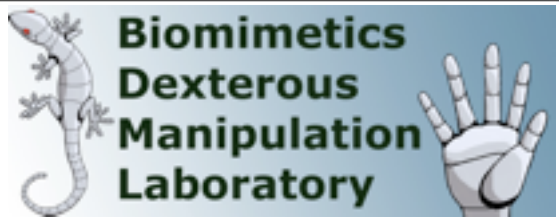
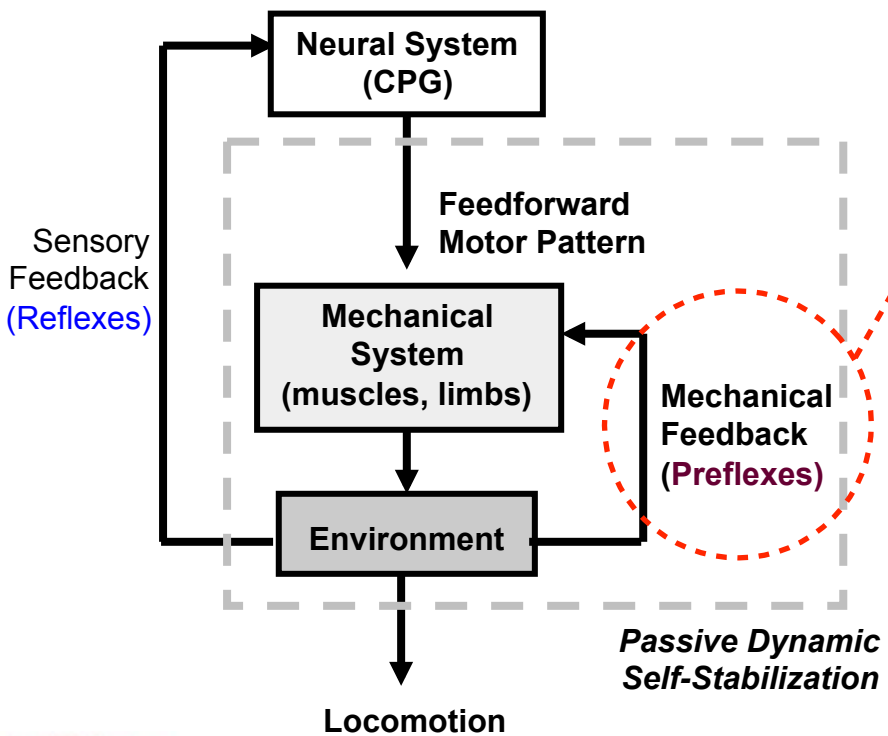


Robots with Tunable Suspensions based on Artificial Muscles

M.R. Cutkosky*
Mechanical Engineering, Stanford University
http://bdml.stanford.edu

*with thanks to S. Dastoor, H. Stuart & S. Wang

Motivation: tuneable suspensions for *small, fast robots*

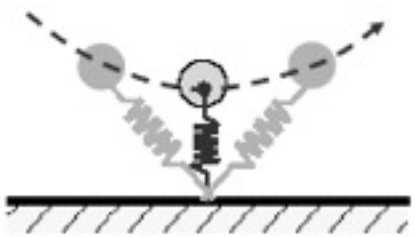


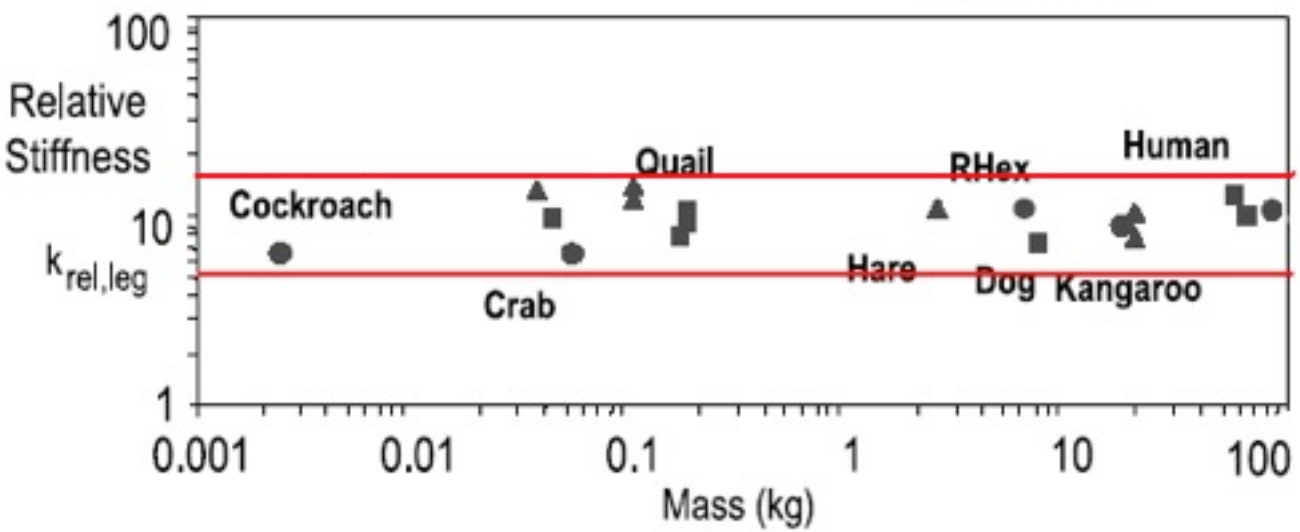
Full and Koditschek, 1999

Tuned, passive mechanical properties that increase robustness, reduce energy consumption, simplify control

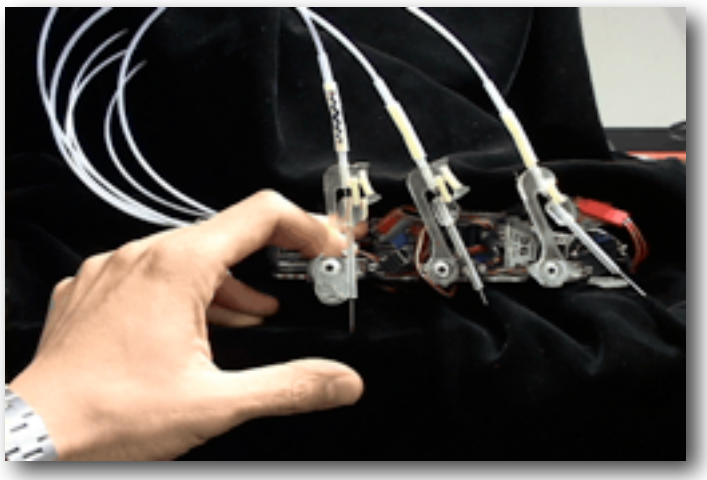
Motivation

Animal Locomotion





Koditschek, Full, and Buehler (2004)



A specific motivation

Biomimetics Dexterous Manipulation Laboratory

Colugo Kinetics (Byrnes, Lim, Spence, *Proc. R. Soc. B, 2008*)

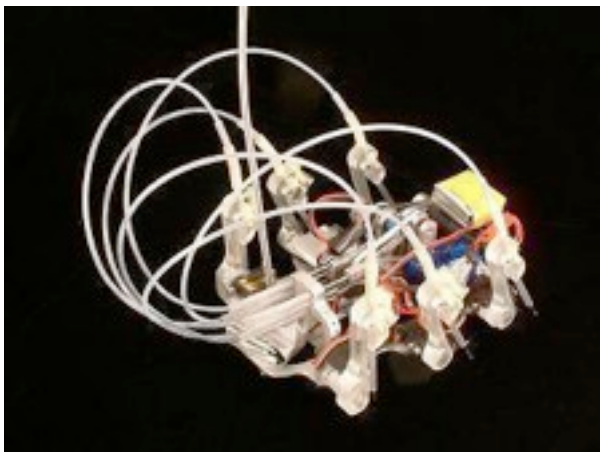
How much could we enlarge the range of possible landing conditions with a *dynamically variable* suspension?

Current suspension: nonlinear, but fixed

Motivation

How do you choose compliance?

Cyclic Locomotion



Transient Event

Fixed compliance

↓

System	**Environment**	**Task**
Mass (payload) Geometry	Surface stiffness External disturbances	Gait Grasping

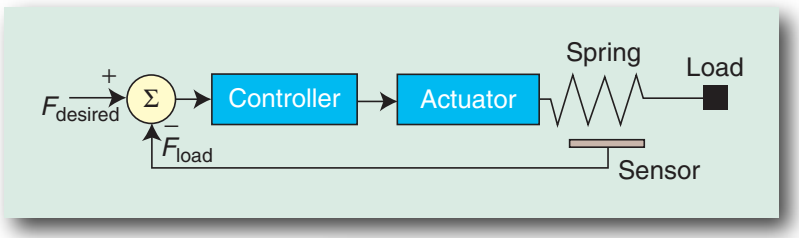
↓

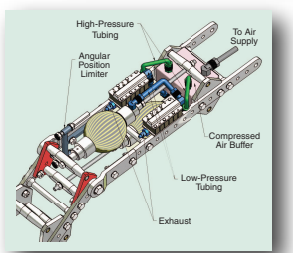
What if these change?

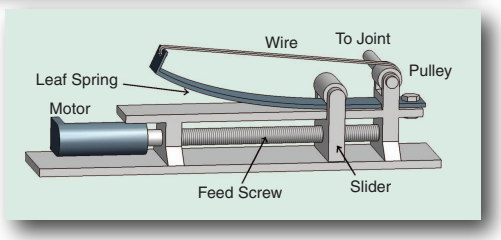
Background

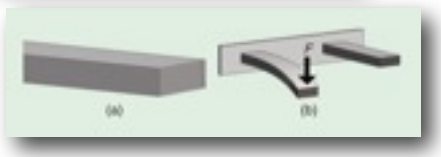
Tunable Stiffness

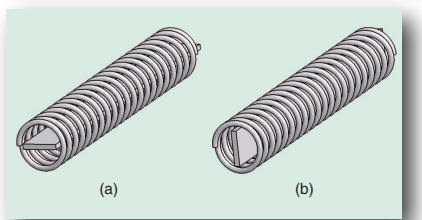
- **Series Elastic Actuation**
  - Pratt (1995)
- **Variable Geometry**
  - Hollander (2004)
  - Seki (2000)
  - Kawamura (2002)
  - Galloway (2009)
- **Antagonistic Systems**
  - Hurst (2004)
  - Migliore (2005)
  - Tonietti (2005)
  - Verrelst (2005)
- **Variable Mechanism**
  - Sardellitti (2011)
  - Van Ham (2007)
  - Wolf (2008)

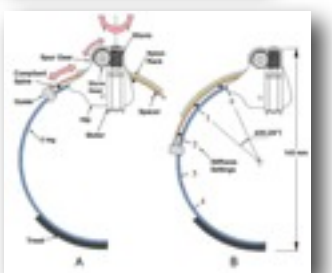


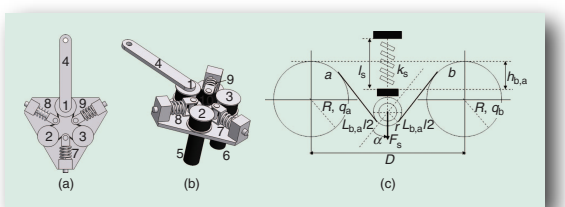


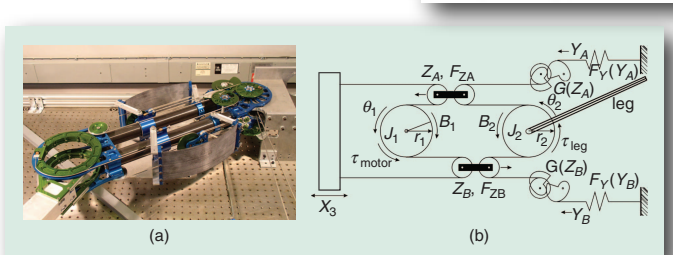


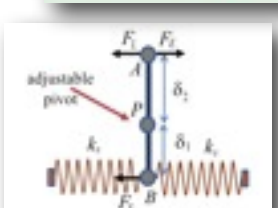


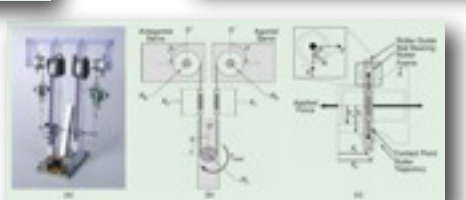


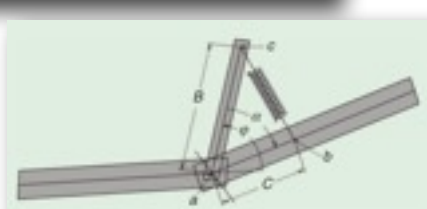










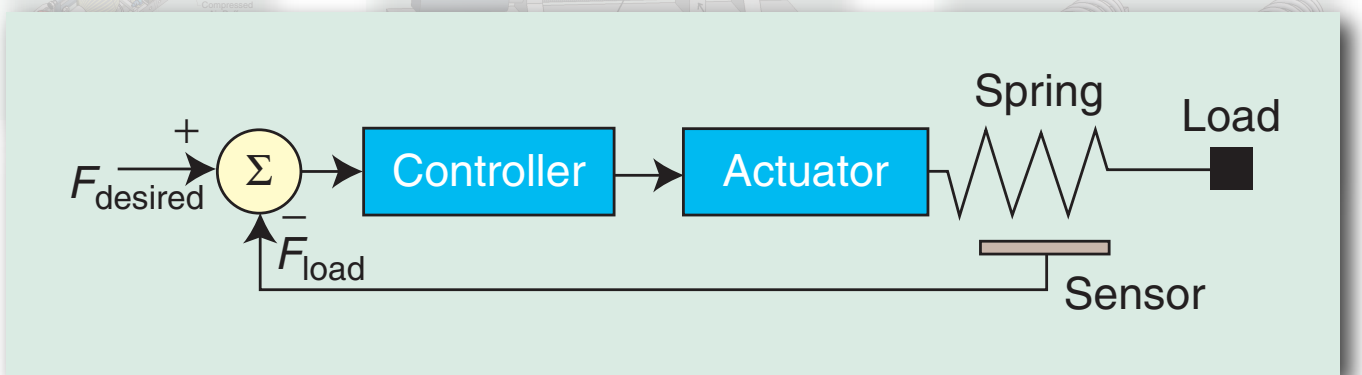


6

Background

Tunable Stiffness

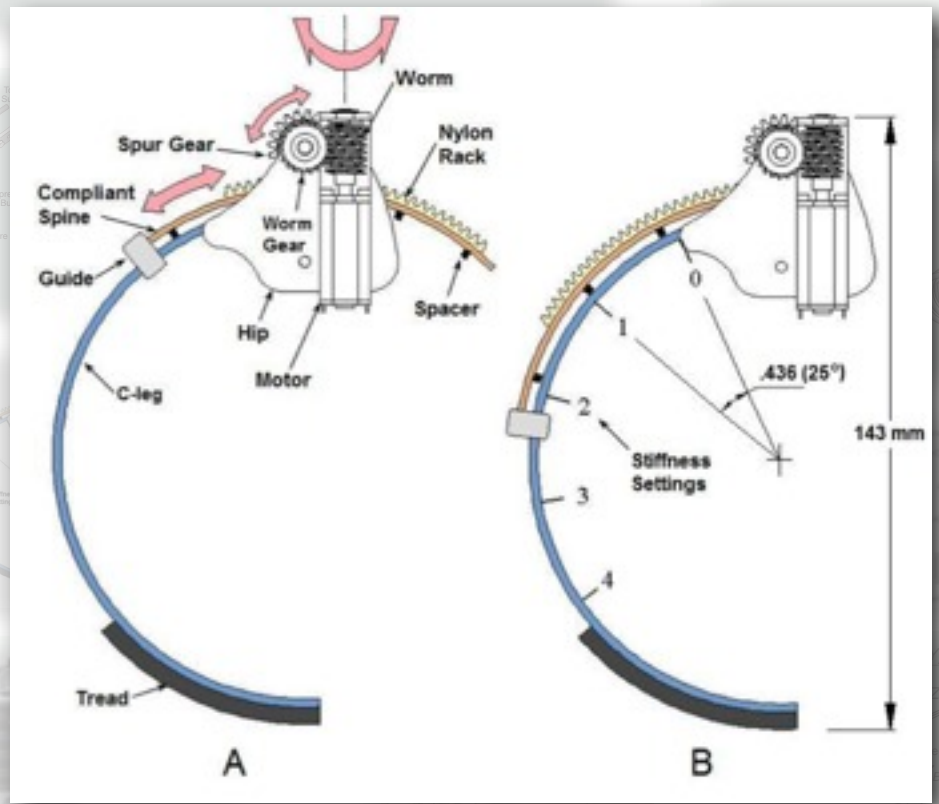
- **Series Elastic Actuation**
  - **Pratt (1995)**
- **Variable Geometry**
  - Hollander (2004)
  - Seki (2000)
  - Kawamura (2002)
  - Galloway (2009)
- **Antagonistic Systems**
  - Hurst (2004)
  - Migliore (2005)
  - Tonietti (2005)
  - Verrelst (2005)
- **Variable Mechanism**
  - Sardellitti (2011)
  - Van Ham (2007)
  - Wolf (2008)



Background

Tunable Stiffness

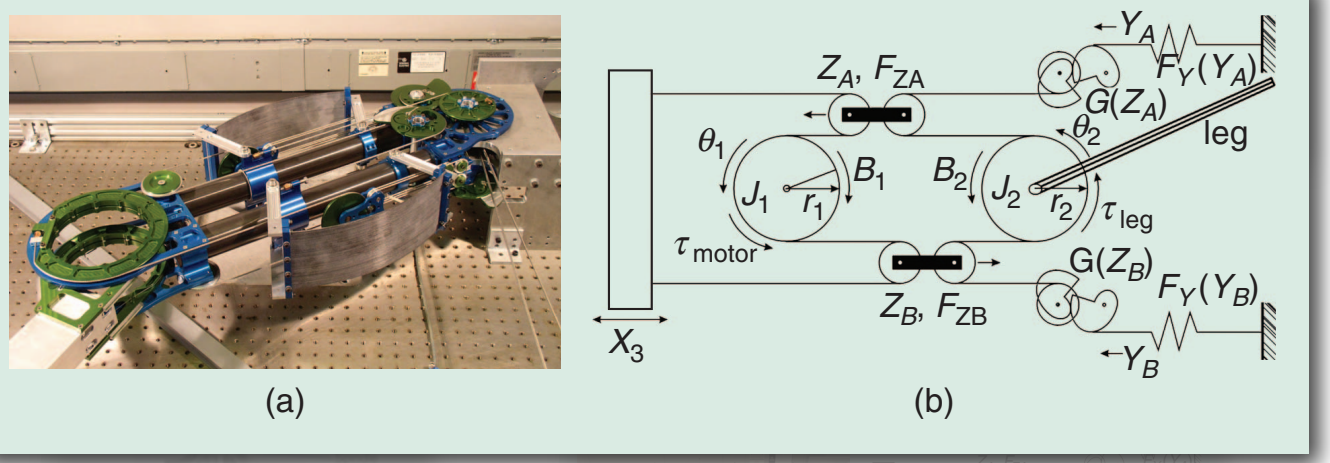
- **Series Elastic Actuation**
  - Pratt (1995)
- **Variable Geometry**
  - Hollander (2004)
  - Seki (2000)
  - Kawamura (2002)
  - **Galloway (2009)**
- **Antagonistic Systems**
  - Hurst (2004)
  - Migliore (2005)
  - Tonietti (2005)
  - Verrelst (2005)
- **Variable Mechanism**
  - Sardellitti (2011)
  - Van Ham (2007)
  - Wolf (2008)



Background

Tunable Stiffness

- **Series Elastic Actuation**
  - Pratt (1995)
- **Variable Geometry**
  - Hollander (2004)
  - Seki (2000)
  - Kawamura (2002)
  - Galloway (2009)
- **Antagonistic Systems**
  - **Hurst (2004)**
  - Migliore (2005)
  - Tonietti (2005)
  - Verrelst (2005)
- **Variable Mechanism**
  - Sardellitti (2011)
  - Van Ham (2007)
  - Wolf (2008)



Background

Tunable Stiffness

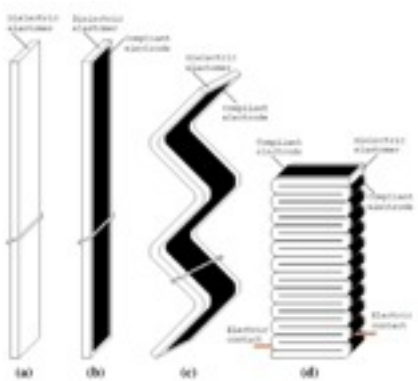
- **Series Elastic Actuation**
  - Pratt (1995)
- **Variable Geometry**
  - Hollander (2004)
  - Seki (2000)
  - Kawamura (2002)
  - Galloway (2009)
- **Antagonistic Systems**
  - Hurst (2004)
  - Migliore (2005)
  - Tonietti (2005)
  - Verrelst (2005)
- **Variable Mechanism**
  - Sardellitti (2011)
  - Van Ham (2007)
  - Wolf (2008)

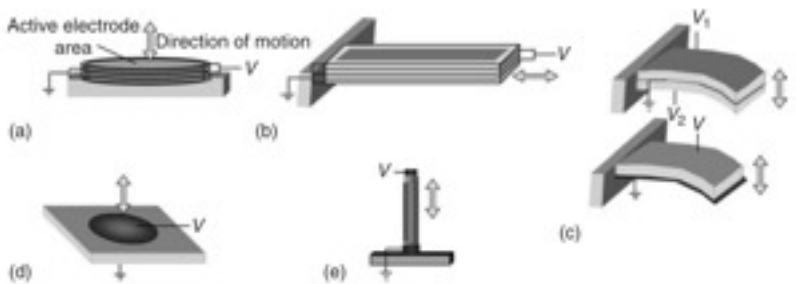
- **Mechanical Complexity**
- **Scalability**
- **Weight**
- **Volume**
- **Energy Density**
- **Mechanical Time Constant**

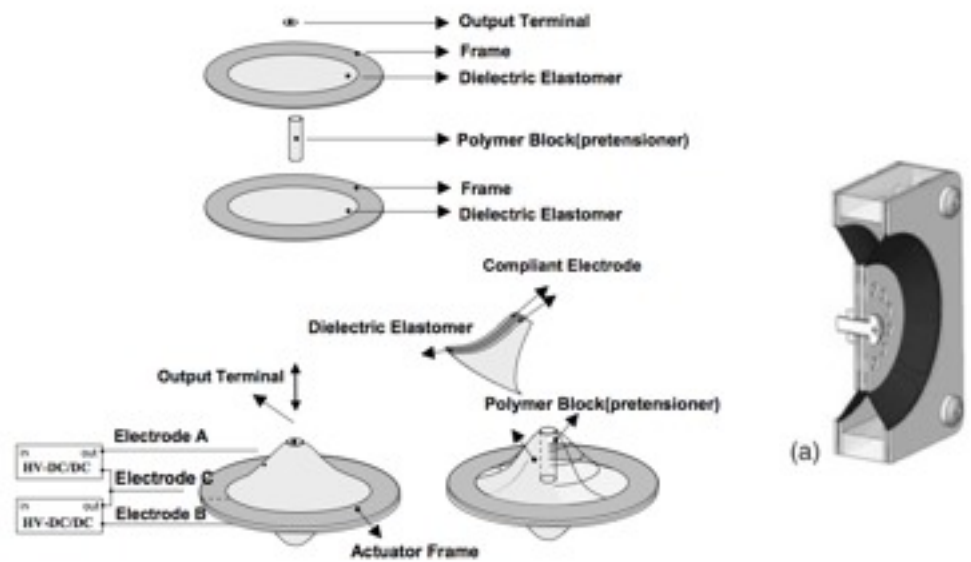
Background

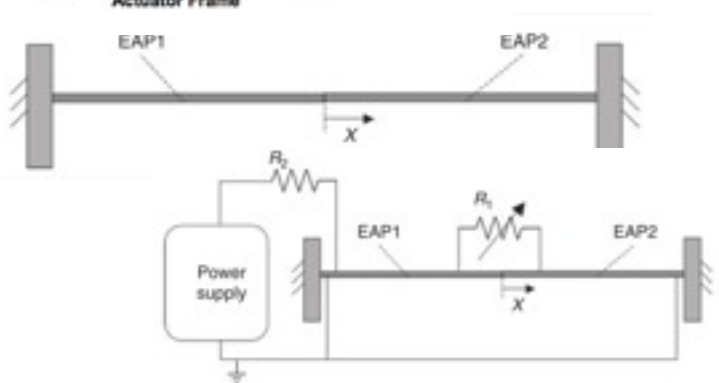
Electroactive Polymers

- **Principle of Operation**
  - Pelrine and Kornbluh (2000)
- **Geometry and Design**
  - Choi (2003)
  - Rosenthal (2000)
- **Modeling**
  - Wissler (2005)
- **Scalable Manufacturing**
  - Carpi (2007), Kovacs (2007)
- **Suspensions**
  - Pelrine (2008)



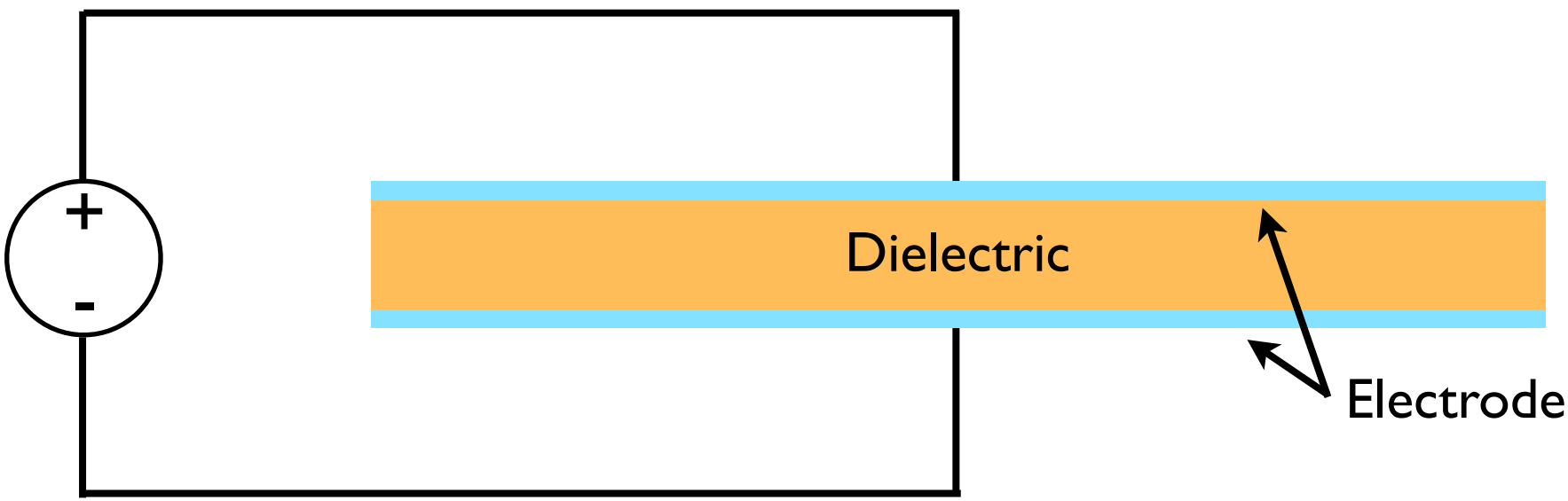






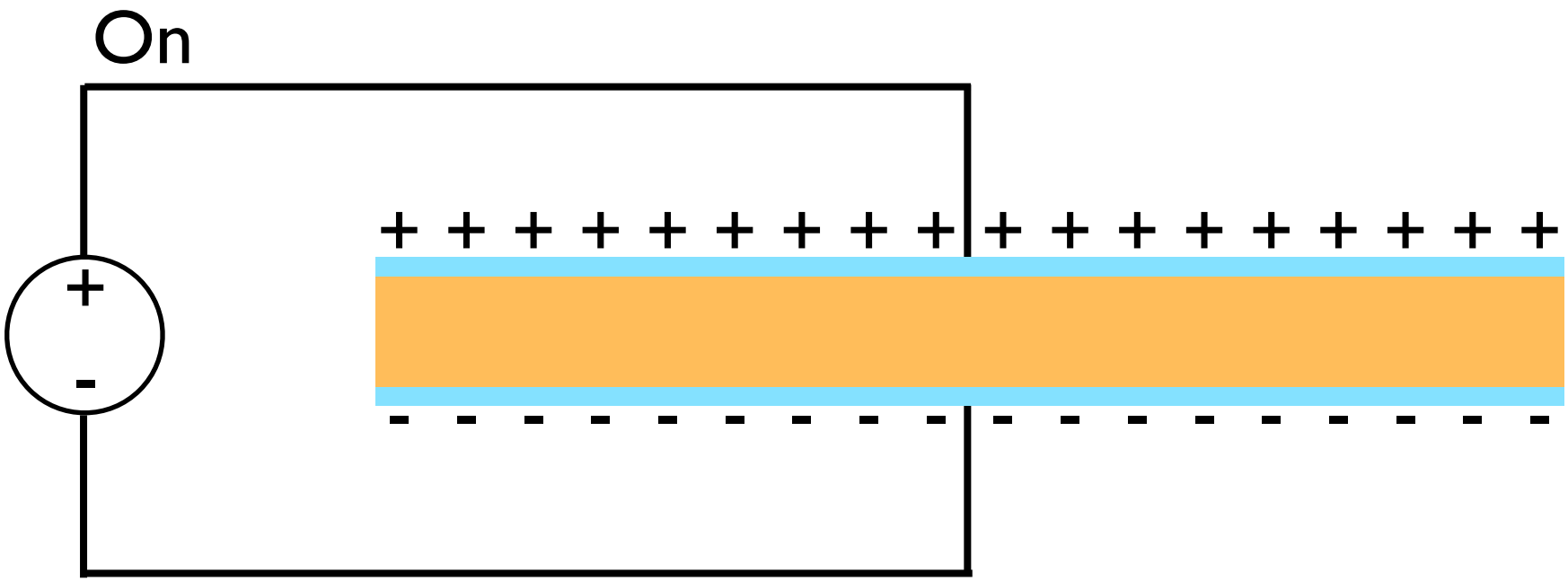
Background

Electroactive Polymers



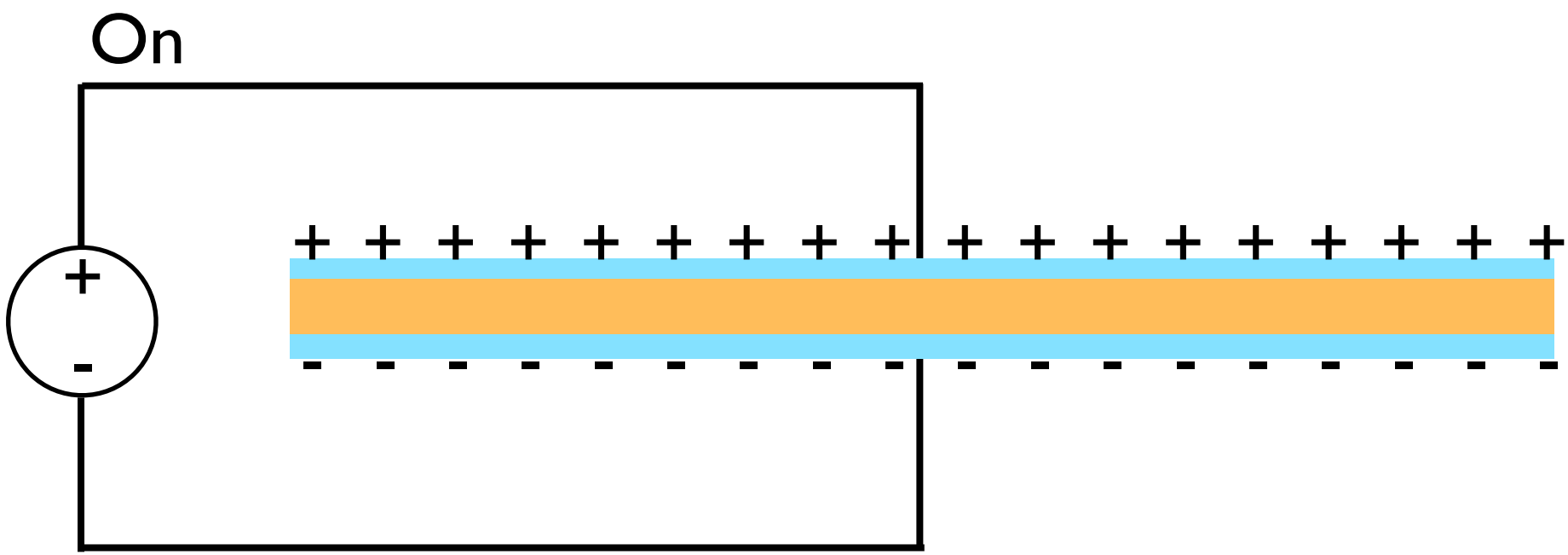
Background

Electroactive Polymers



Background

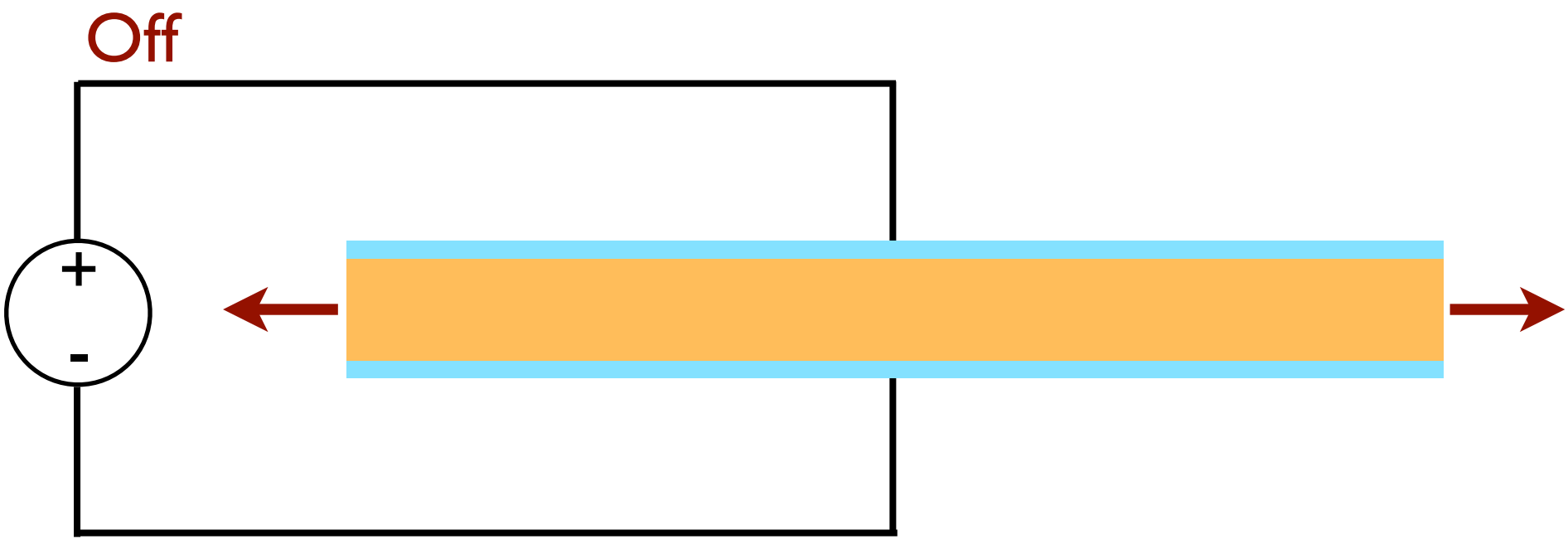
Electroactive Polymers



$$p = \epsilon_0 \epsilon_r E^2 = \frac{\epsilon_0 \epsilon_r V^2}{t^2}$$

Background

Electroactive Polymers



Background

Electroactive Polymers

Dielectric

- High Voltage
- Low,Uniform Thickness
- High Dielectric Constant
- Low Elastic Modulus

↓

Soft, uniformly thin, strong insulator

↓

3M VHB 4910

Electrode

- Compliant
- Low Modulus
- Low Resistance

↓

Very soft, thin, stretchy, conductive

↓

Carbon + silicone oil

Frame

- Easy to fabricate
- Insulating (HV)
- Stiff, lightweight

↓

Rigid, light, strong insulator

↓

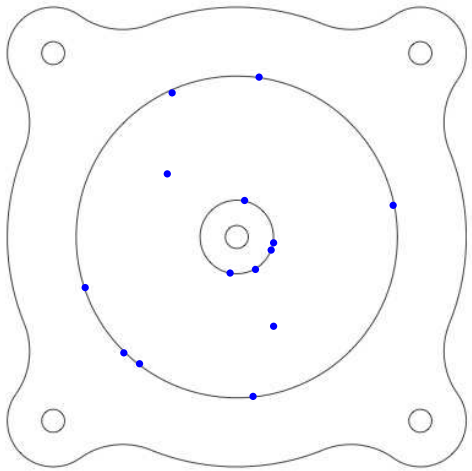
Fiberglass

Electroactive Polymers

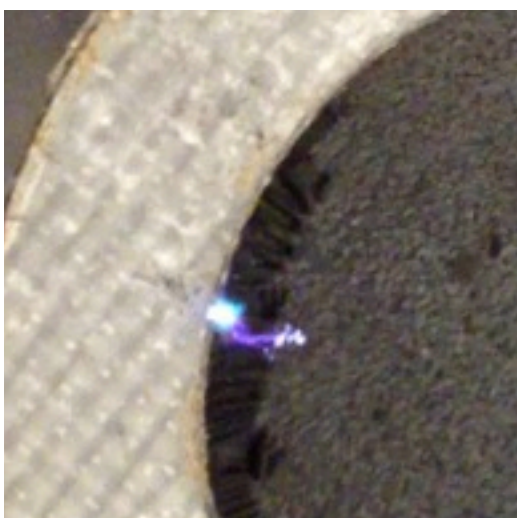
Edge Treatment

Mechanical film stress

Empirical failure locations



Electrical arcing failure



Eventual Mechanical Failure

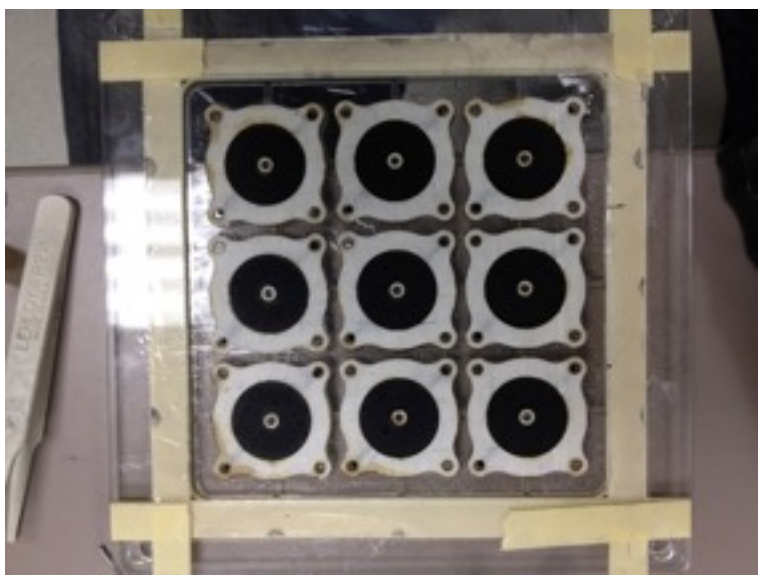
Sanjay's EAP Questions

- Why would anyone choose to work with thin films that are stretchy, sticky, and easily torn?
- And cover them with a goopy combination of carbon powder and oil?
- And energize them to 6000 volts?

An intact 4-diaphragm unit

Typical failures...

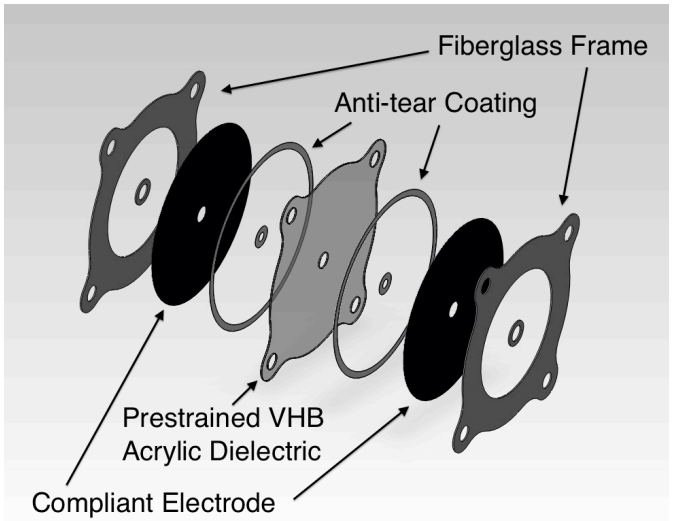
Manufacturing Process

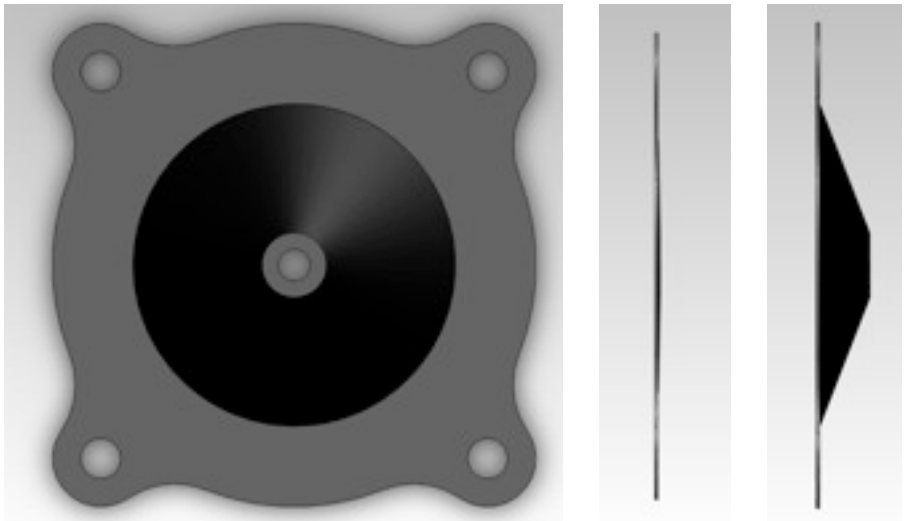


Fabricate in batches:

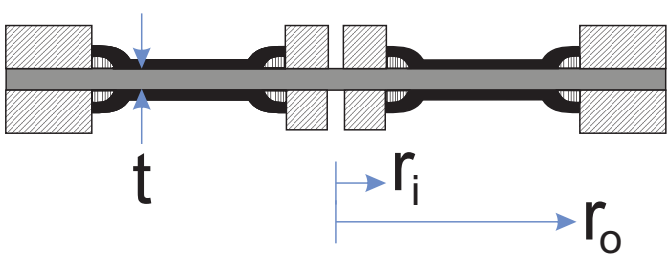
- Use VHB film stretched 400%.
- Lasercut acrylic fixtures maintain tension and alignment.
- Use masks to add silicone anti-tear layers at inner, outer edges.
- Actuator frames are lasercut fiberglass
- Spray carbon grease through additional masks.

Module Design





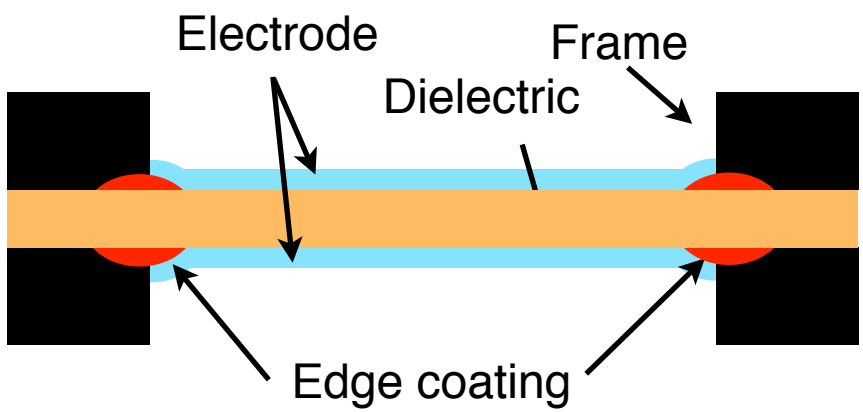
- Carbon electrode coating
- Anti-tear coating
- Fiberglass frame
- Prestrained VHB4910 acrylic



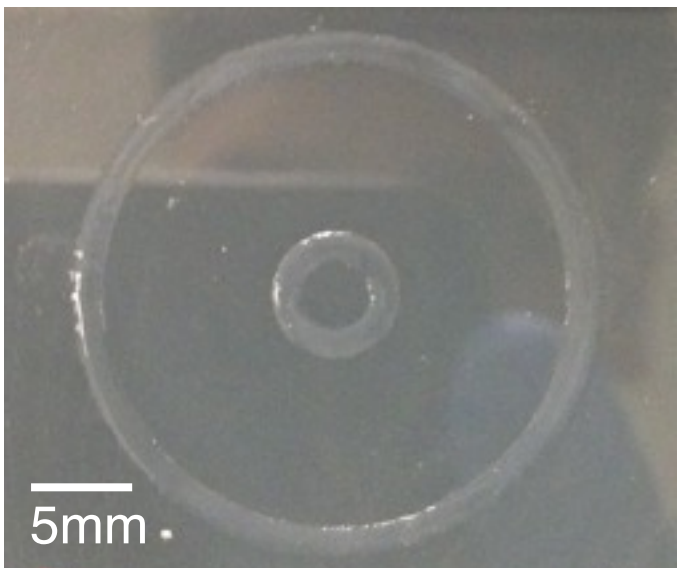
20

Electroactive Polymers

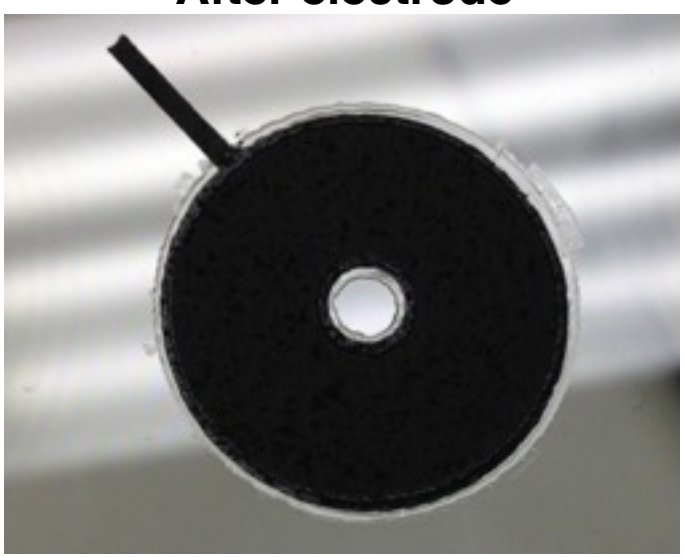
Edge Treatment



Before electrode



After electrode



Electroactive Polymers

Manufacturing Process

1 hour build time

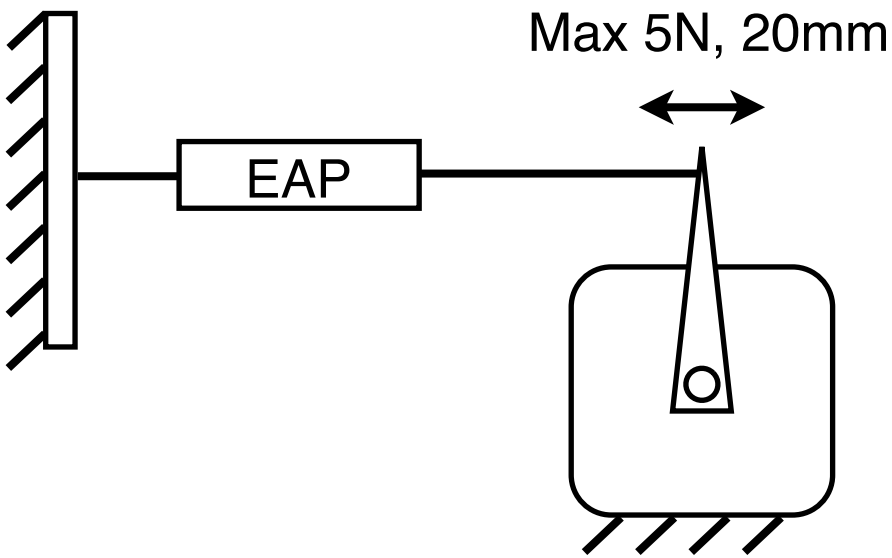
~100% yield

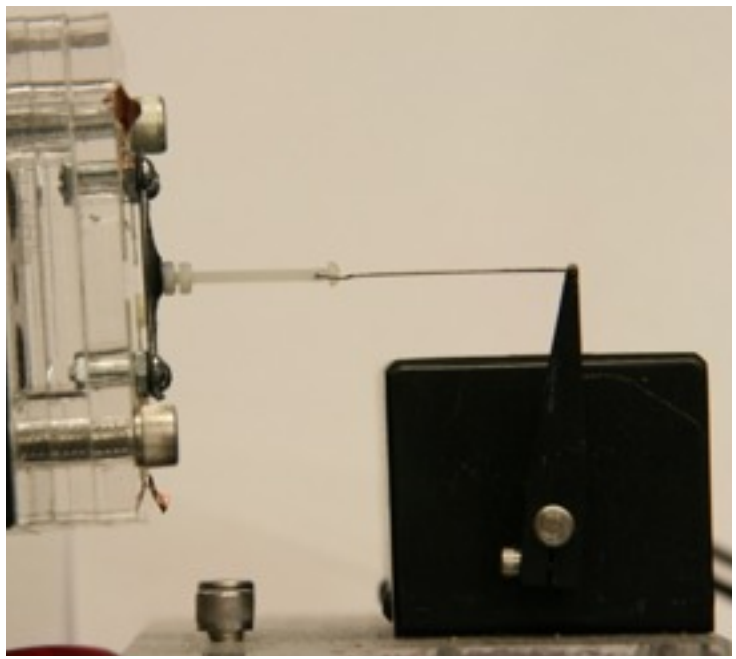
Reliable (>10,000 cycles)

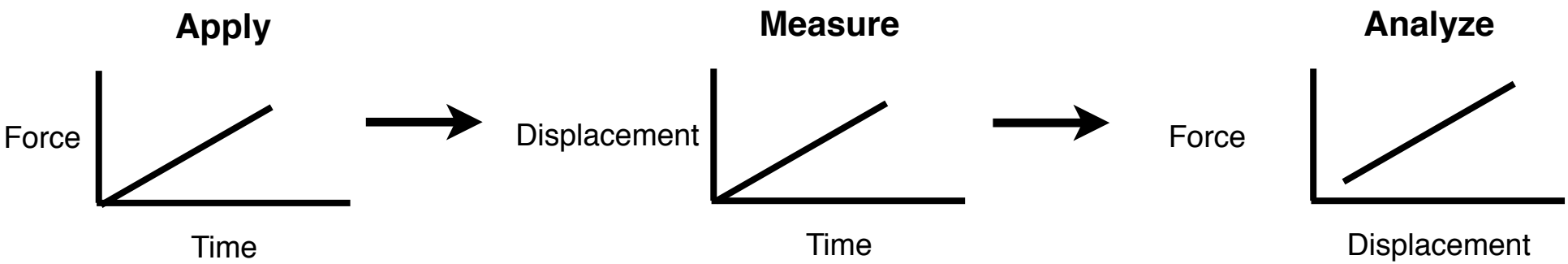
Consistent across batch

Status of January 23 2013:
M.S. student Shiquan Wang has been learning this process from Sanjay Dastoor and Hannah Stuart

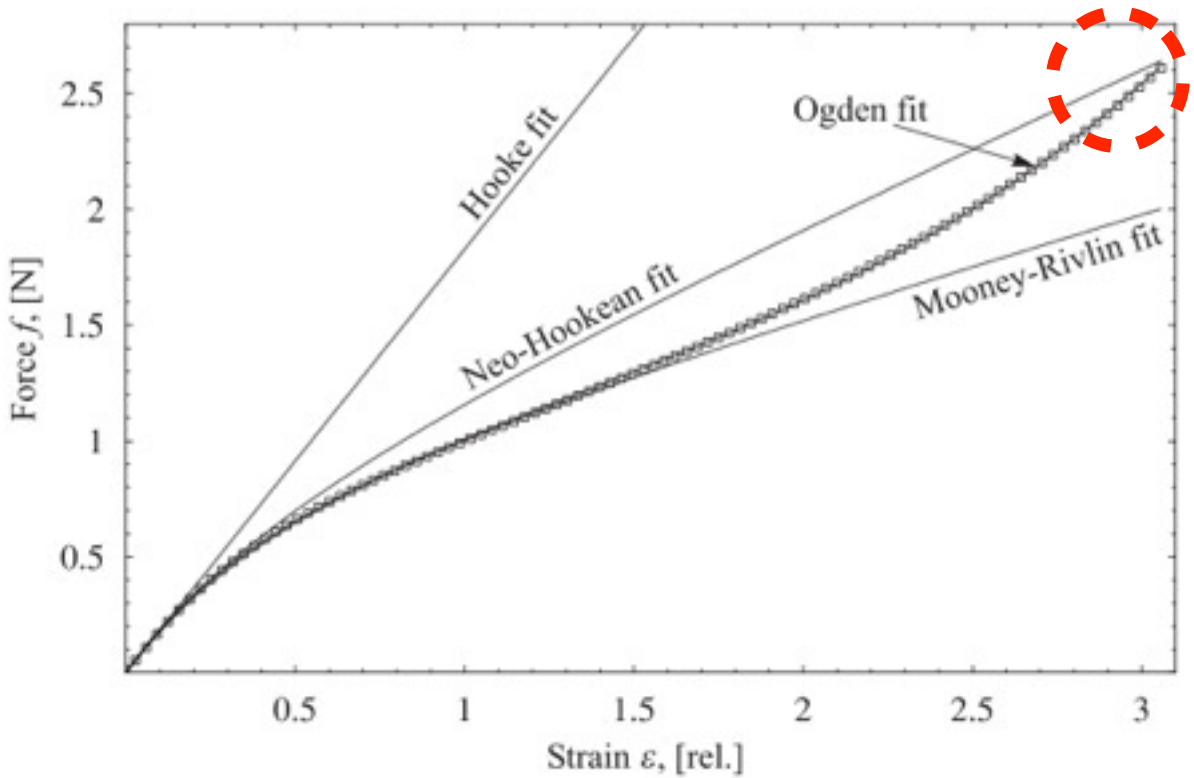
Modeling and Measurement







Modeling

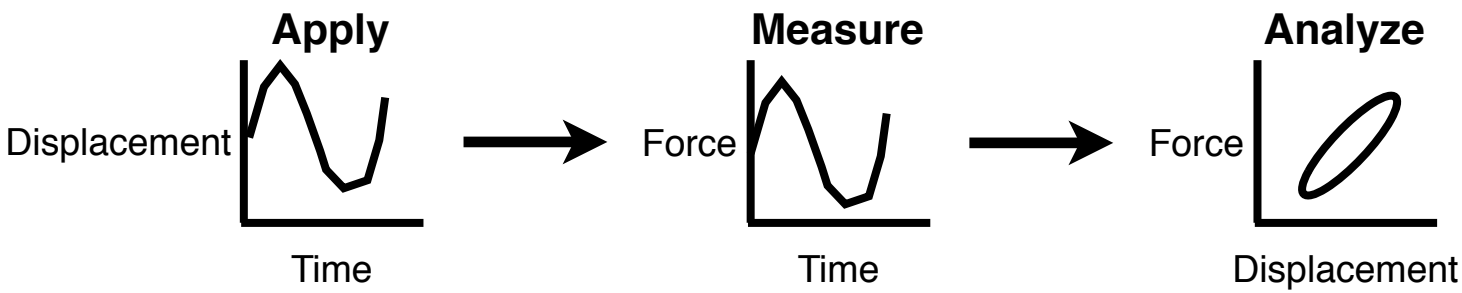


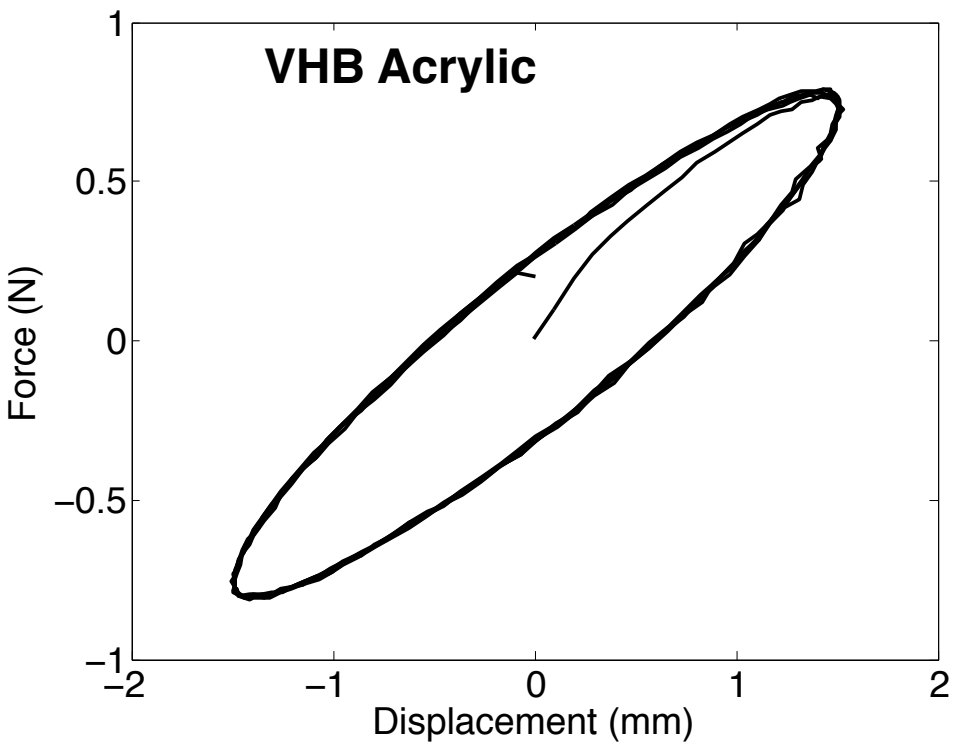
From Kofod 2001

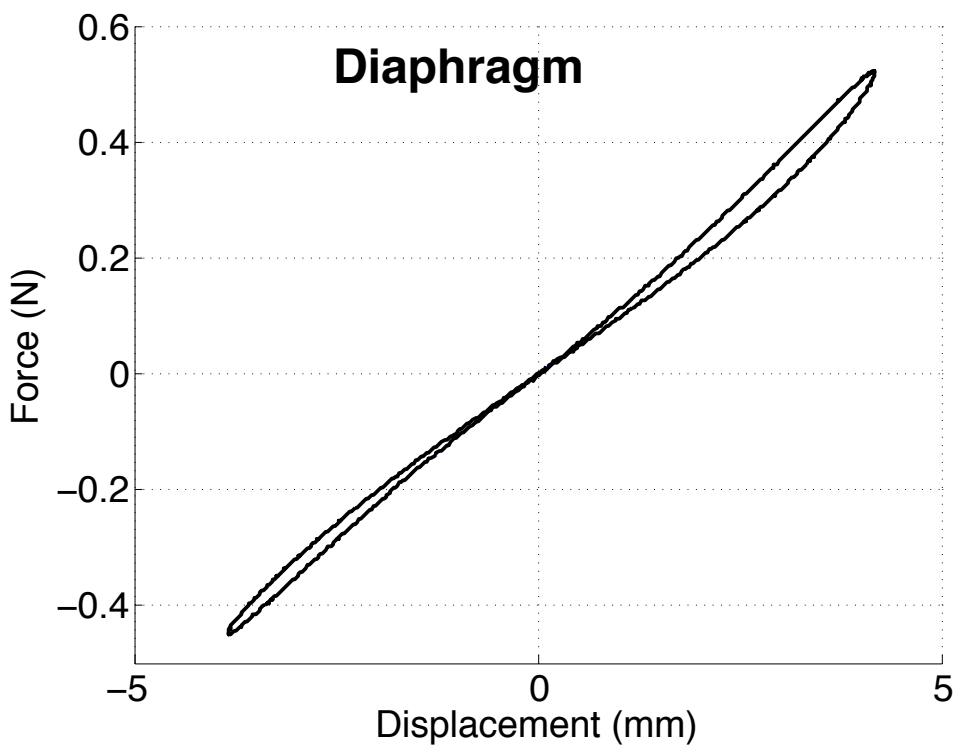
Model	Hooke	Neo-Hookean	Mooney-Rivlin	Ogden
Strain	0.10	0.40	1.4	3.0+

Tunable Stiffness

Physical Module

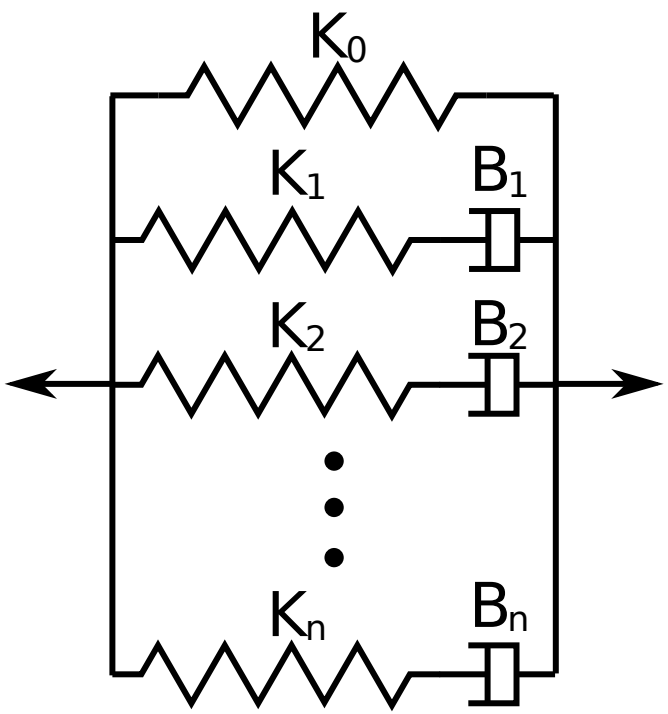






Modeling

Quasi-Linear Viscoelastic (QLV) Model



$$\sigma(t) = \sigma_\infty + \sum_{i=1}^{n} \sigma_i(t)$$

$$\sigma_i(t) = C_i e^{(-\frac{t}{\tau_i})}$$

$$\frac{\mathbf{F}}{\mathbf{X}} = k_0 + \sum_{i=1}^{n} \frac{k_i s}{s + \frac{k_i}{b_i}}$$

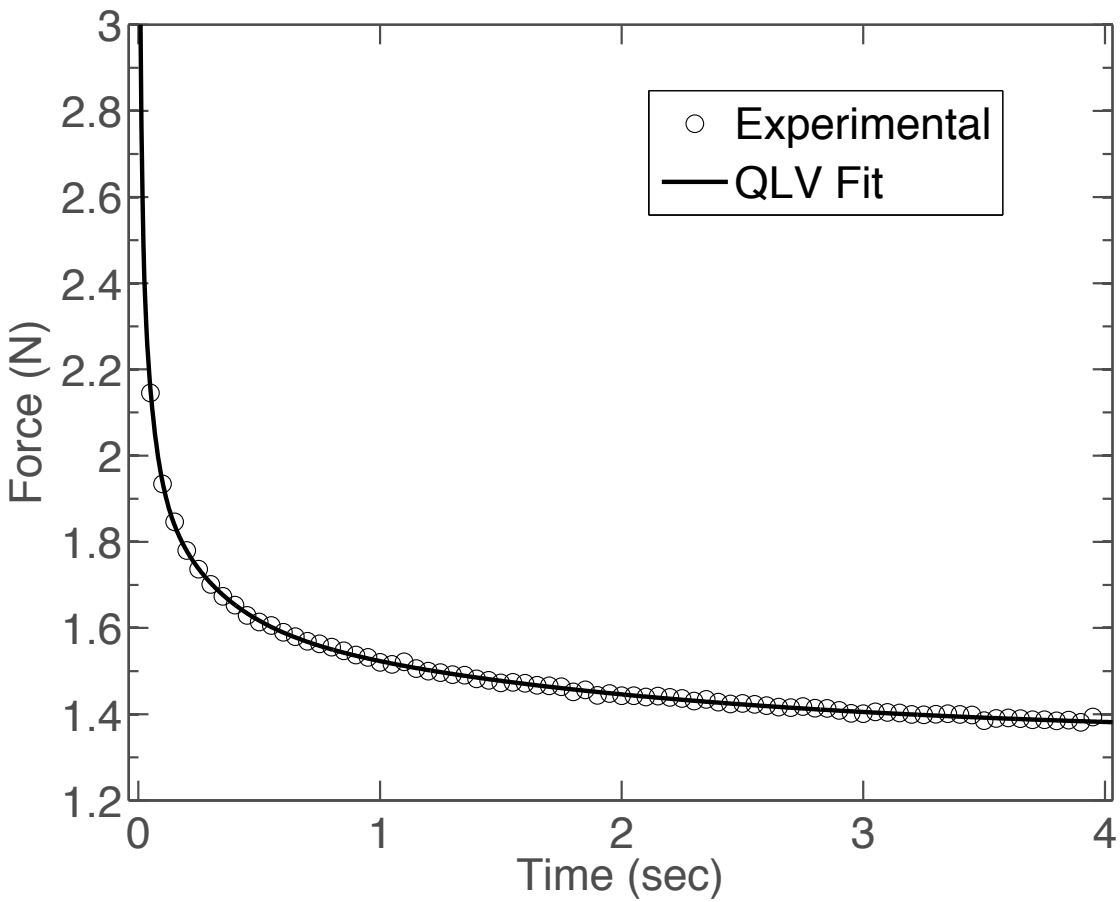
Fung 1972

Captures viscoelastic effects
Linear time-invariant transfer function

Modeling

Quasi-Linear Viscoelastic (QLV) Model

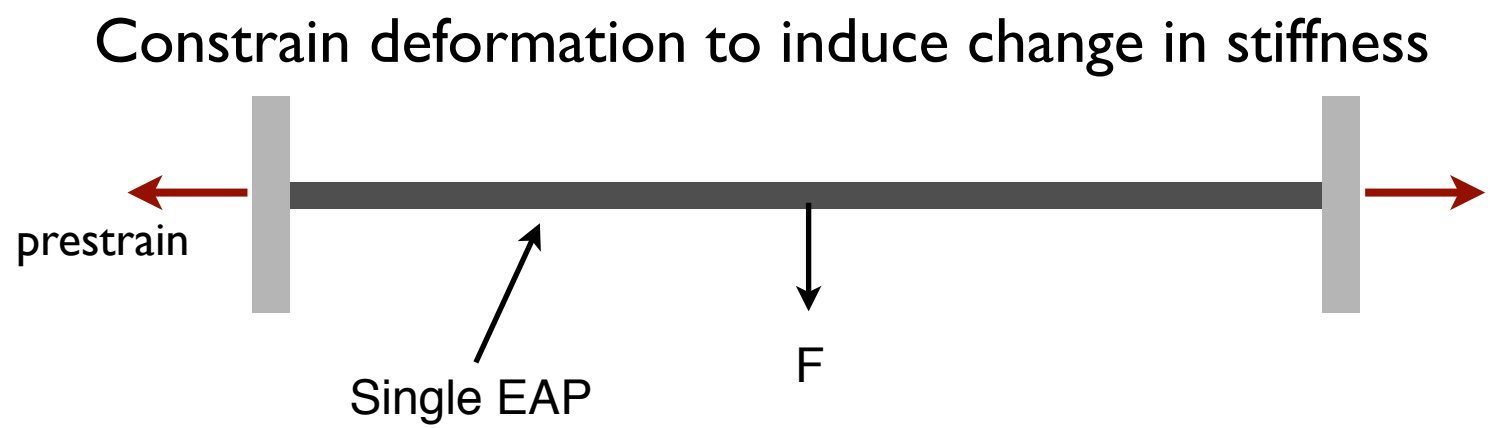
1. Relaxation test (Step input in displacement, measure force)
2. Fit sum of decaying exponentials + constant to force data
3. Measure goodness of fit
4. Repeat for increasing *n* until good fit

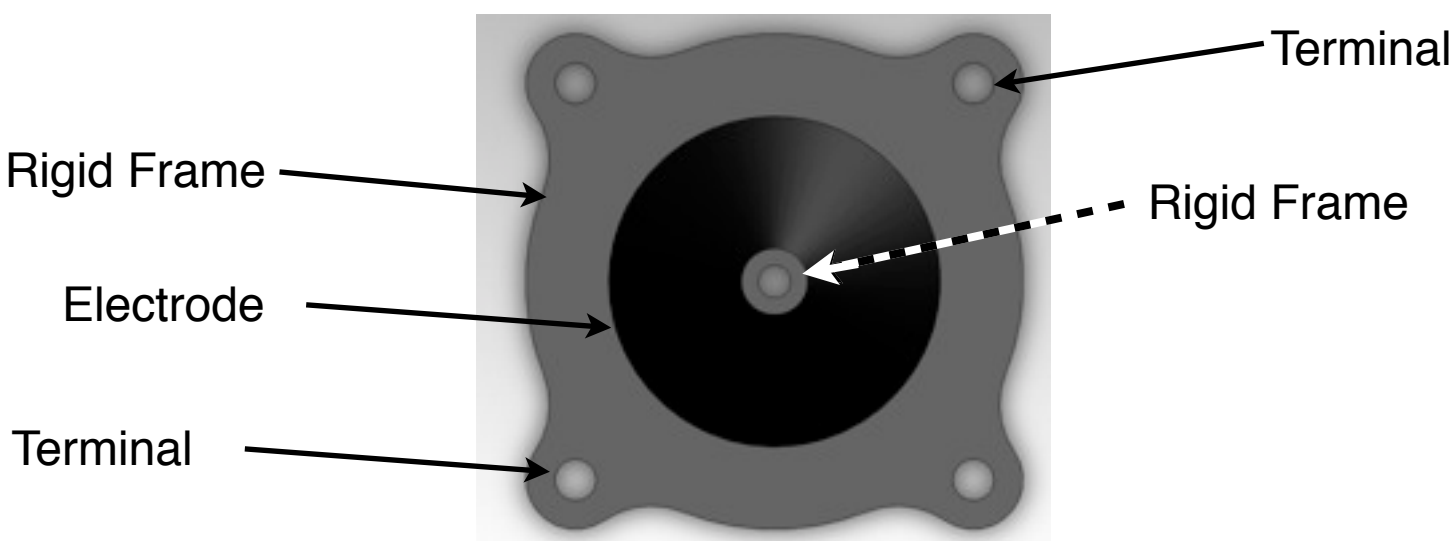


n	$R^2 value$
1	0.874
2	0.931
3	0.987
4	0.999

Tunable Stiffness

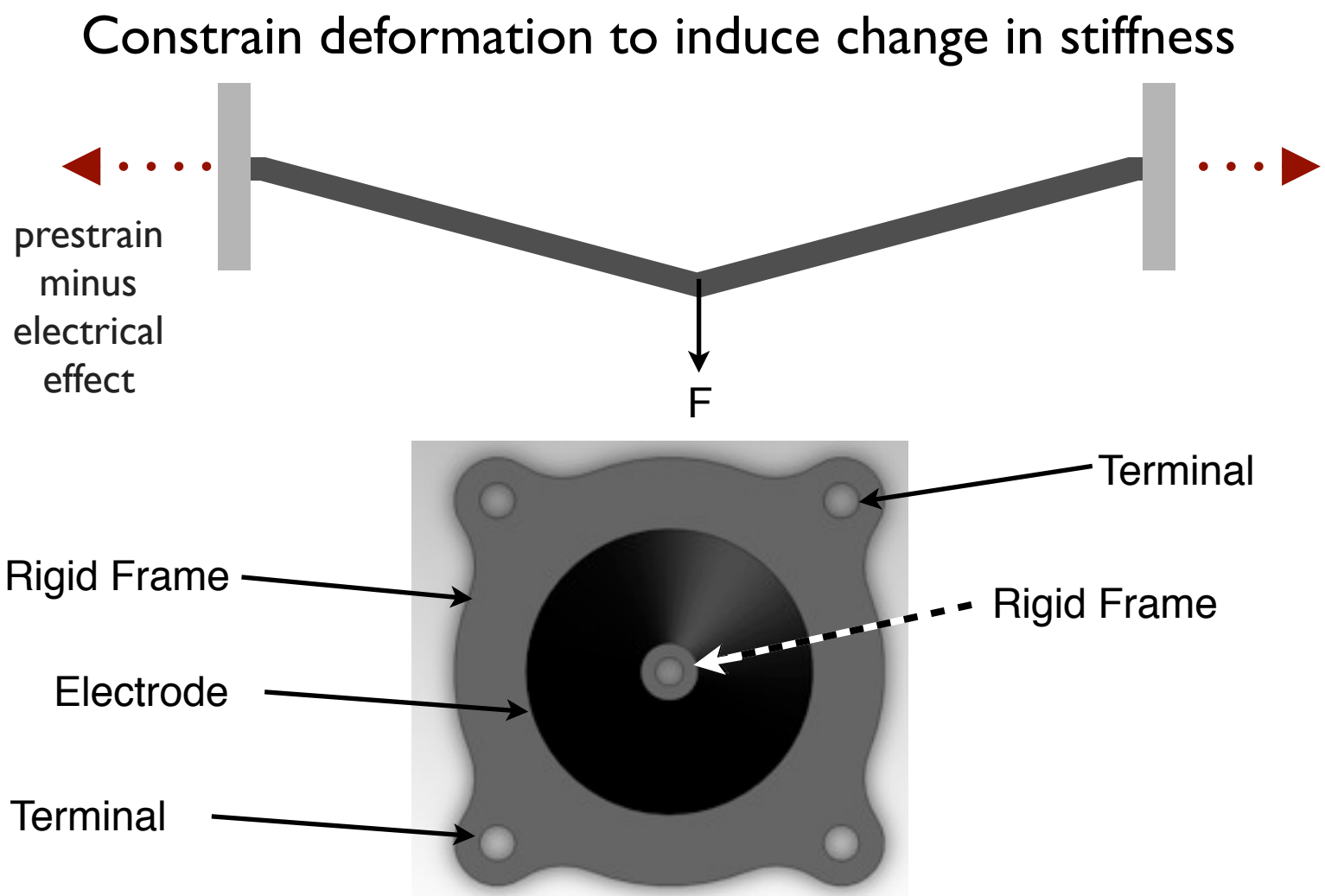
Principle of Operation





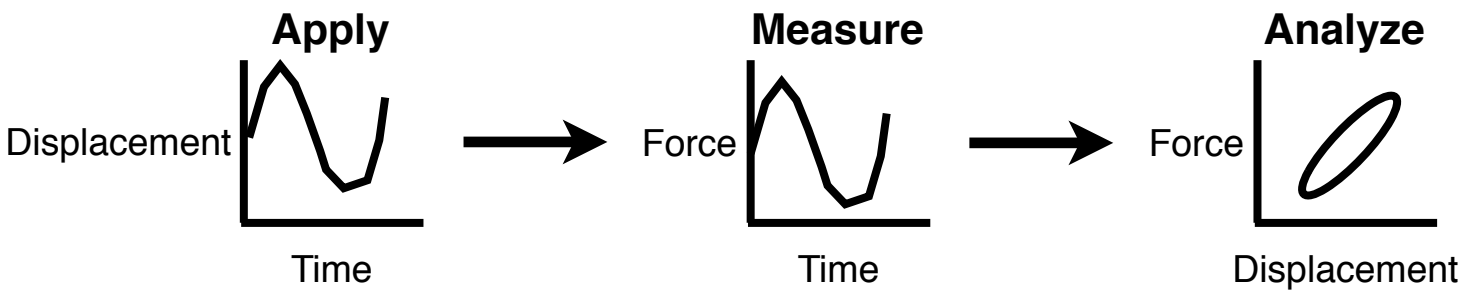
Tunable Stiffness

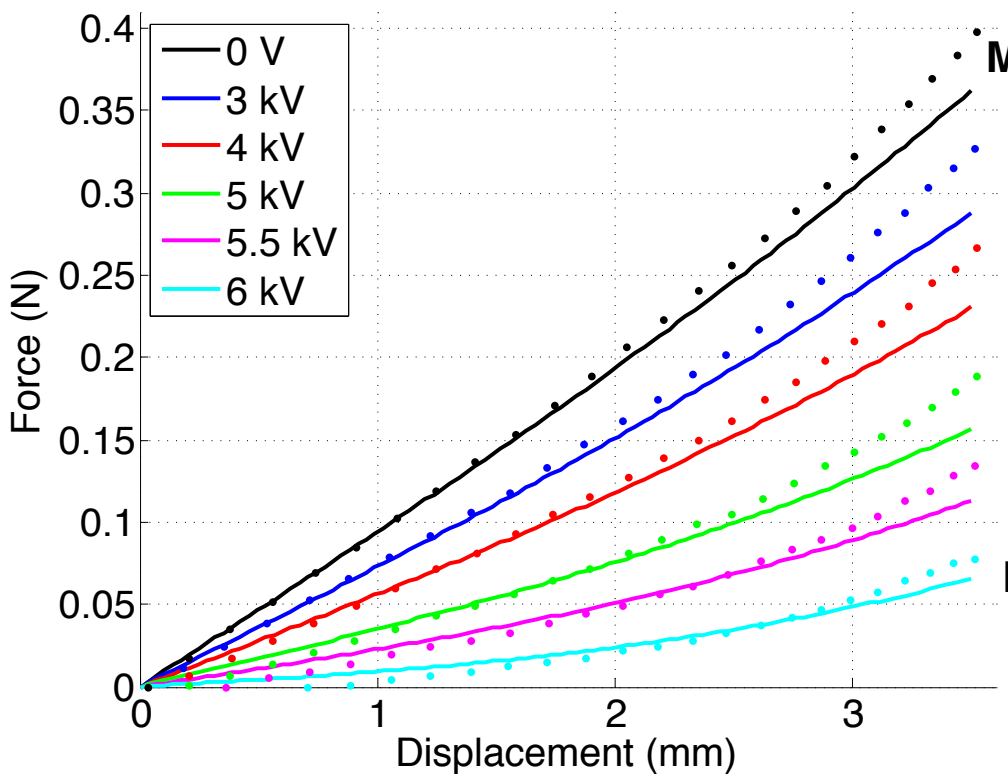
Principle of Operation



Tunable Stiffness

Stiffness Range



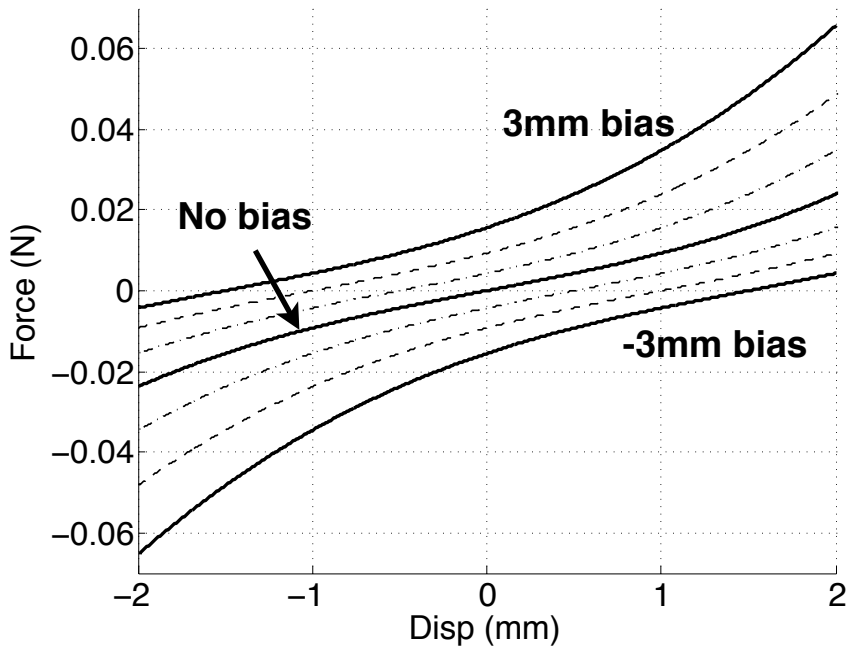


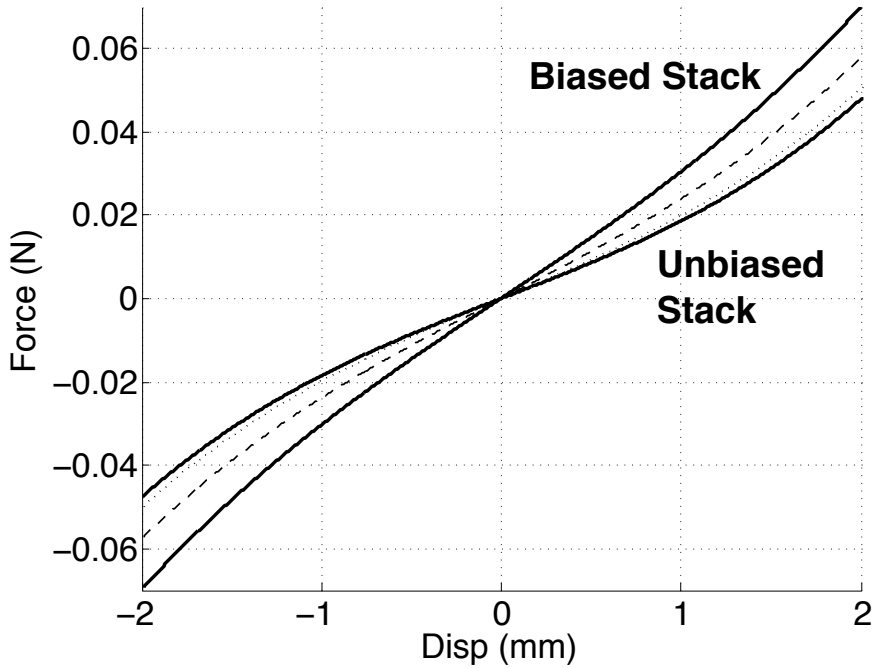
Maximum stiffness = 102 N/m

Minimum stiffness = 15 N/m

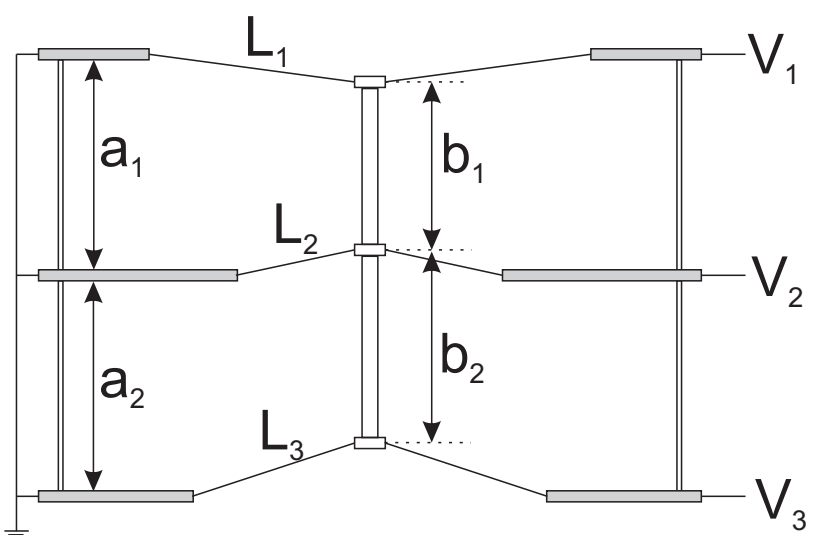
Tunable Stiffness

Linearization





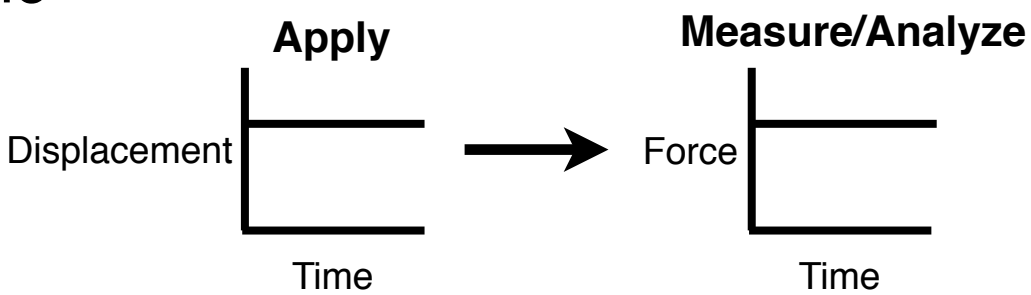
- Changing offset of inner ring spacing relative to outer ring spacing will bias films out-of-plane
- Combined (parallel) stiffness will be shifted and linearized as a result

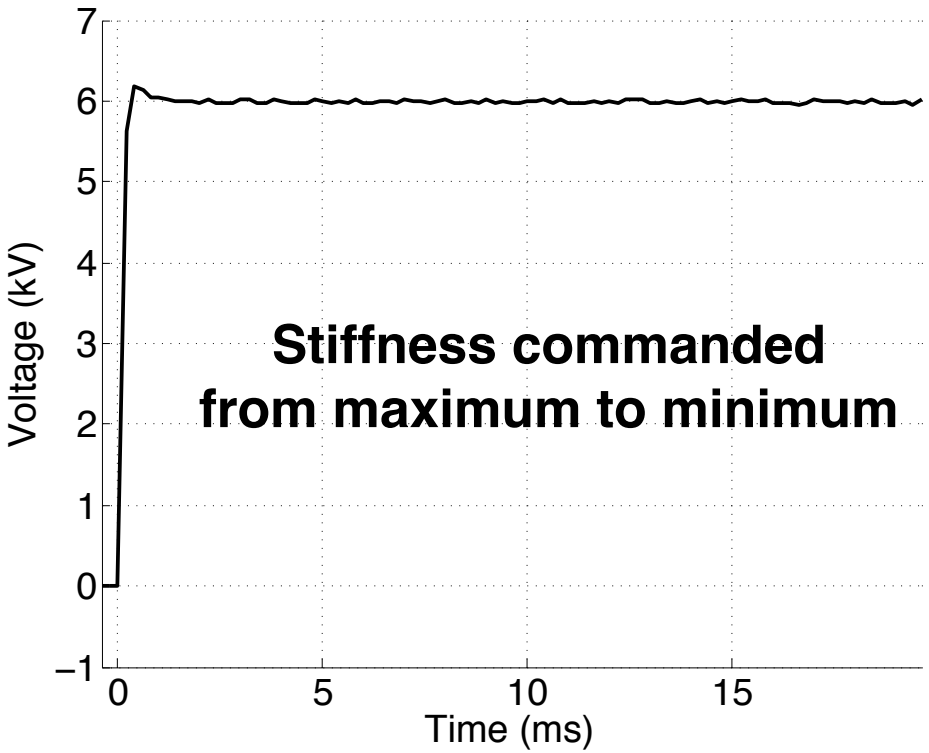


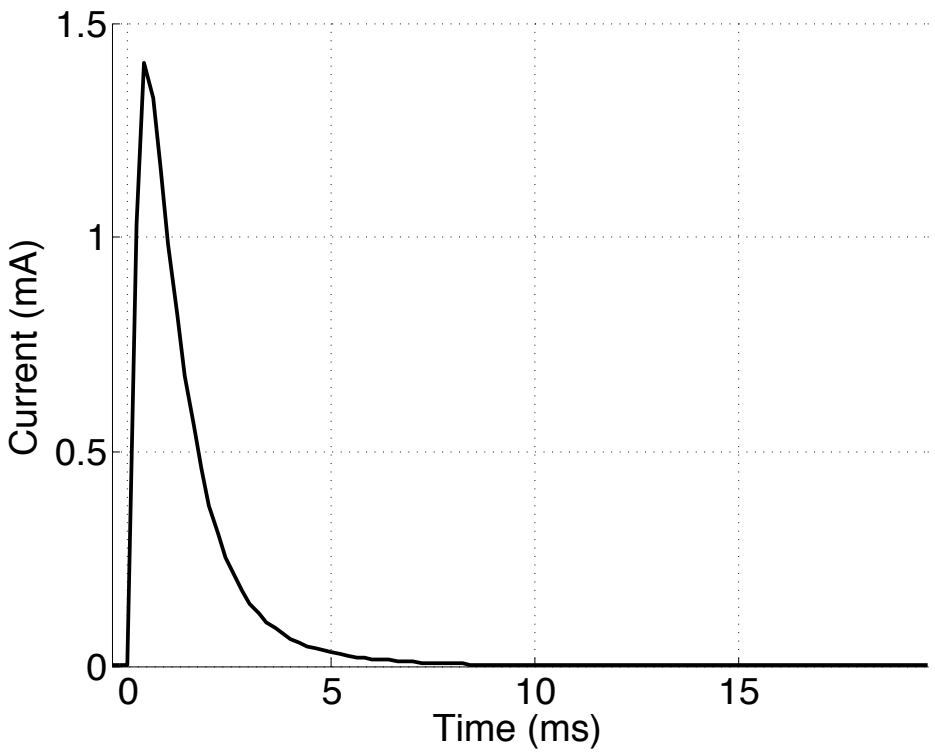
31

Tunable Stiffness

Response Time

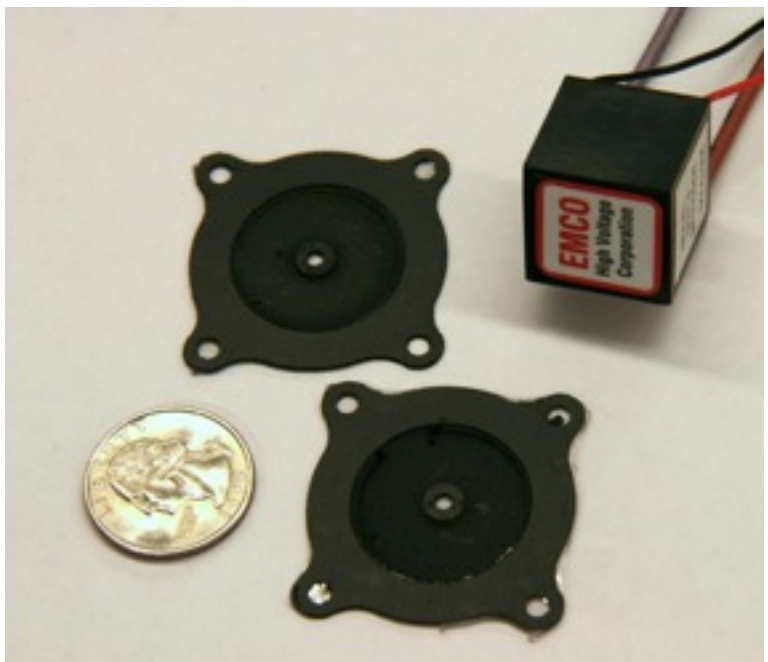




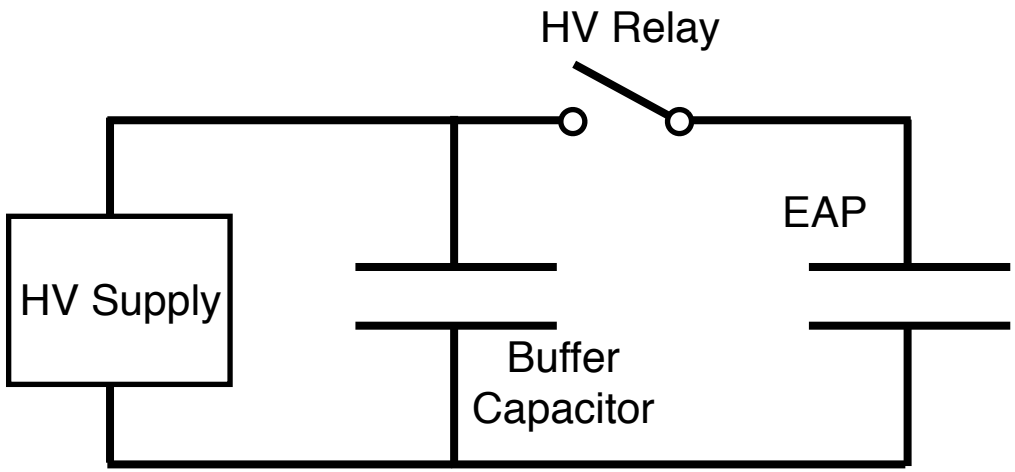


Tunable Stiffness

Response Time

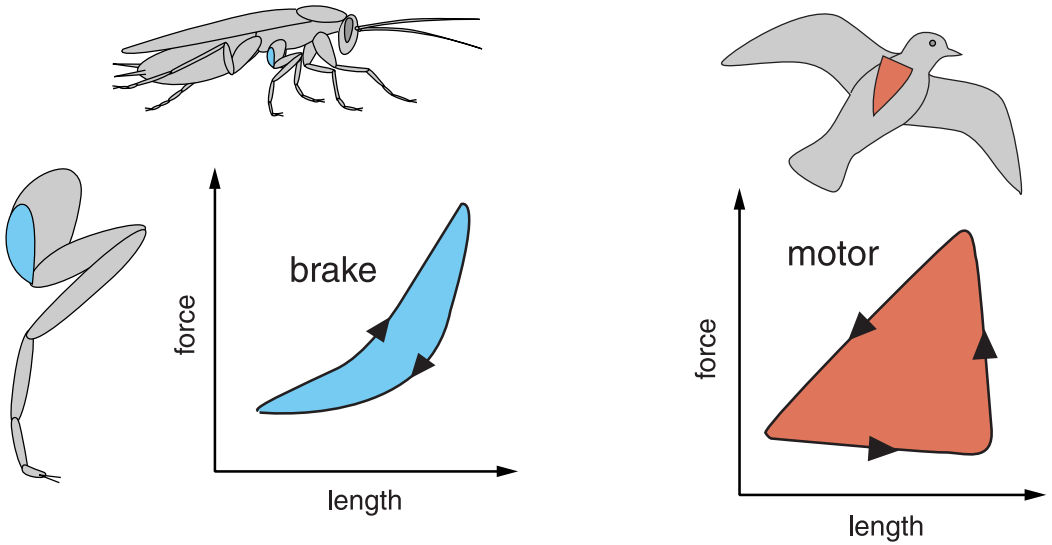


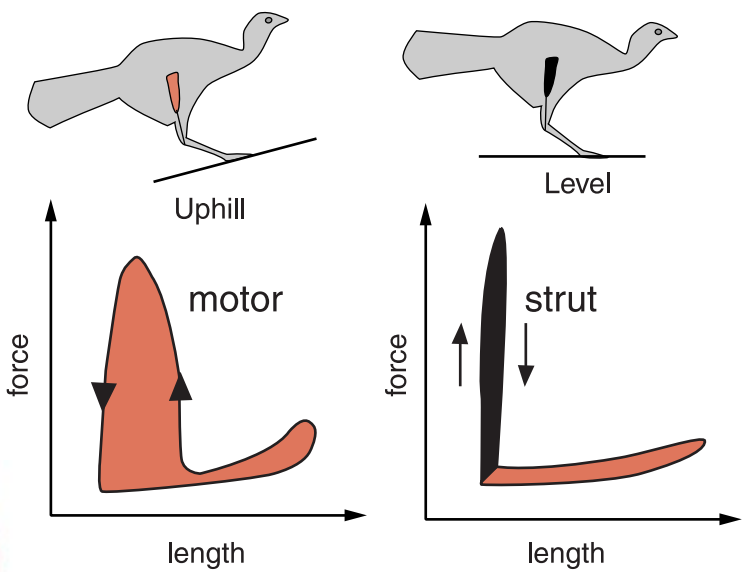
0.5W Power Supply
Input: 5VDC @ 250mA
Output: 6kV @ 50µA



Power Supply	Cont. Current (mA)	Peak Current (mA)
Trek 610B	2	2
Emco Q101	0.05	0.05
Buffered Q101	0.05	2000

Using variable stiffness in workloops





Dickinson et al., *Science*, 2000

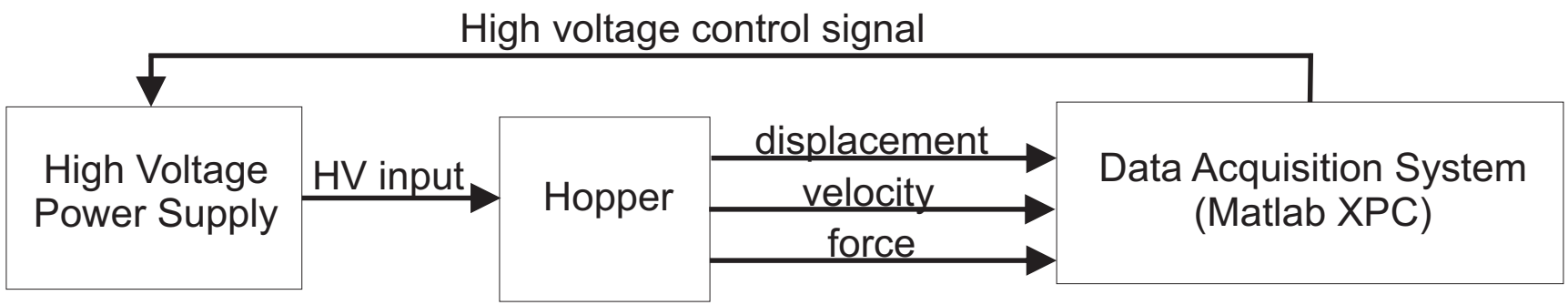
Animals use muscles as motors, brakes and springs,

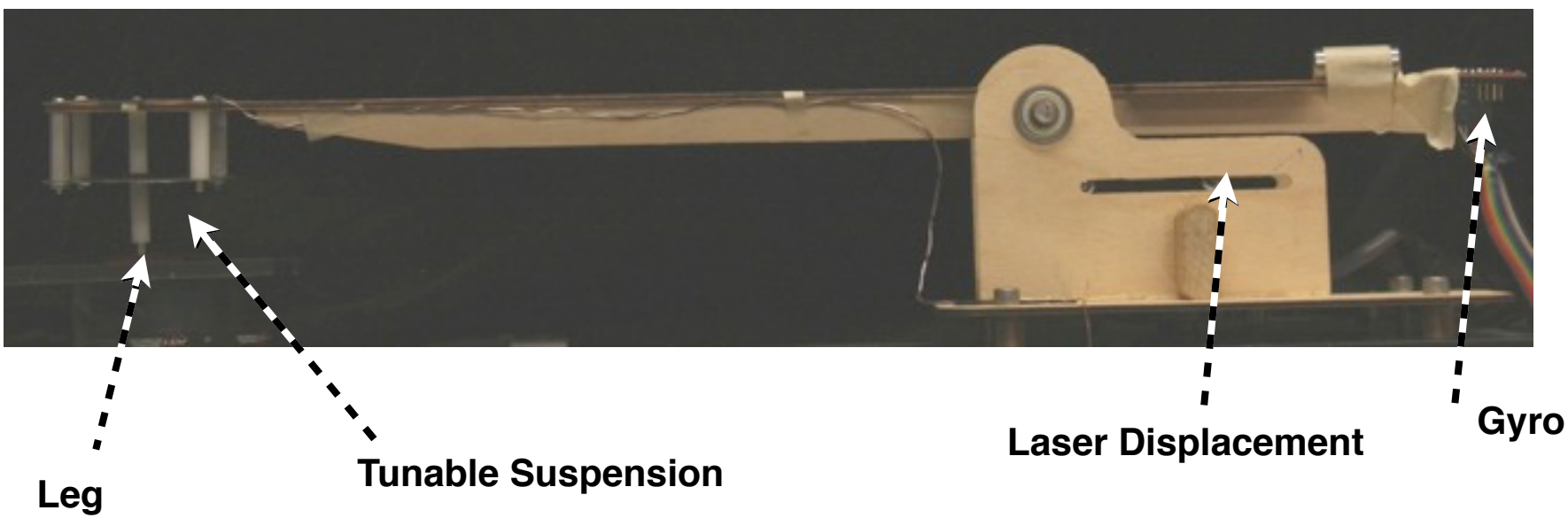
adding, removing or storing energy, depending on how stiffness is varied at different points in a work cycle.

We have the same opportunity, with an ability to vary stiffness by up to 10x in <5ms.

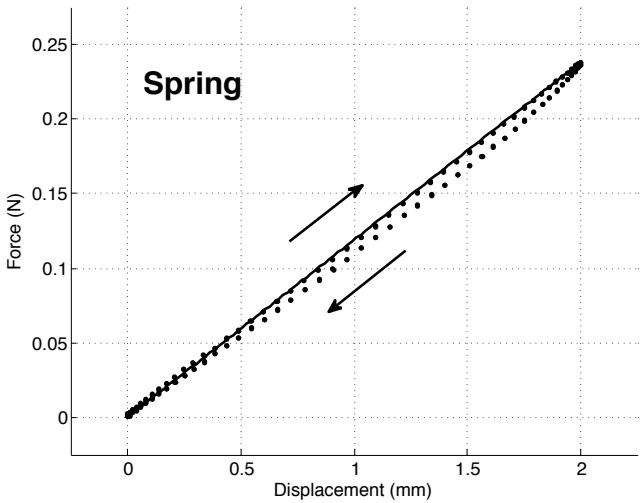
Applications to Tunable Dynamics

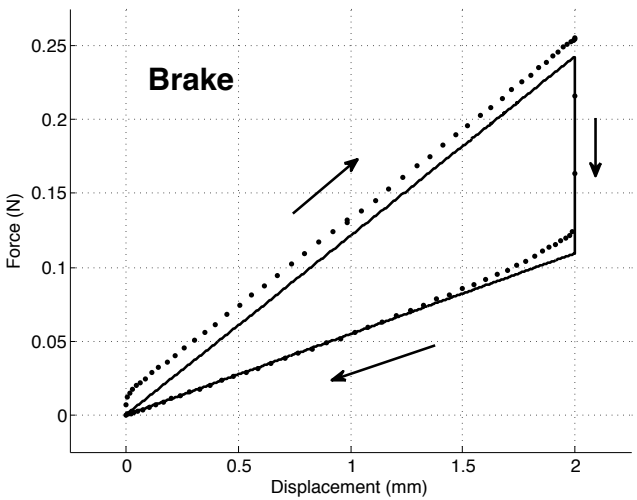
Experimental Hopper

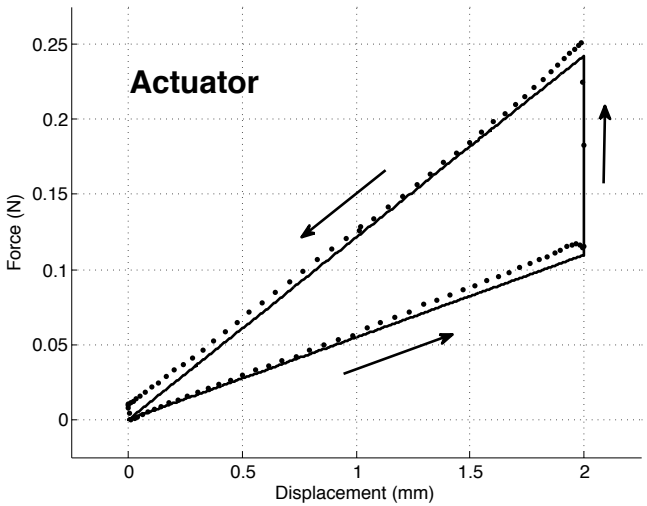




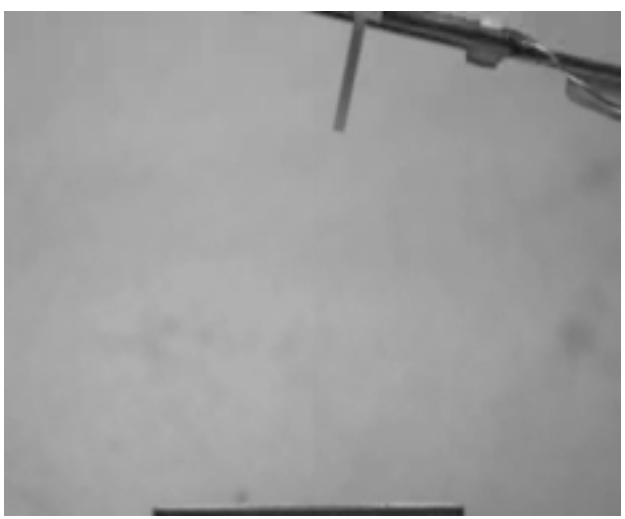
Application to a hopping platform

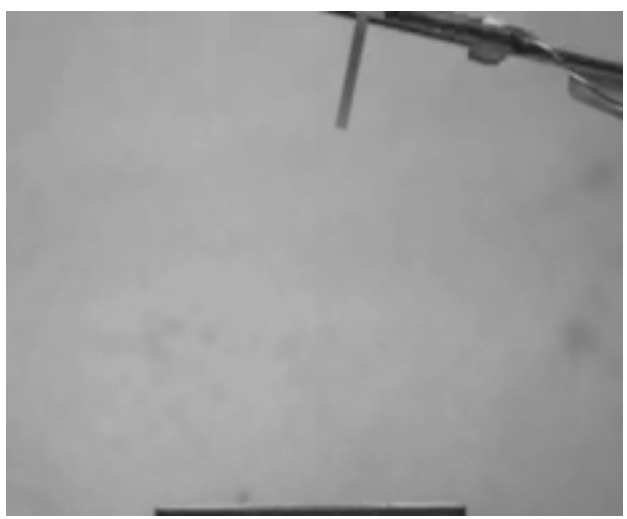


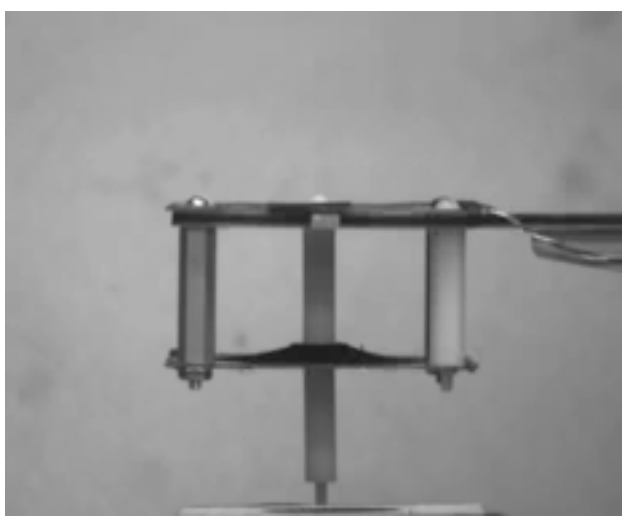




Slowed to 0.12x





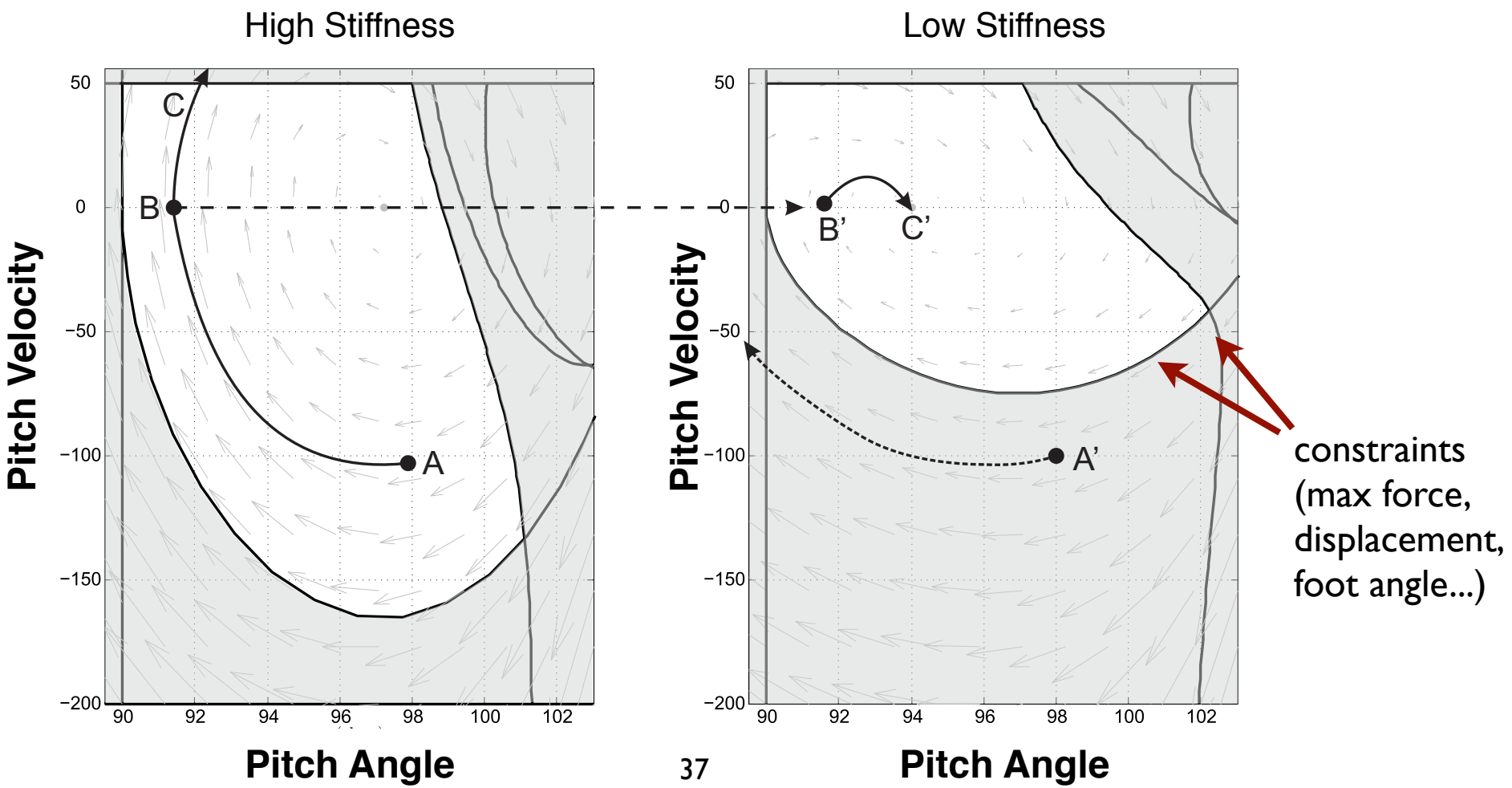


Applications to Transient Dynamics

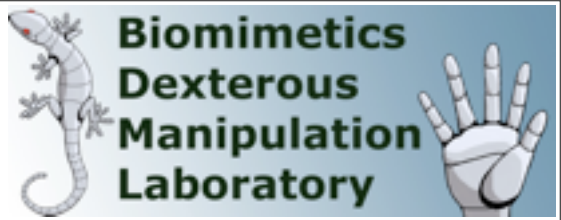
Motivation

A' leads to failure.
A to B to C leads to failure.
A to B, switch stiffness to B', to C' leads to success.

with Alexis Lussier-Desbiens (SU), and R. Tedrake (MIT) - ICRA2012



Conclusions



Electroactive polymers are well suited for use in dynamically variable suspensions in small, light robots:

- low weight
- low power consumption
- fast response
- augment useful passive properties via control

Batch manufacturing of modular units provides acceptable yield & durability.

A particularly interesting application is landing from jumps and glides.

Thanks to ARL Robotics CTA and Bio-X fellowship for support.