing

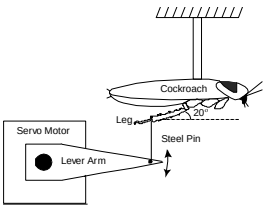


- Leg NOT in contact with ground
- Forces act on small mass
- Damping for perturbation rejection advantageous

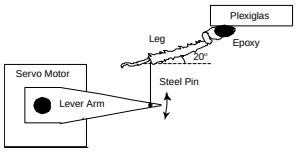
Dynamic Oscillations

Oscillate leg at multiple frequencies & displacements to determine stiffness, damping, and resilience

Free Coxa Preparation



Fixed Coxa Preparation

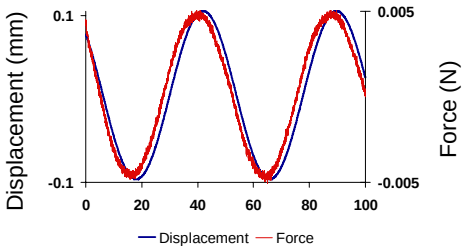


Dynamic Measurements

Sagittal Plane Oscillation

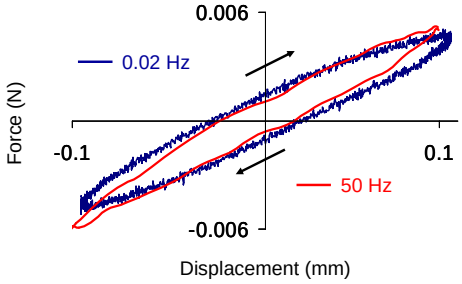
Primarily Exoskeleton

0.2 mm, 0.02 Hz

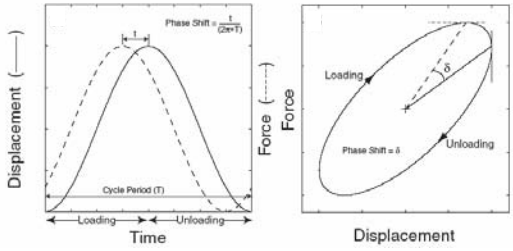


Dynamic Measurements

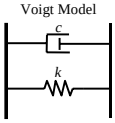
Frequency has Little Effect on Force or Area



Modeling Dynamic Oscillations



Voigt Model



$$F = m\ddot{x} + c\dot{x} + kx$$

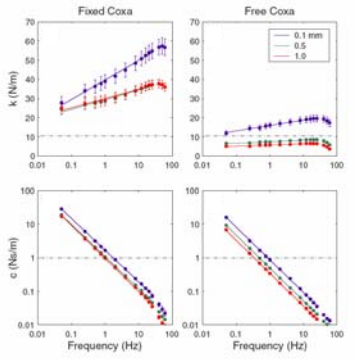
ODE, with analytic solutions

Has Complex Analog

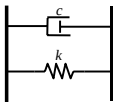
$E^* = E' + iE''$

$\tan(\delta) = E''/E'$

Voigt Model Parameters



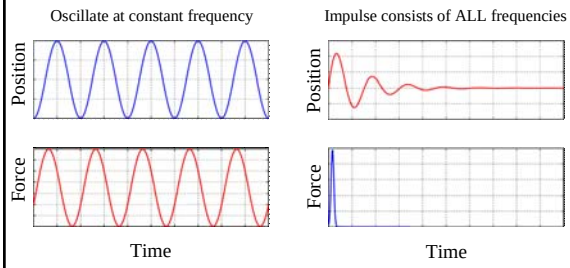
Voigt Model



Both k & c dependent on frequency

ANCOVA, $p < 0.05$

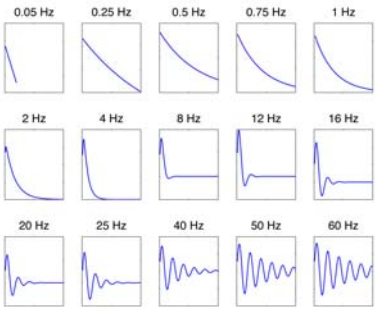
Dynamic Oscillations Versus Impulse Perturbations



$$F = m\ddot{x} + c\dot{x} + kx$$

$$x(t) = \frac{\bar{f}}{m\omega_d} e^{(-\zeta\omega_n t)} \sin(\omega_d t)$$

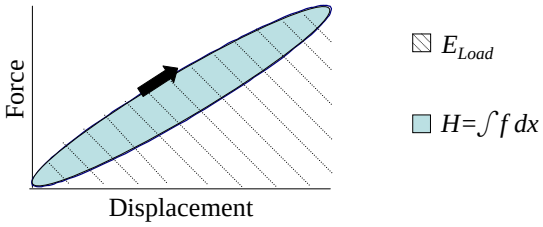
Voigt Model Impulse Response



$$x(t) = \frac{\bar{f}}{m\omega_d} e^{(-\zeta\omega_n t)} \sin(\omega_d t)$$

Measuring Resilience

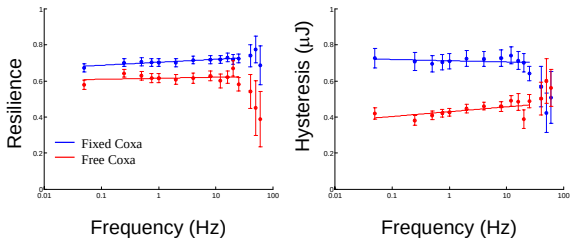
$$R = \frac{(E_{Load} - H)}{E_{Load}}$$



Resilience and Hysteresis

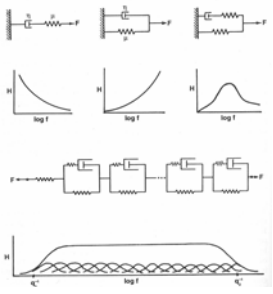
0.5 mm displacement

Both resilience and hysteresis independent of frequency
ANCOVA, $p > 0.05$



Hysteresis and Frequency

- No simple combination of springs and dampers will give constant hysteresis.
- Only an infinite number will produce such behavior.



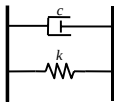
Fung (1994)

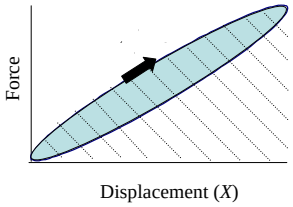
Damping Models

$$R = \frac{(E_{Load} - H)}{E_{Load}}$$

E_{Load} $H = \int f\,dx$

Voigt Model





Viscous Damping Model

$E_{load} \approx 2kX^2$

$H = \pi c \omega X^2$

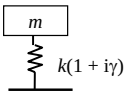
$\therefore R \alpha 1/\omega$

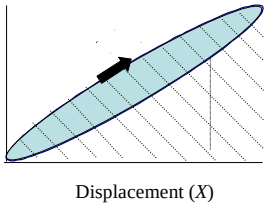
Damping Models

$$R = \frac{(E_{Load} - H)}{E_{Load}}$$

E_{Load} $H = \int f\,dx$

Hysteretic Damping Model





Hysteretic Damping Model

$E_{load} \approx 2kX^2$

$H = \pi\gamma kX^2$,

Where γ is the hysteretic material constant

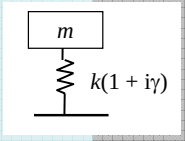
$\therefore R$ independent of ω

Hysteretic Damping Model

Advantages

- Captures hysteresis and resilience effects of biological materials
- Constant parameters allow predictions voigt model cannot make

Disadvantages

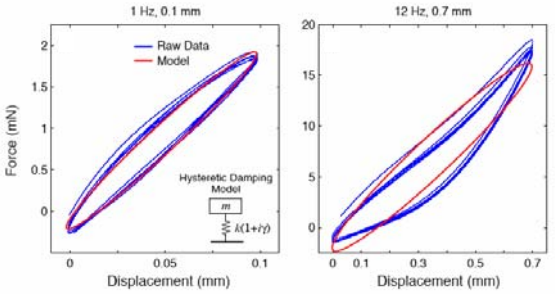


$F = m\ddot{x} + k(1+i\gamma)x$

For sinusoidal displacement inputs:

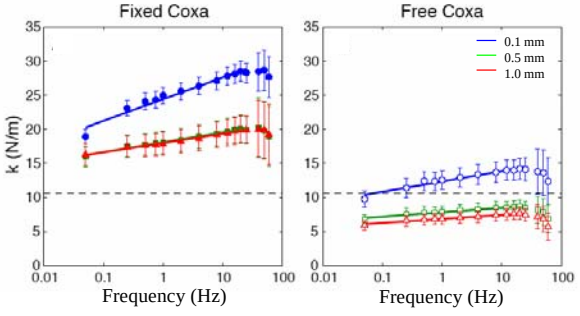
$F(t) = A[(k - \omega^2 m)\cos(\omega t) - \gamma k \sin(\omega t)]$

Hysteretic Model Fitting



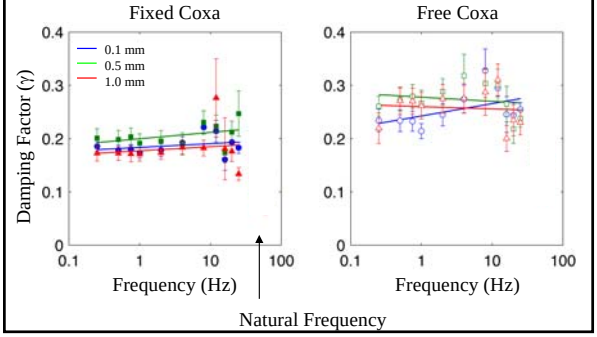
Stiffness (k)

Stiffness weakly dependent on frequency
ANCOVA, $p < 0.05$

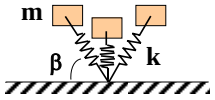


Structural Damping Factor (γ)

γ independent of frequency
ANCOVA, $p > 0.05$



Predicting Energetic Benefits



May store and return as much as 40% of the E_{COM}

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Advantages

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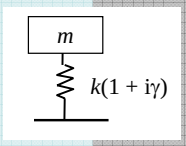
- Constant parameters allow predictions voigt model cannot make



Disadvantages

- Simple only for sinusoids
- Not analytically solvable

$$F = m\ddot{x} + k(1+i\gamma)x$$

For sinusoidal displacement inputs:

$$F(t) = A[(k-\omega^2 m)\cos(\omega t) - \gamma k \sin(\omega t)]$$

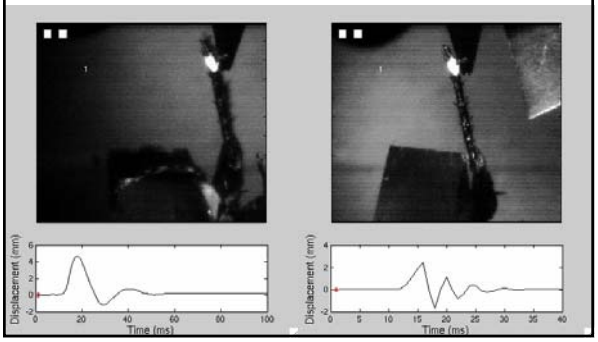
For force impulse perturbations:

$$x(t) = \frac{\tilde{f}}{\pi}\int_0^\infty \frac{[k-m\omega^2]\cos\omega t + k\gamma \sin\omega t}{[k-m\omega^2]^2 + k^2\gamma^2} d\omega$$

Impulse Perturbations

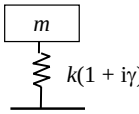
Free Coxa w/o tarsus
25 fps

Fixed Coxa w/o tarsus
10 fps



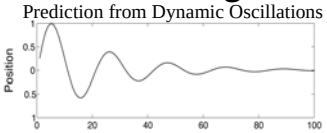
Hysteretic Model Fitting

Dynamic Oscillation Guess
k = 15
γ = 0.3

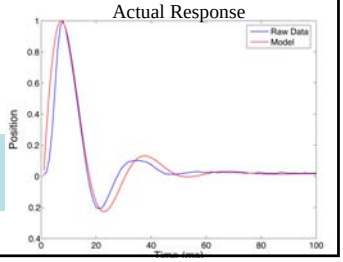


Impulse Perturbation Values
k = 6.41
γ = 0.81

Prediction from Dynamic Oscillations

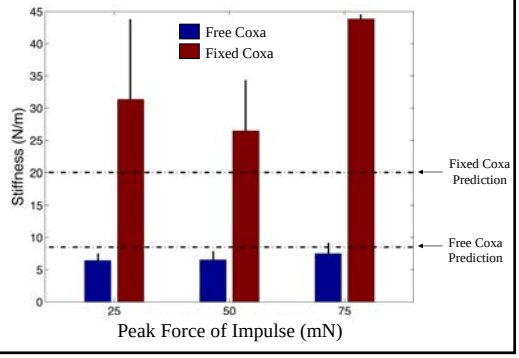


Actual Response



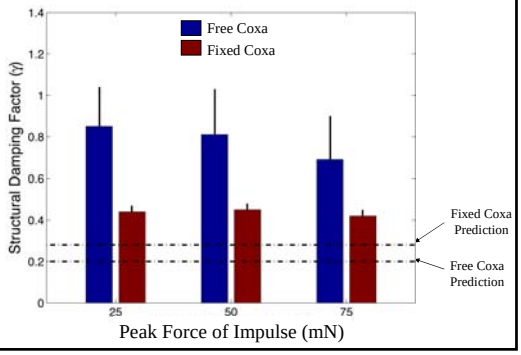
Hysteretic Model Parameters

Stiffness (k) values are similar for oscillation and impulse tests

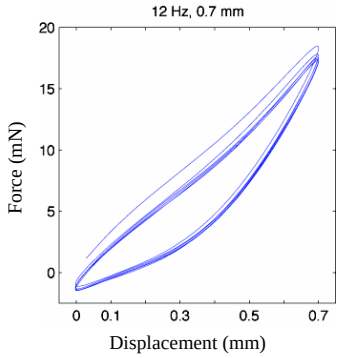


Hysteretic Model Parameters

Damping (γ) values are underestimated by oscillation tests

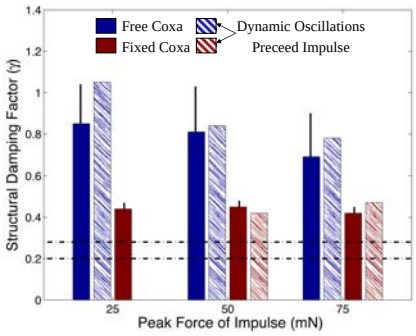


Improving on Simplest Model



Improving on Simplest Model

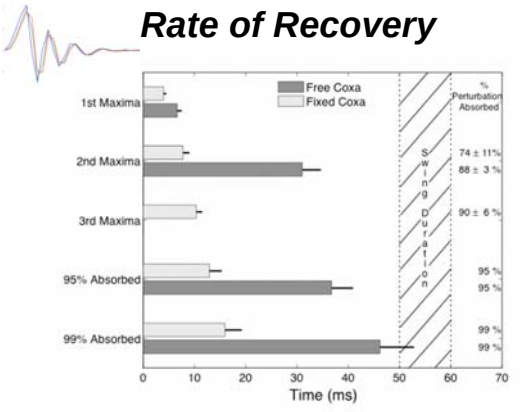
Overcoming static friction not an issue



Improving on Simplest Model

- Leg rings at predicted frequency (stiffness is ok)
- Perturbation absorbed faster than predicted (damping underestimated)
- Energy absorbed in dorsal-ventral, medial-lateral, & anterior-posterior directions

Rate of Recovery



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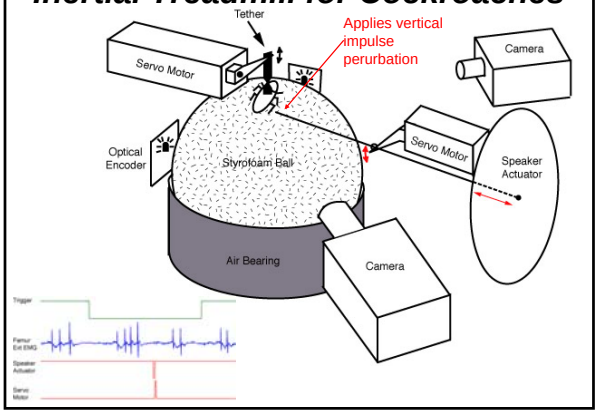
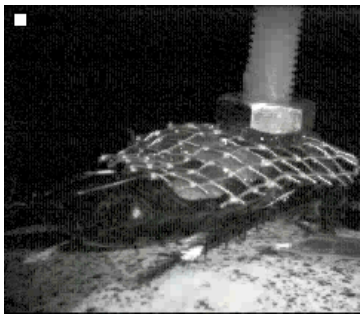
- Conclusions

Inertial Treadmill for Cockroaches



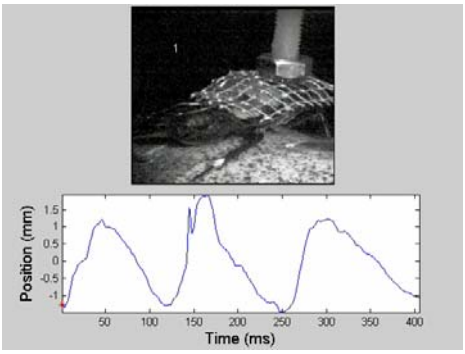
Impulse Perturbation on Running Cockroach

Actual Speed



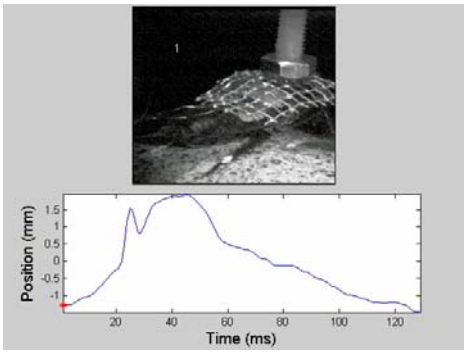
Impulse Perturbation During Running

Slowed down 30x

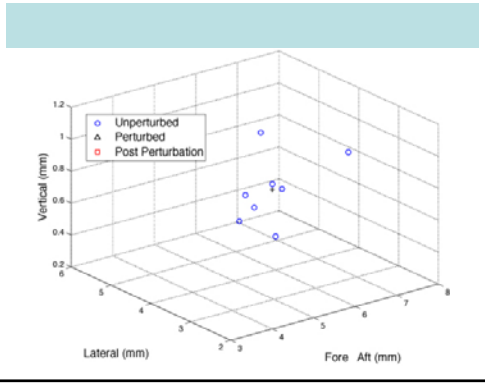


Impulse Perturbation During Running

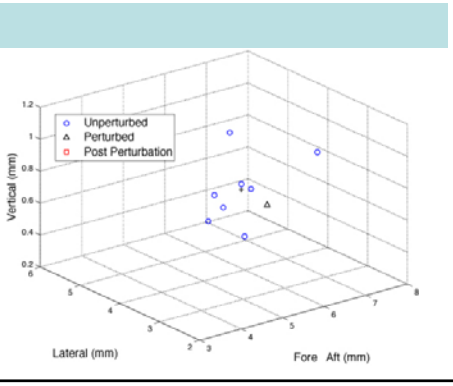
Slowed down 100x



Foot Placement

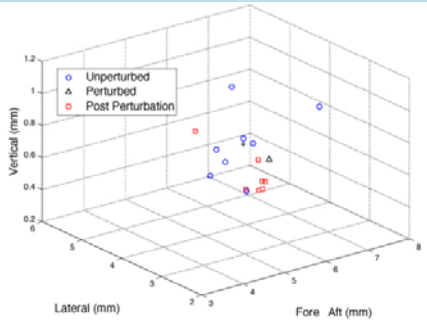


Foot Placement



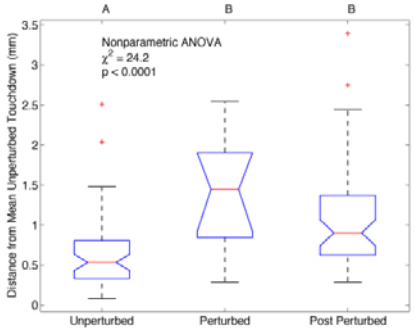
Foot Placement

Foot placement after perturbation clusters farther from average unperturbed touchdown point and does not recover

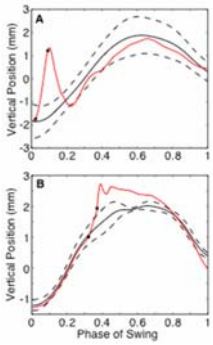


Foot Placement

Foot placement after perturbation 1 mm farther from average unperturbed touchdown point



Leg Trajectory



7.0 ± 2.2 ms

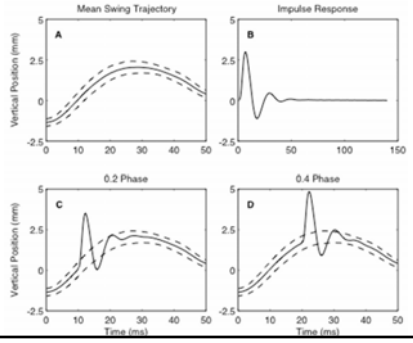
Perturbations early in swing recover rapidly

20.4 ± 1.9 ms

Perturbations late in swing take longer to recover

Leg Trajectory

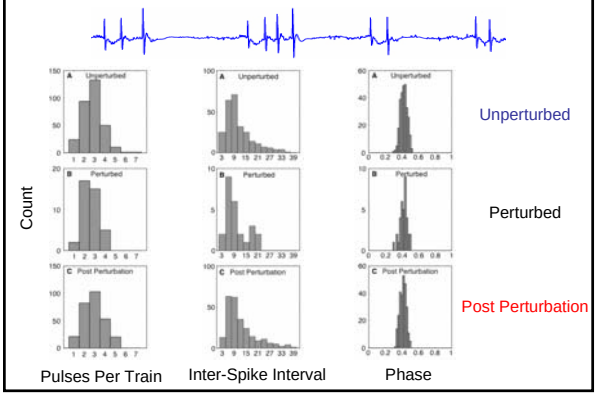
Perturbations early in swing recover as predicted by passive leg response



Reflex Conduction Velocity

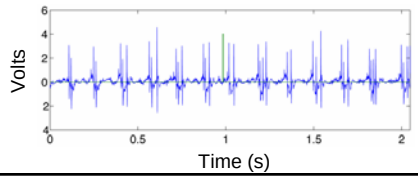
- 7 ms -- fastest EPSP to reach muscle following tactile stimulus in locusts
  (Höltje and Hustert, 2003)
- 10 ms -- latency between EPSP and muscle force production in *Blaberus* (Full and Meijer, 2001)
- 17 ms -- latency between tactile stimulus and leg movement in American cockroach (Schaefer *et al*, 1994)

EMG Response



Neural Response is Present

- Stance phase 10 ms longer immediately following perturbation (20 ms longer in later strides)
- Changes in inter-spike interval and pulses per train similar to speed effects
- No unexpected muscle activity observed within 40 ms of perturbation



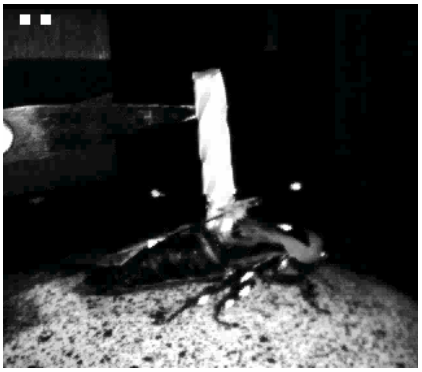
H_o: Recovery in active legs due largely to passive material properties

- 1 mm foot placement offset is never corrected
- Trajectory recovers in <17 ms
- No change in speed-corrected EMG activity for inter-spike interval, phase, or pulses per train

Road Map

- Introduction
- Passive Properties of Isolated Limbs
  - Dynamic Oscillations
  - Impulse Perturbations
- Properties in Active Animals
  - Single Leg in Swing
  - Support Tripod in Stance
- Conclusions

Inertial Treadmill for Cockroaches

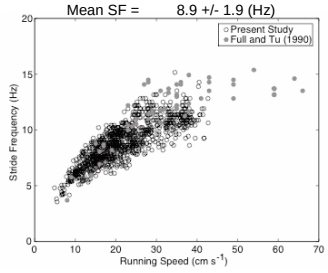


Kinematics

Kinematic relationships match closely with free running animals

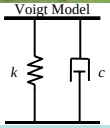
	Trackway (Kram et al, 1997)	Inertial Treadmill
Pitch	±5°	±3.5°
Yaw	±4°	±2.0°
Roll	±7°	±1.0°

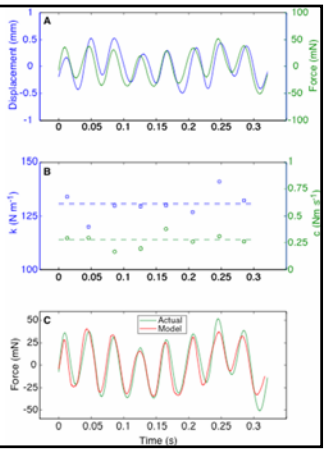
Mean Speed = 22.2 +/- 8.3 (cm/s)
Mean SF = 8.9 +/- 1.9 (Hz)



Dynamic Force Oscillations

Voigt Model

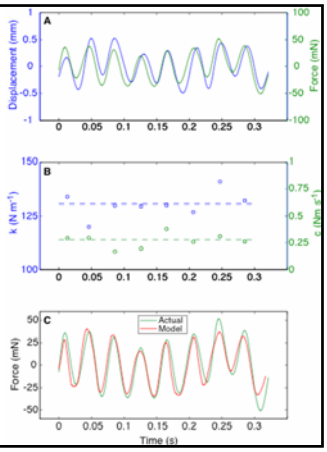




Dynamic Force Oscillations

Model Parameters are independent of cycle #

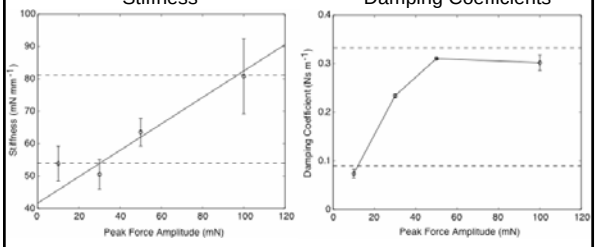
Model faithfully reproduces data



Voigt Model Parameters

Stiffness

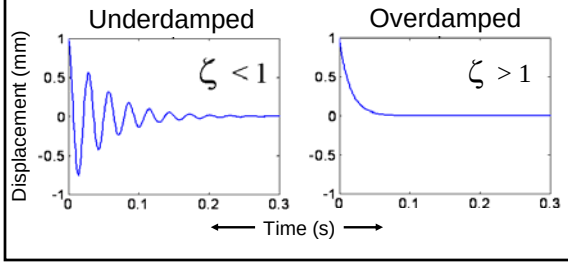
Damping Coefficients



Properties of support tripod almost exactly predicted by properties of passive, ablated hind limb

Damping ratio (ζ)

$$\zeta = \frac{c}{2\sqrt{km}}$$



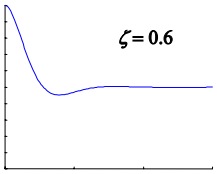
Self-stabilization during stance?

Horizontal Plane

- Input lateral impulse of 85% forward momentum
- Resultant velocity begins to decline within 13.5 ms
- Lateral velocity returned to normal within 31 ms

Sagittal Plane

- Damping coefficient the same in lateral and sagittal planes
- Damping ratio (ζ) in sagittal plane between 0.3-0.7



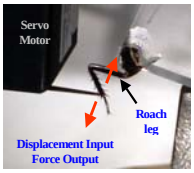
Jindrich and Full, 2002

Conclusions

- Mechanical properties of the active legs and support tripod in the sagittal plane arise from the passive properties of legs
- These properties are well suited for both increasing efficiency as well as simplifying control
  - Resilient legs and support tripod may store and return as much as 40% of the E_{COM} during stance
  - Damping in legs allows for passive self-stabilization of legs during swing
  - Damping ratio of support tripod suggests self-stabilization during stance also likely

Biological Inspiration

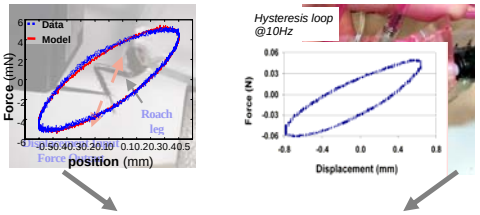
Study biological materials, components, and their roles in locomotion.



Biological Inspiration

Study biological materials, components, and their roles in locomotion.

Study Shape Deposition Manufacturing (SDM) materials and components.



Models of material behavior and design rules for creating SDM structures with desired properties

Sprawlita

Using bio-inspired tuned, springy legs:

- Fast hexapedal robot (>4 BL/s)
- robust (traversal over hip-height obstacles)

Sprawlita
3rd generation

Mass	*0.270 kg*
Dimensions	*0.16 x 0.11 x 0.07 m*
Speed	*2.5 body/sec*
Leg frequency	*5 Hertz*
Build date	*January 2000*

RHex

Uses spring-mass dynamics to overcome obstacles 3 times hip height

Acknowledgements

- UC-Berkeley Poly-PEDAL Lab
  - Bob Full
  - Anna Ahn
  - Noah Cowan
  - Dan Goldman
  - Devin Jindrich
  - Tom Libby
  - Kenneth Meijer
  - Anne Peattie
  - Shai Revzen
  - Simon Sponberg
- Berkeley Biomechanics Center
  - Mimi Koehl
  - Robert Dudley
  - Sheila Patek
- Stanford University
  - Mark Cutkosky
  - Sean Bailey
  - Jorge Cham
  - Sanjay Dastoor
- Office of Naval Research
- Defense Advanced Research Projects Administration