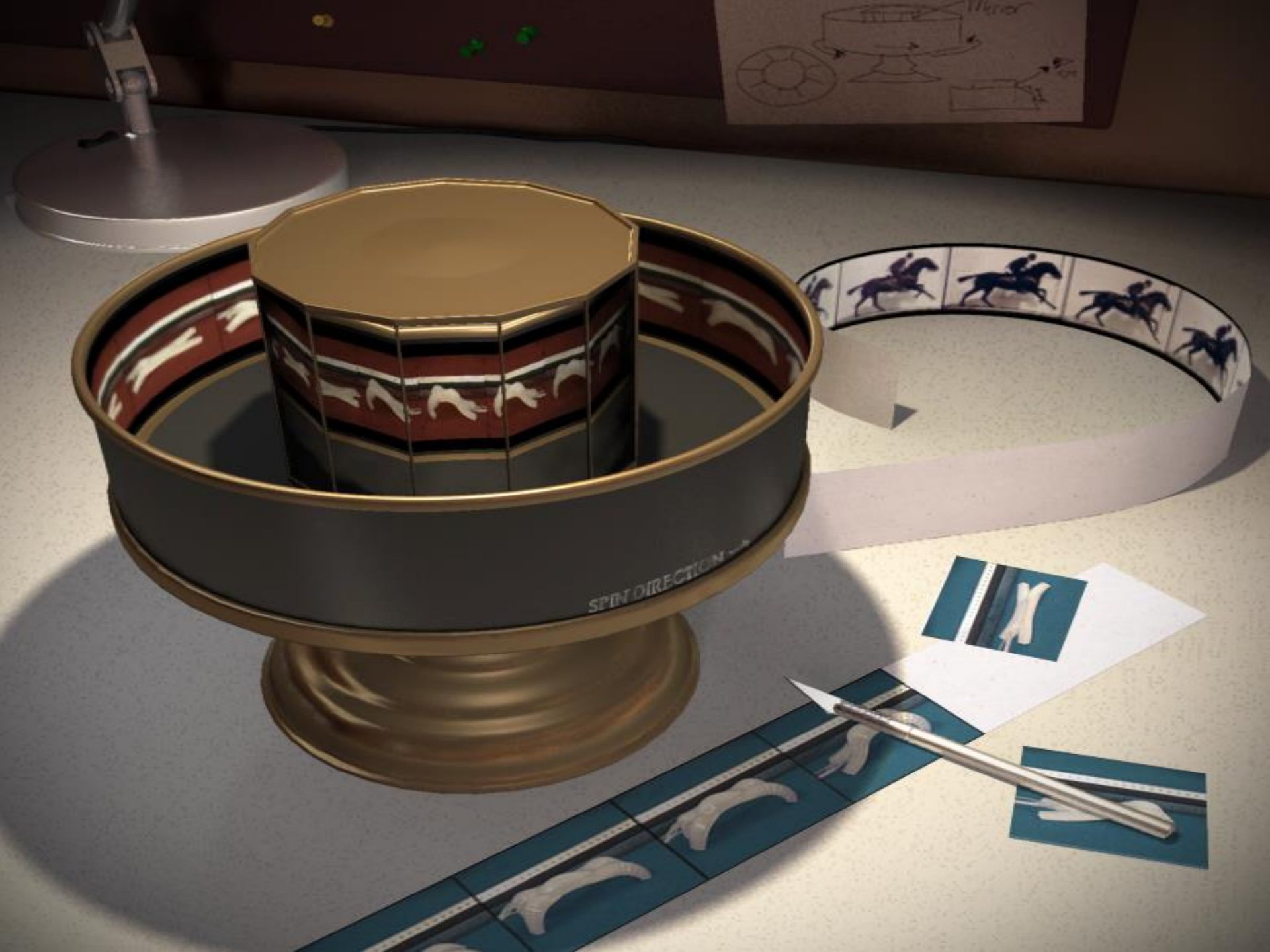
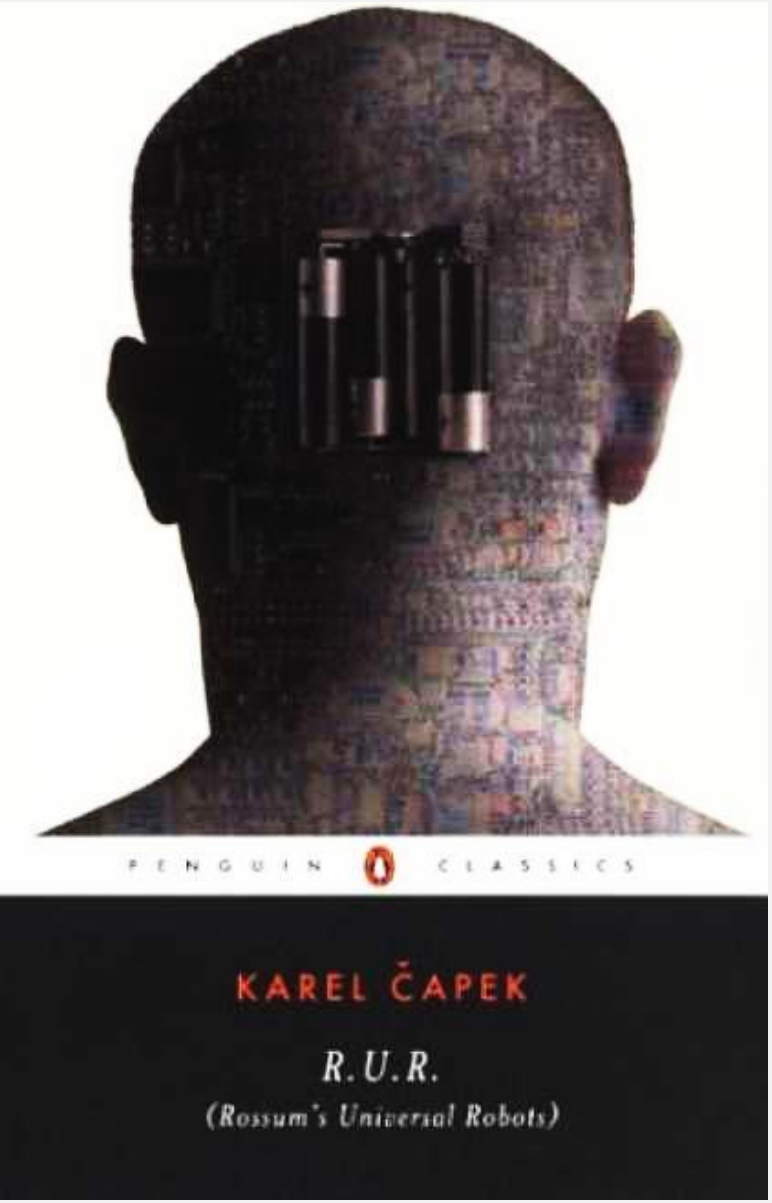

SPIN DIRECTION

Soft Robotics – Actuator Design and Manufacturing

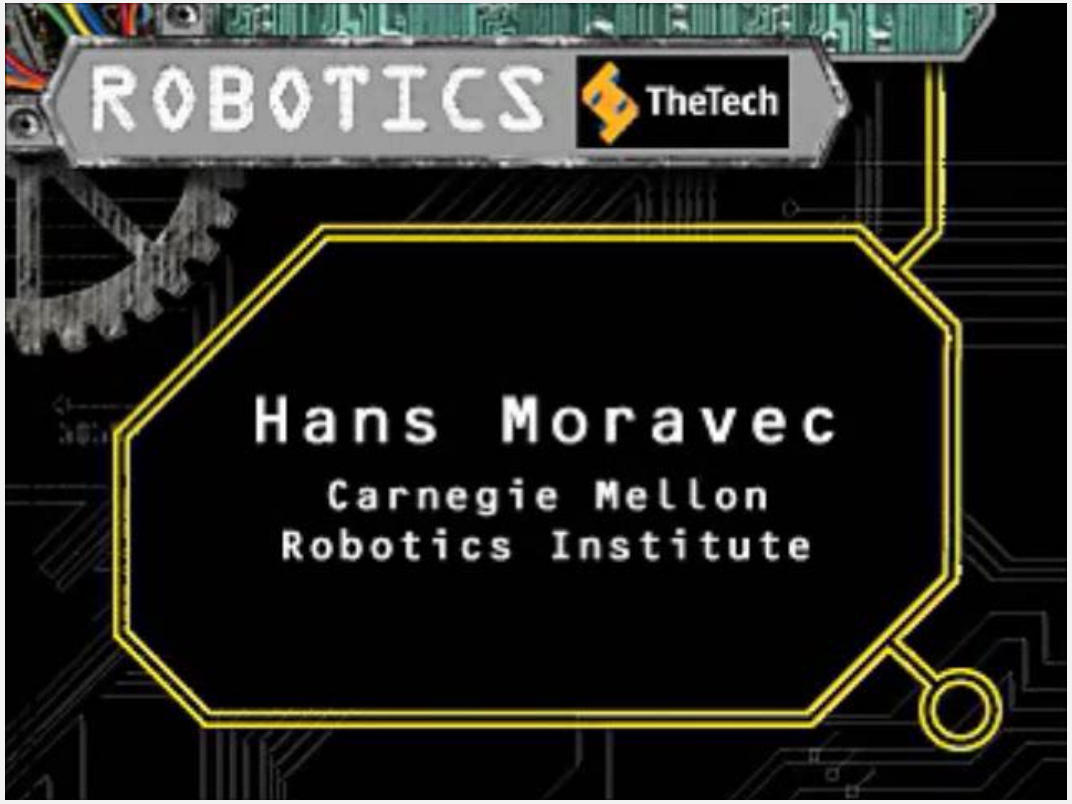
Robert F Shepherd
Cornell University

Mechanical Engineering
Material Science
Systems Engineering

What is a robot?



Etymology: The word “robota” in Czech means drudgery, or slave labor. The robots in R.U.R. were actually grown from a sludge – or synthesized!



A robotocists’s definition: “a robot is a machine that acts like an animal: that can sense the world and physically act in it…”

“Hard” Robot state of the art

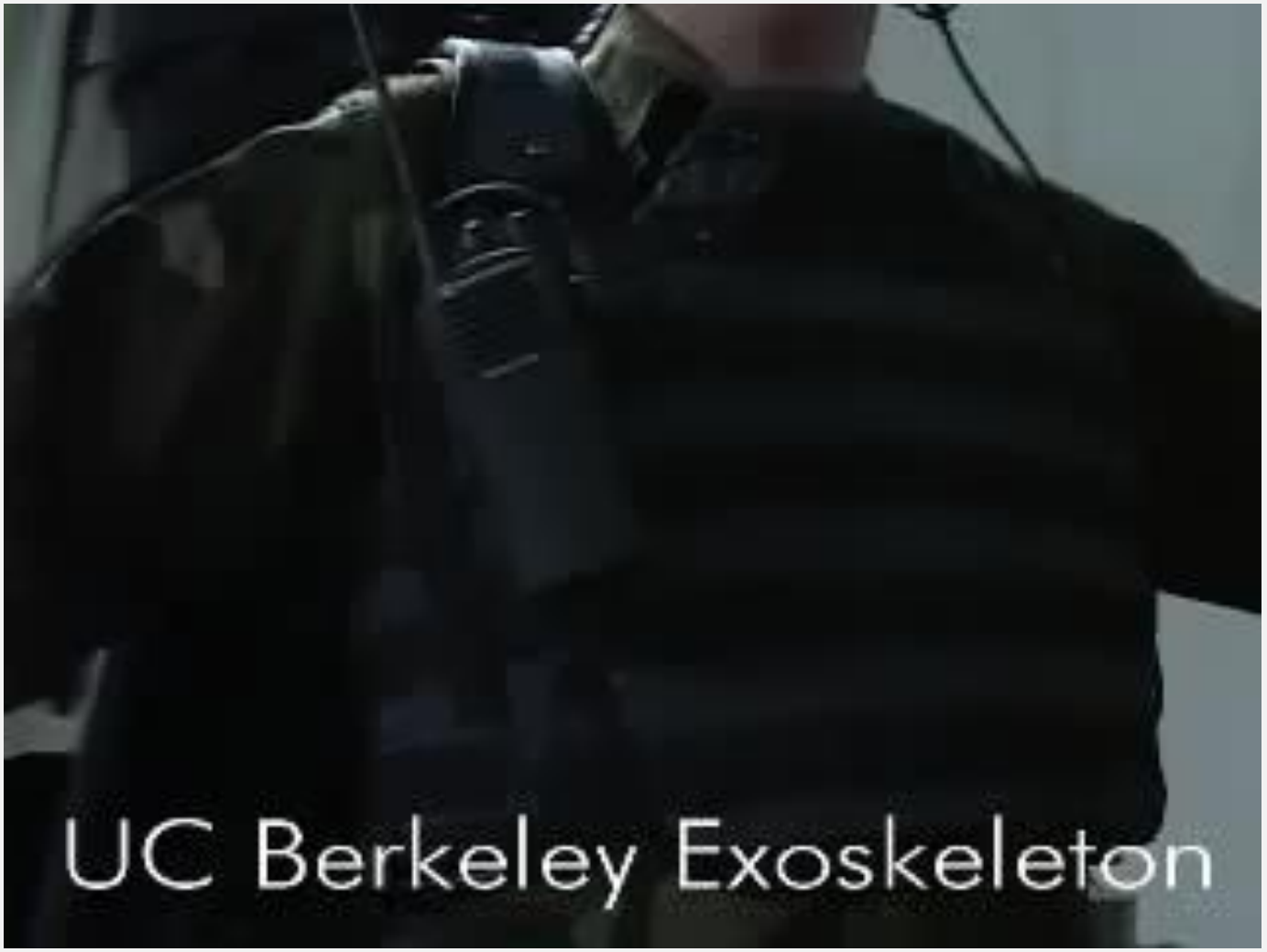
Hard robot manipulators

Examples of multiple end effectors

These robots are “Fully Actuated”: DOF is equal to the # of actuators

Underactuated systems

Berkeley lower extremity exoskeleton (BLEEX), H. Kazerooni



Lower # of actuators than degrees of freedom

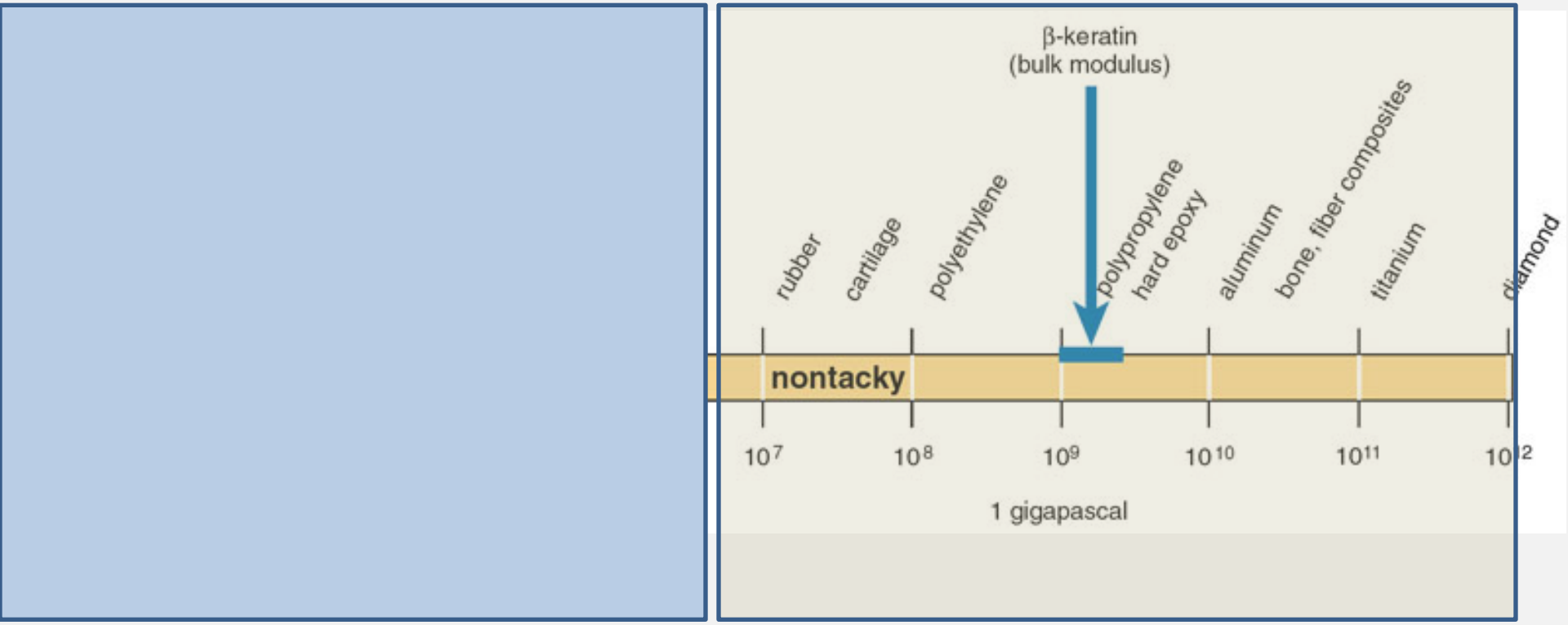
Nature’s state of the art

Adaptable, underactuated system with “infinite degrees of freedom” and sensory feedback loops

A brief survey of soft robots

What do we mean by ‘soft’ ?

Elastic modulus, E, spectrum of materials

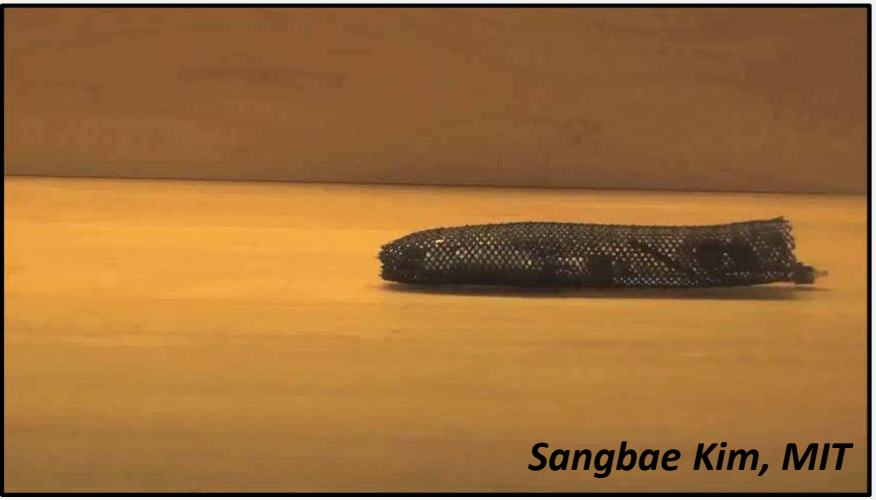


Soft via intrinsic material properties

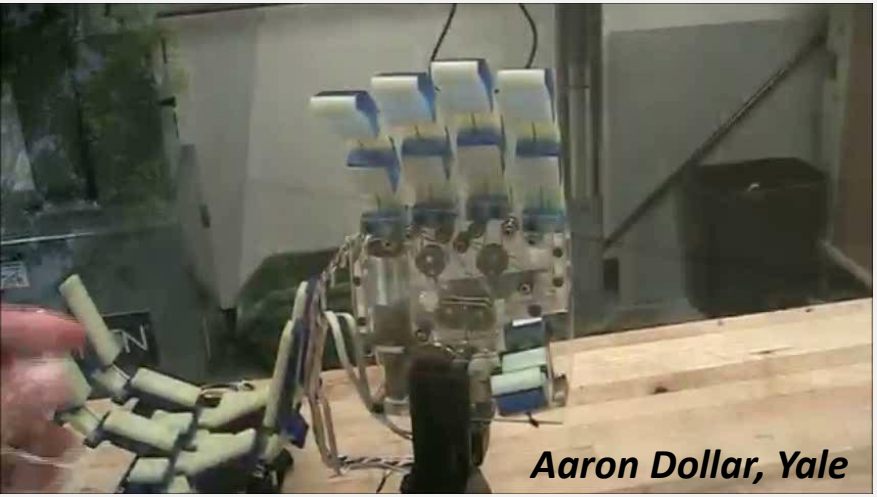
Soft via extrinsic mechanical design

Soft machines from high E material

shape memory alloys



thin plastic, ‘living hinges’



metal windings/multiple linkages

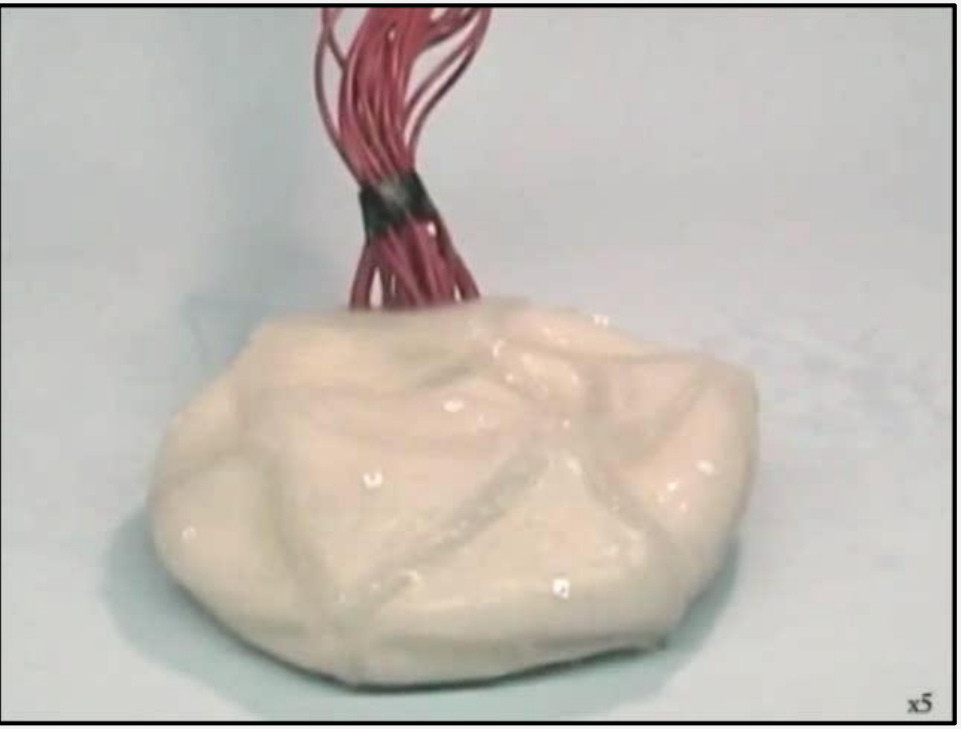
‘Soft’ is an extrinisic property, depending on robot’s architecture; Even metal actuators can be “soft”; relative to object/actuator interaction

Pneumatically actuated fabrics

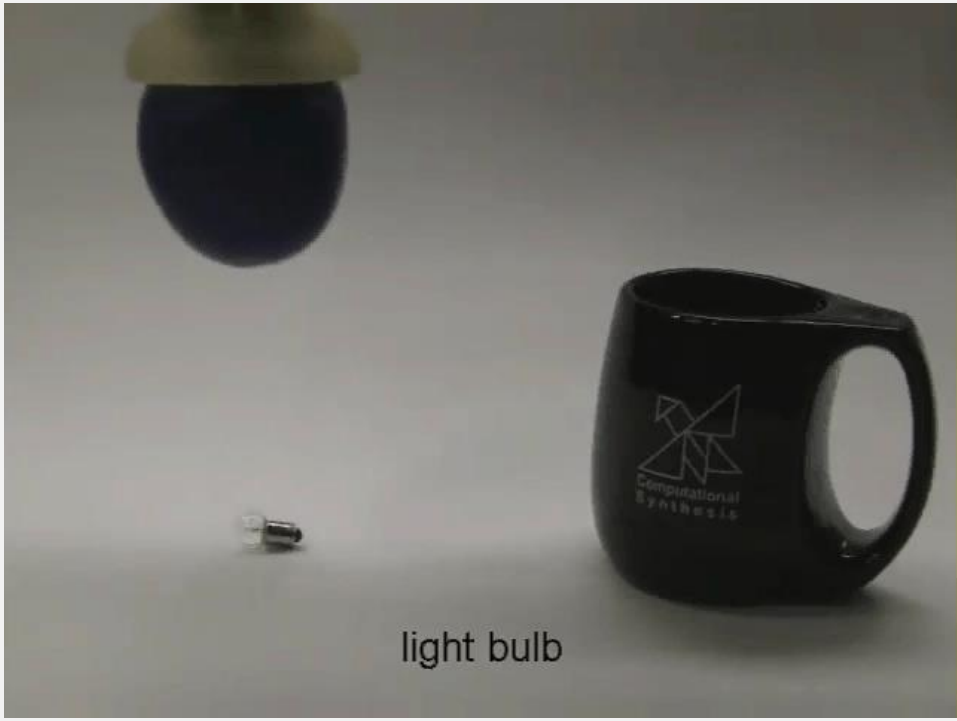
Otherlabs, Inc.

Limited range of motion, but very high strength:weight ratio

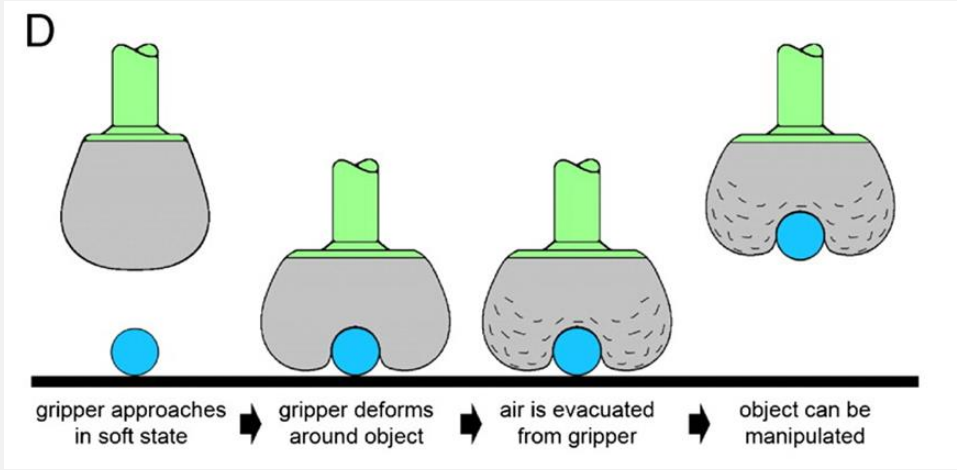
Pneumatically actuated granular media



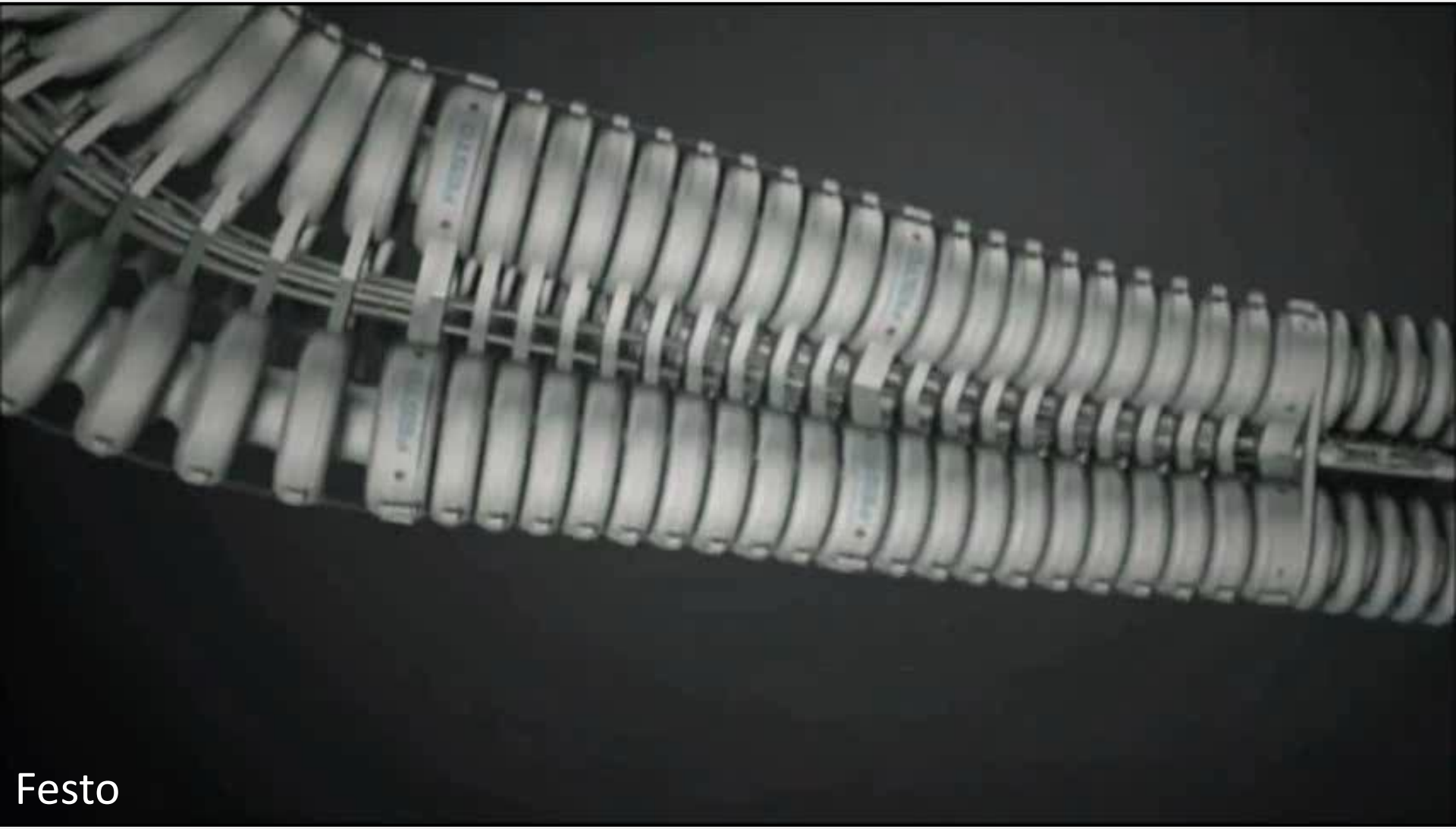
*iRobot



*Lipson/Jaeger, PNAS (2010)



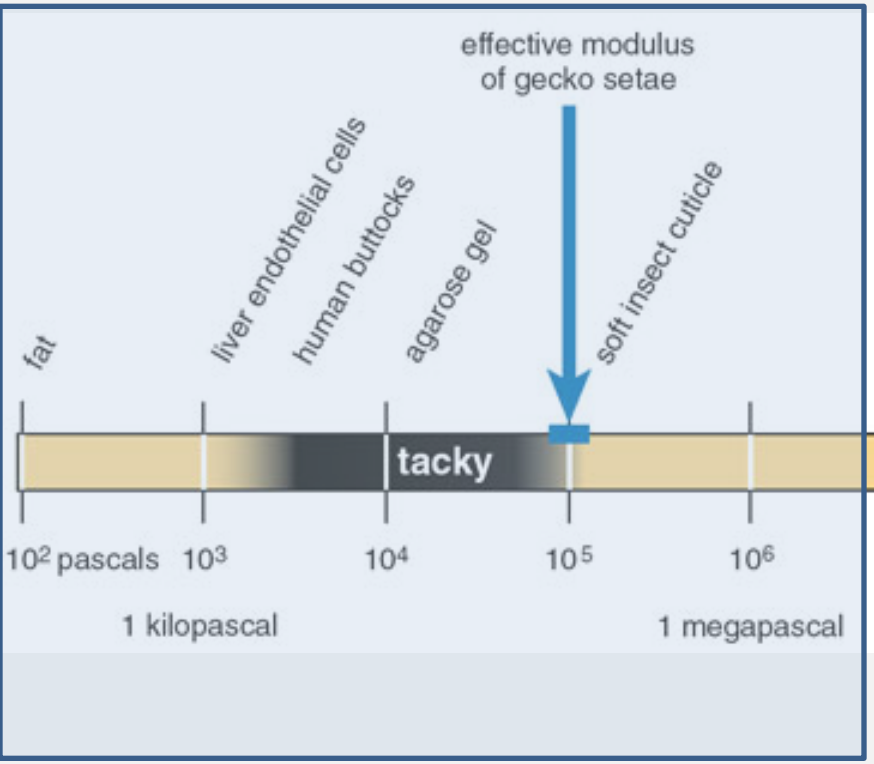
Bellows actuator



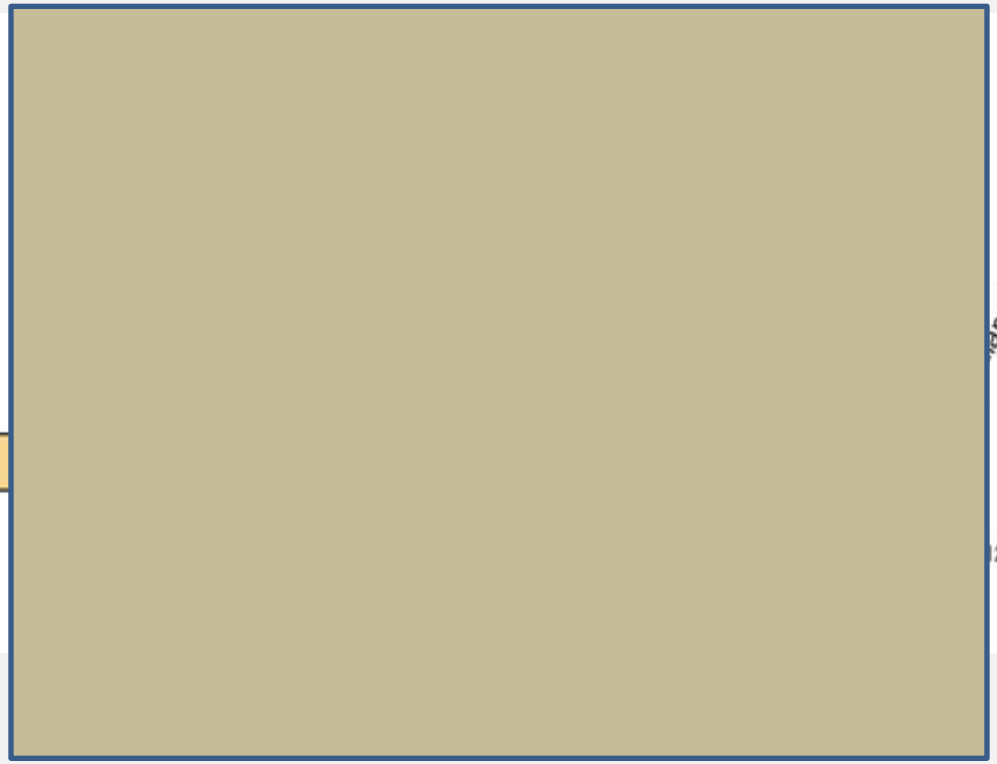
So much surface area, not much strain required for large amplitude actuation; end effector concept here: gripper is not actuator

What do we mean by ‘soft’ ?

Elastic modulus, E, spectrum of materials

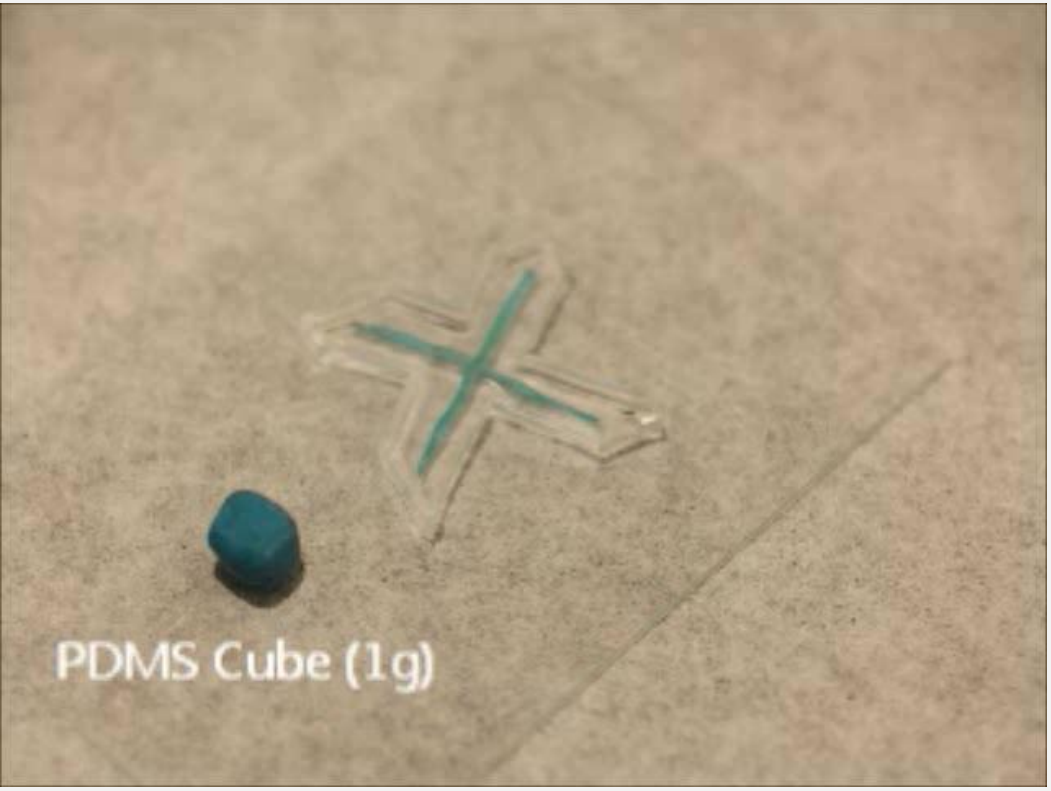


Soft via intrinsic material properties

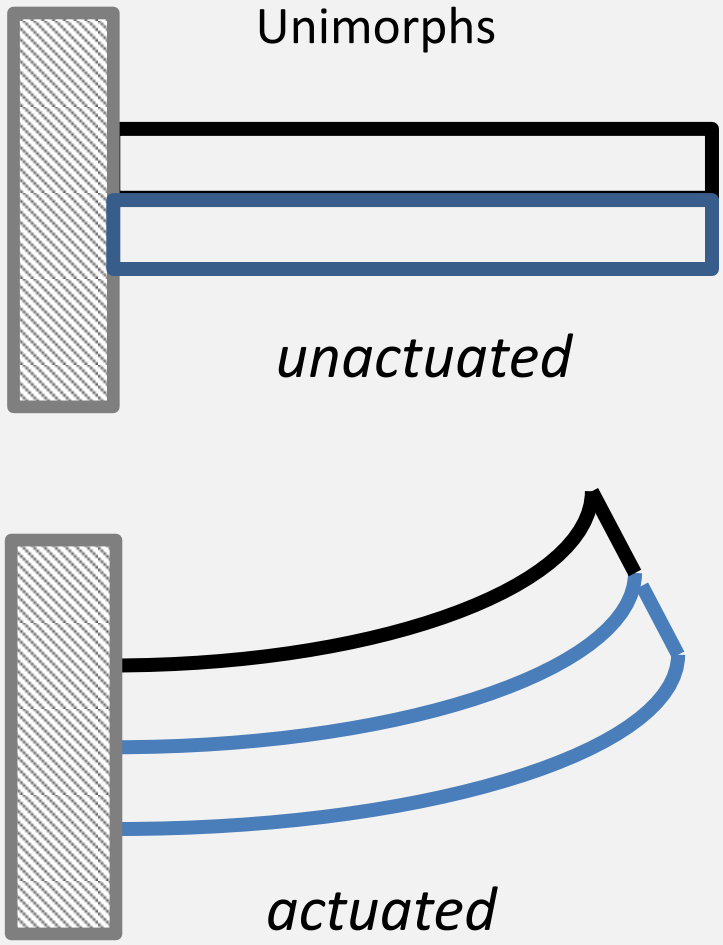


Soft via extrinsic mechanical design

Hydrogel based unimorph actuators



*Palleau E. and Velev O., in review



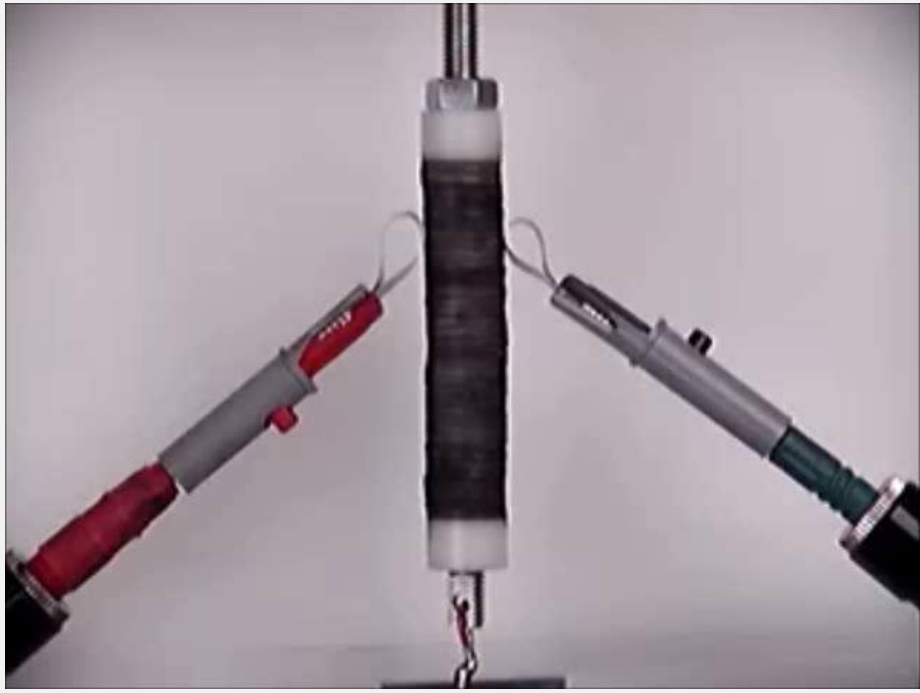
hydrogel based actuators: pH swelling, thermoresponsive, ionic complexation.
Infinite degrees of freedom, compliant – require mass transport through channels - SLOW

Soft, linear actuators

McKibben, pneumatic

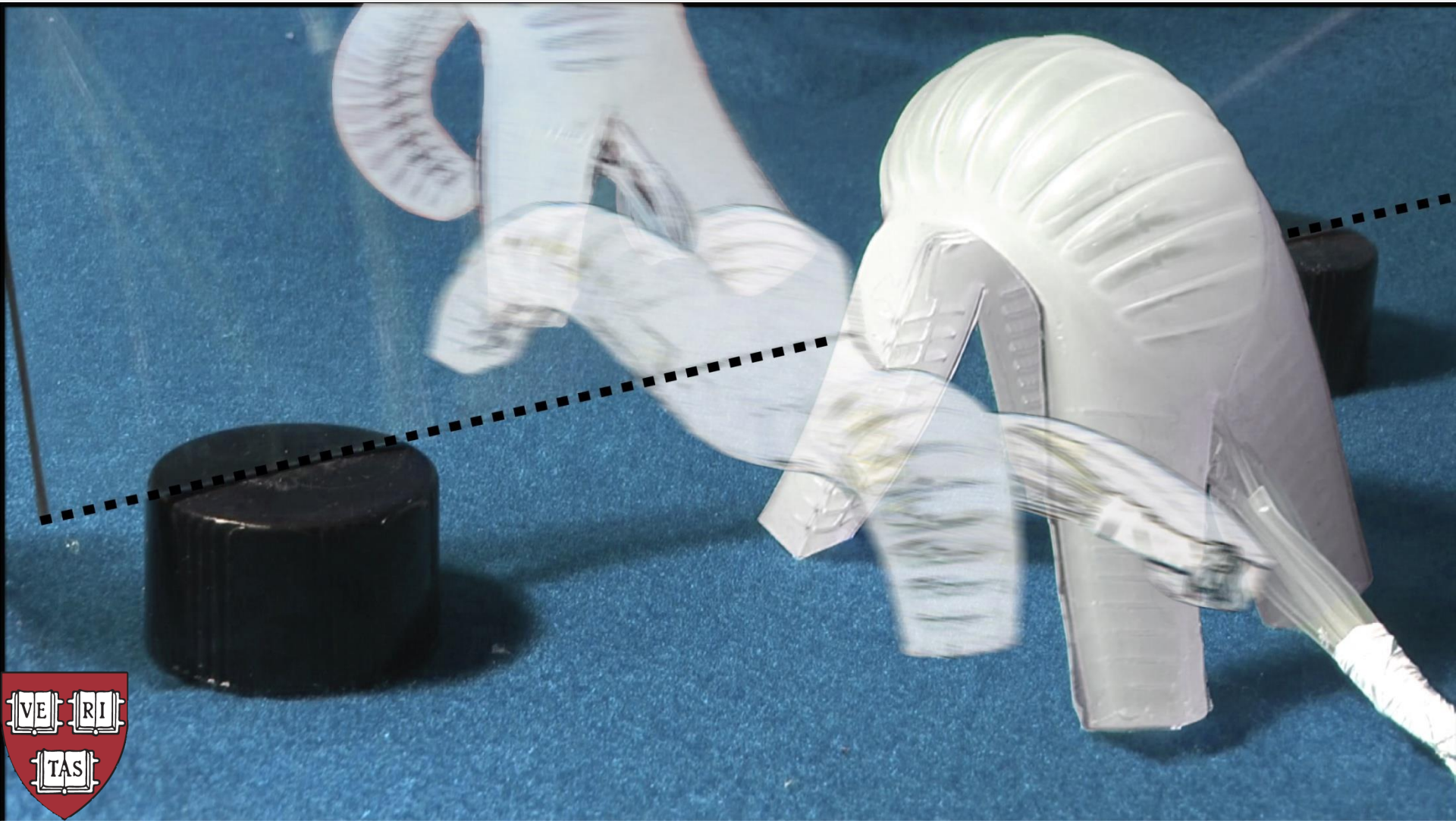
*Festo, Inc.

EAP, maxwell stress

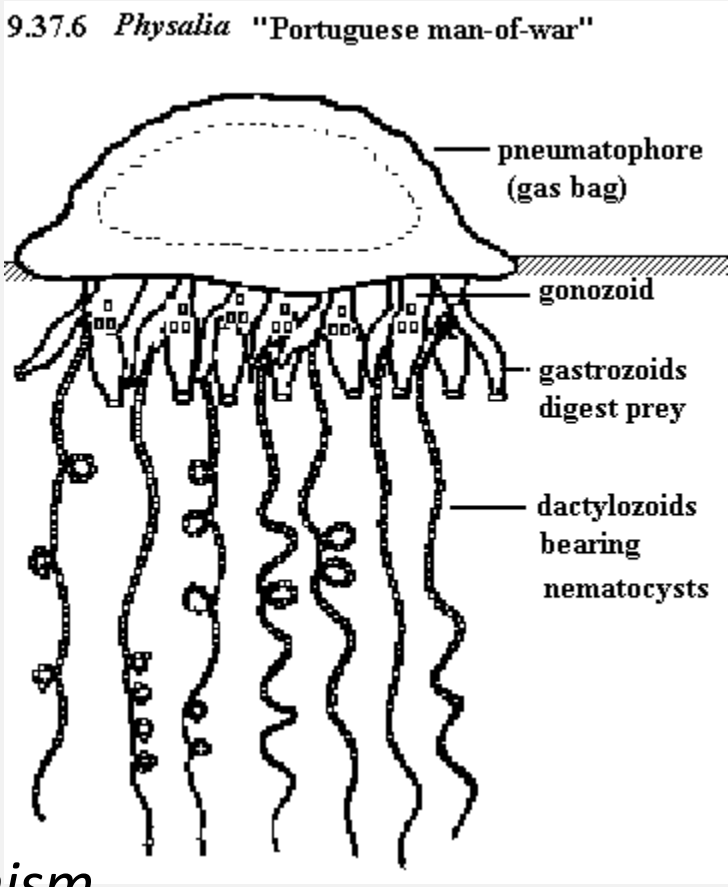


EMPA

A platform for material engineering in robotics



Biological analog – Portuguese Man of War



A pneumatically actuated, soft colonial organism

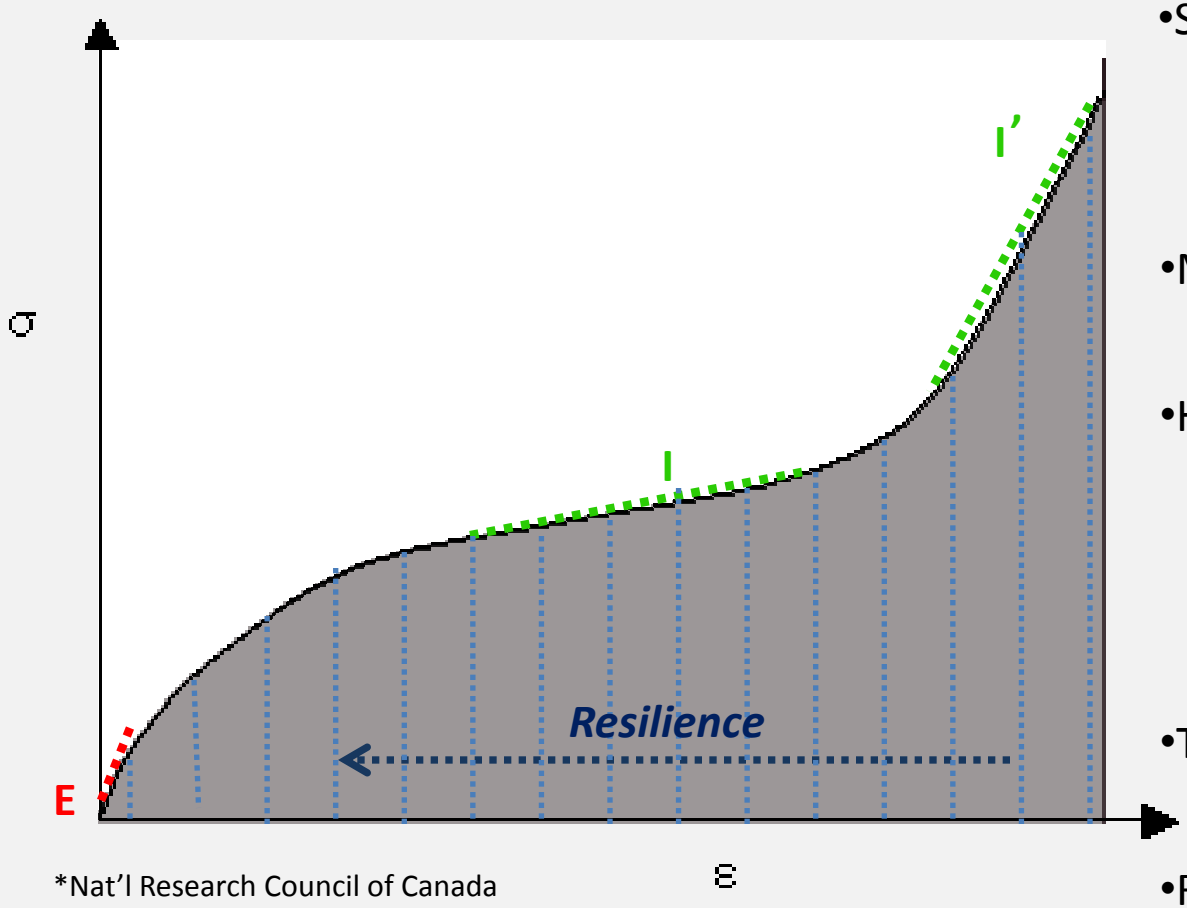
*Wittenberg (1960) – carbon monoxide actuated sails

Material selection and manufacturing of actuators

Measuring material properties

- Elongation at break
  - Natural rubber (1000%)
  - Ecoflex 0030 (~500%)

ELASTOMER MATERIAL PROPERTIES

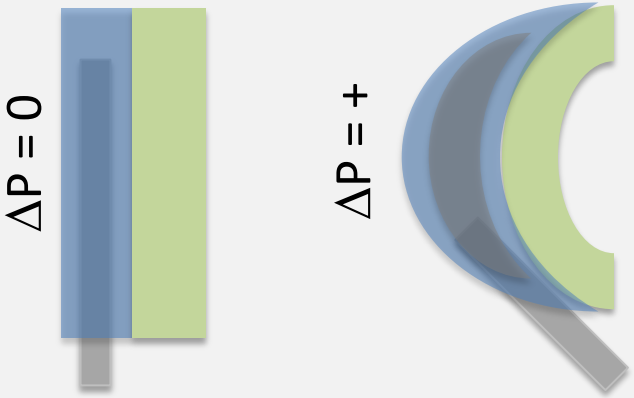


*Nat'l Research Council of Canada

- Elongation at break
  - Natural rubber (1000%)
  - Ecoflex 0030 (~500%)
- Strength
  - Tear strength (ASTM notch test)
  - Ultimate strength
- Modulus
  - Young's (**E**, Elastic)
  - Tangent (**I**)
- Hardness – related to modulus
  - Measured via indentation
  - Proportional to Elastic Modulus
  - Chewing Gum (Shore 0020)
  - Tire Tread (Shore A 70)
  - Hard Hat (Shore D 75)
- Toughness
  - Energy (J/m^3) to material failure
- Resilience
  - How much energy is released during unloading

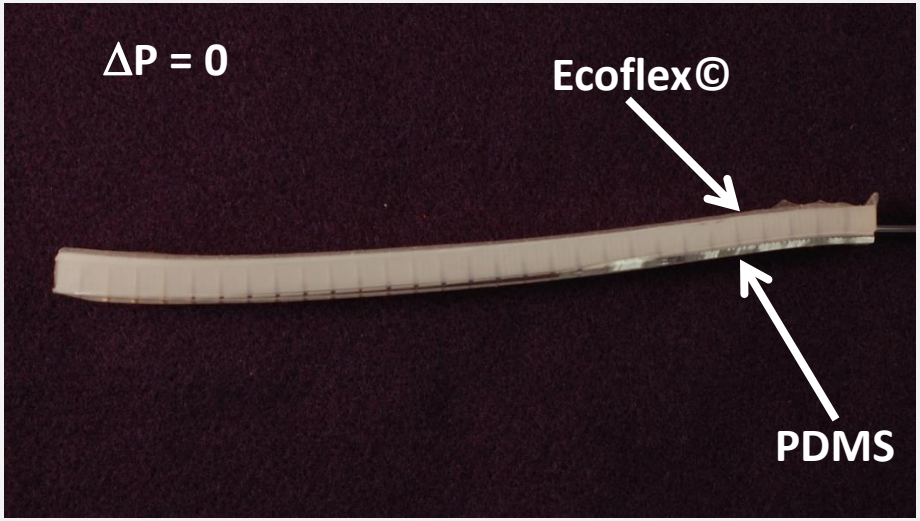
Pneumatic unimorphs

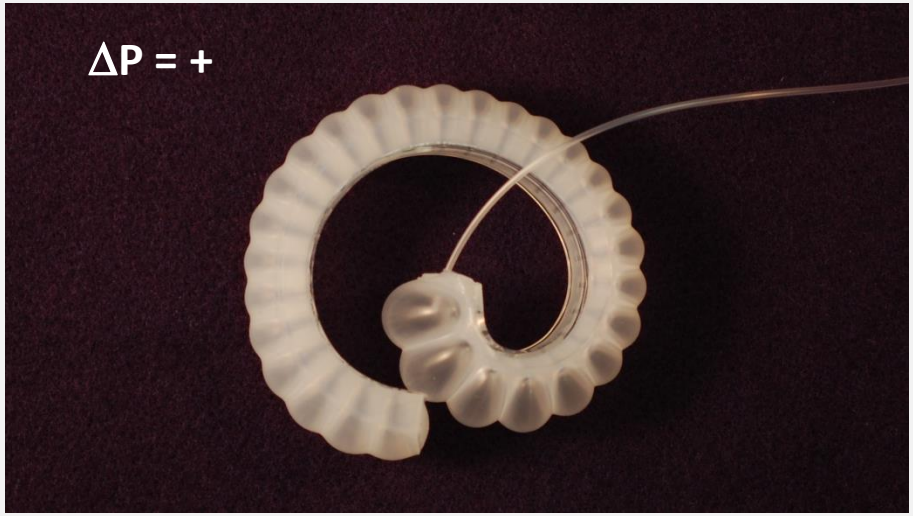
$\kappa_1 < \kappa_2$



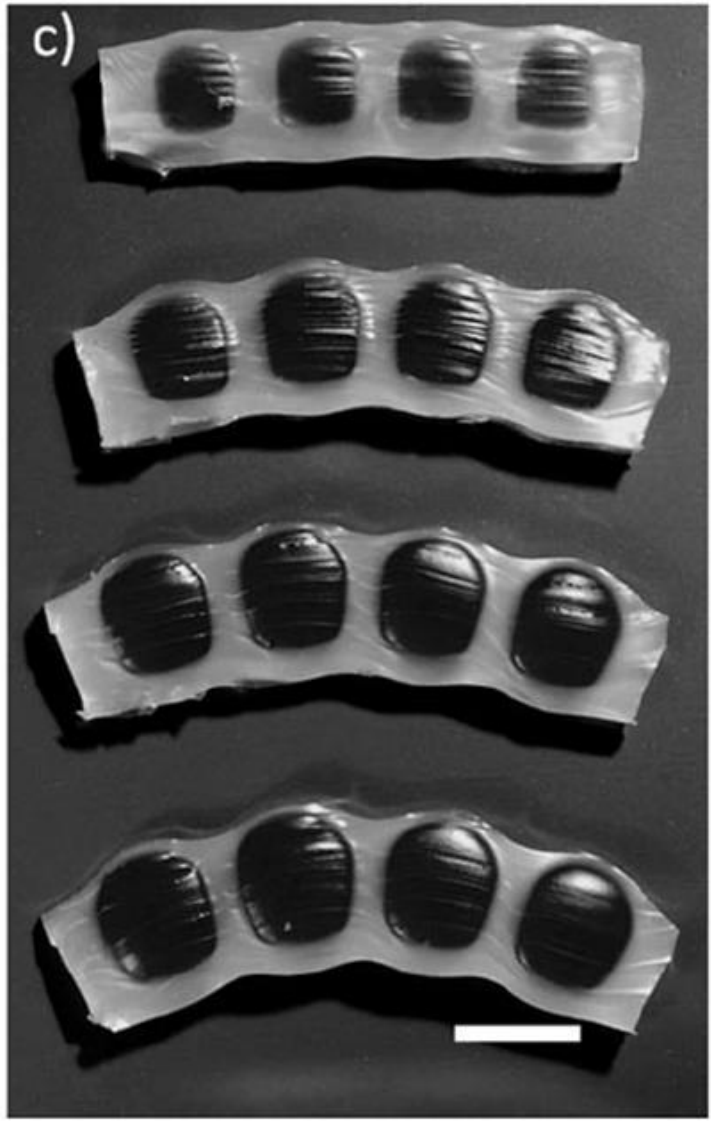
- Differential extension induces curvature
- Embedded pneumatic channels induce strain
- Material's Young's modulus and thickness affect degree of bending
  - —High Strain Material: Ecoflex
  - —Low Strain Materials: PDMS, Fabrics, Paper

actuation of bending component

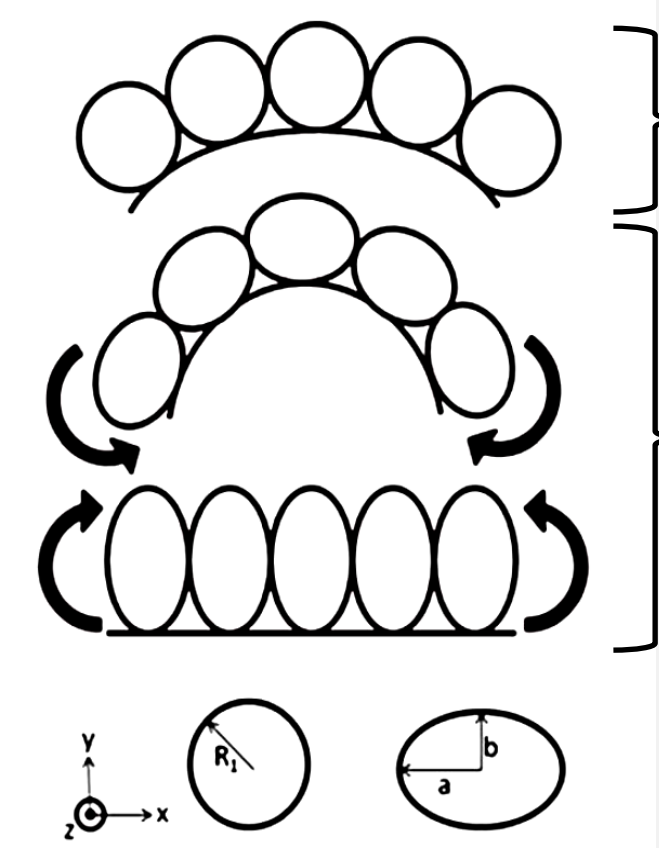




Stiffness dependence on pressure



*Ilievski, et. al. (2011)



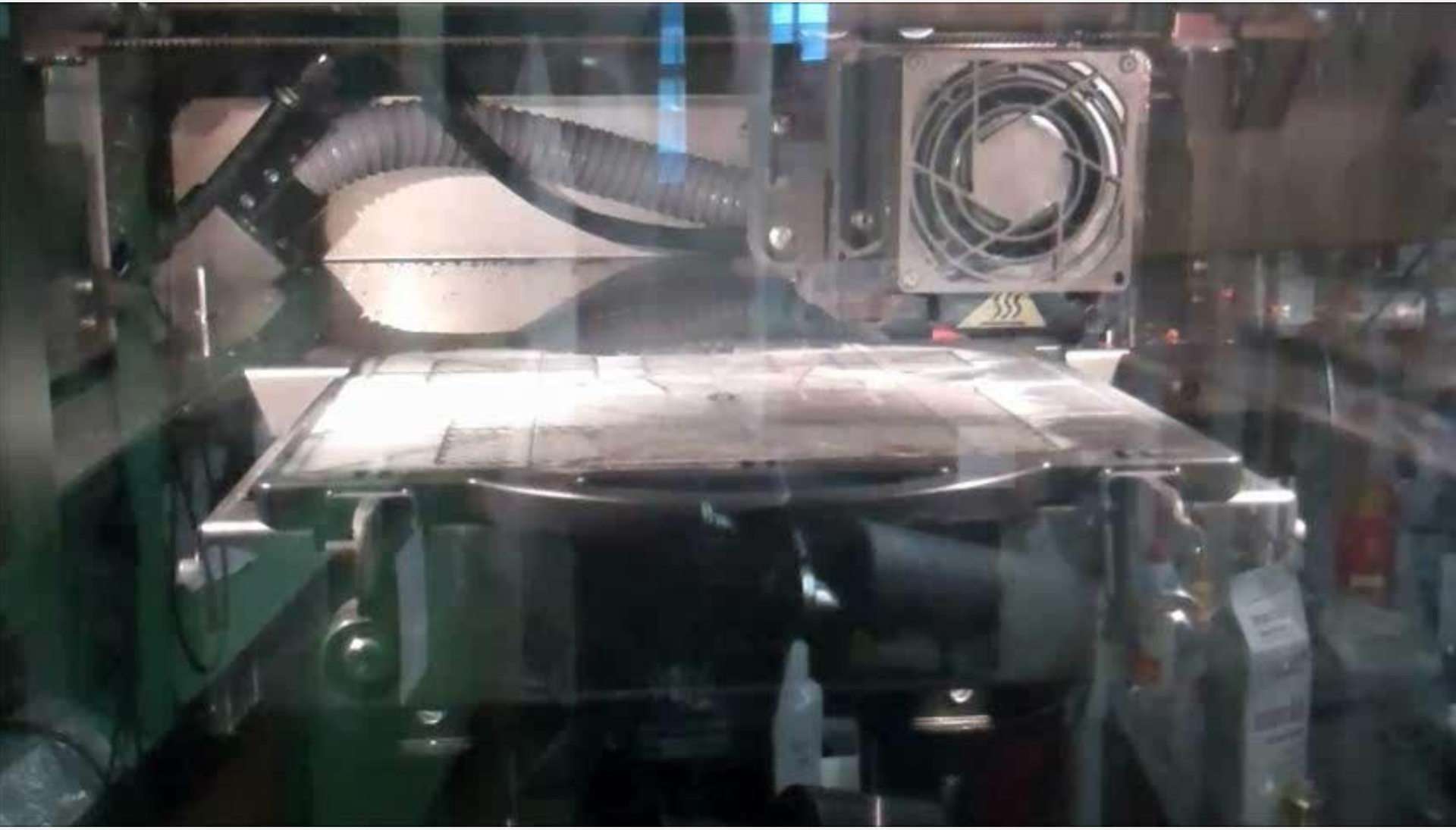
$$PE' - PE = \frac{1}{4} * \frac{\varepsilon^2}{1+\varepsilon} * E * \delta^2 * t_{atm}$$

$$C \approx \pi(2R_1 + \frac{1}{2}\delta^2)$$

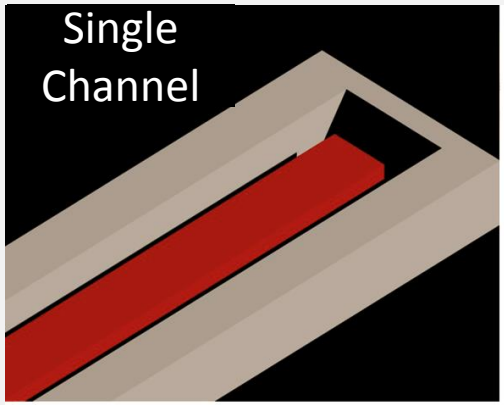
More channels increase the stiffness of the pneu-nets

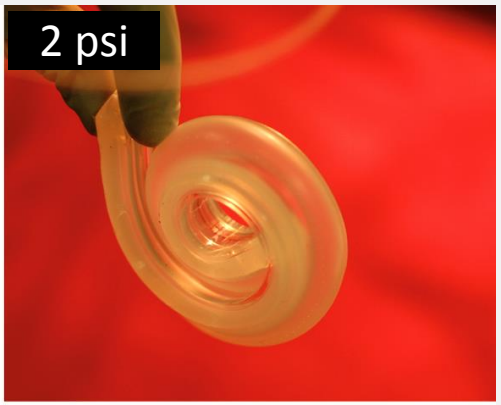
*Shepherd, et. al. (2011)

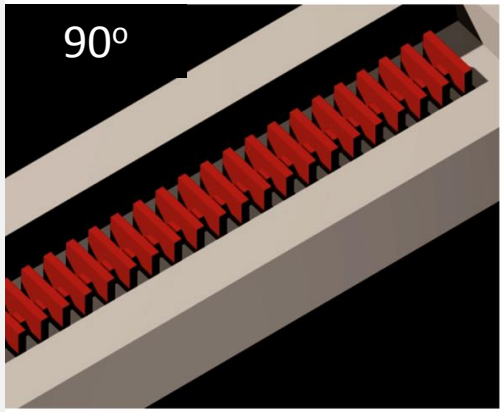
Manufacturing

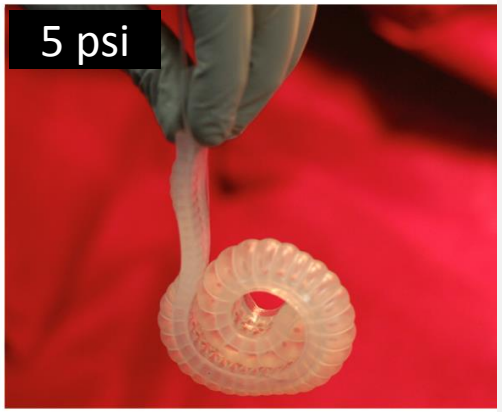


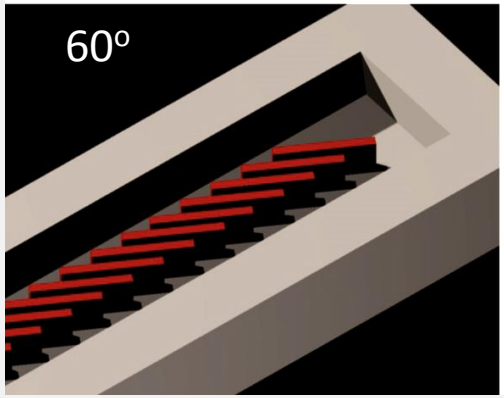
Pneu-net geometry affects mode of actuation

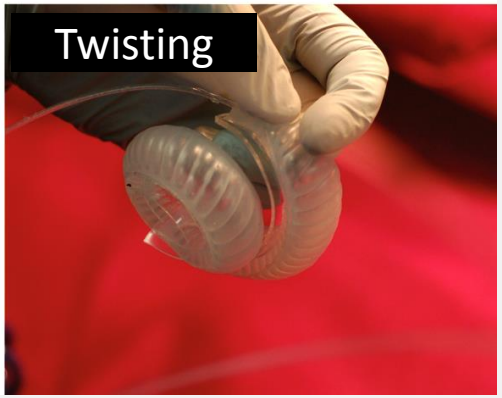


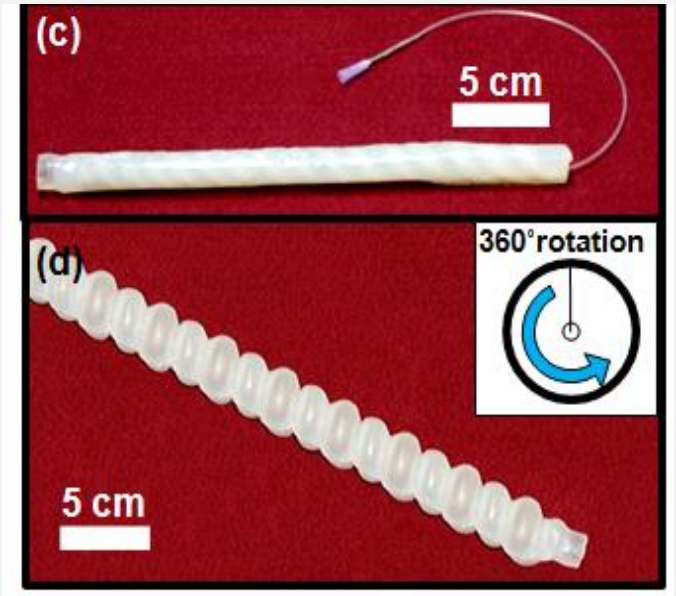






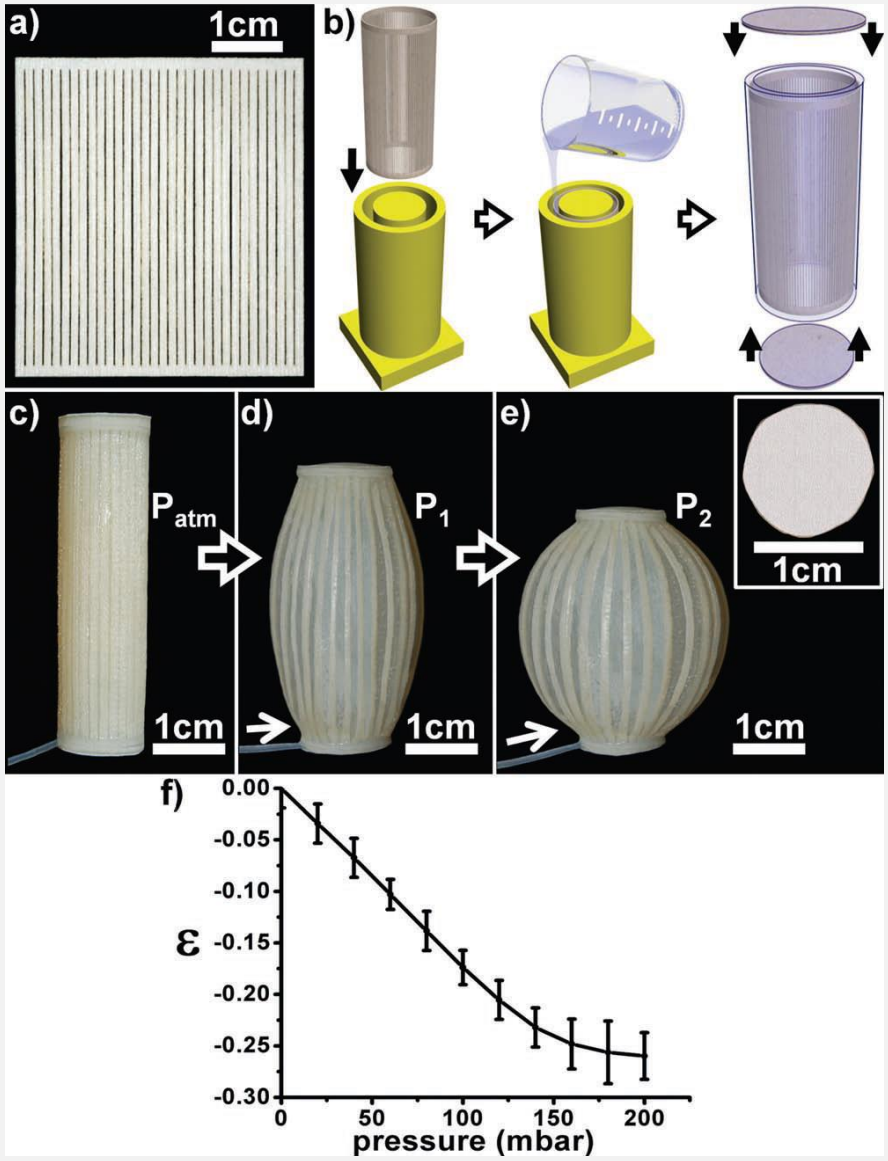


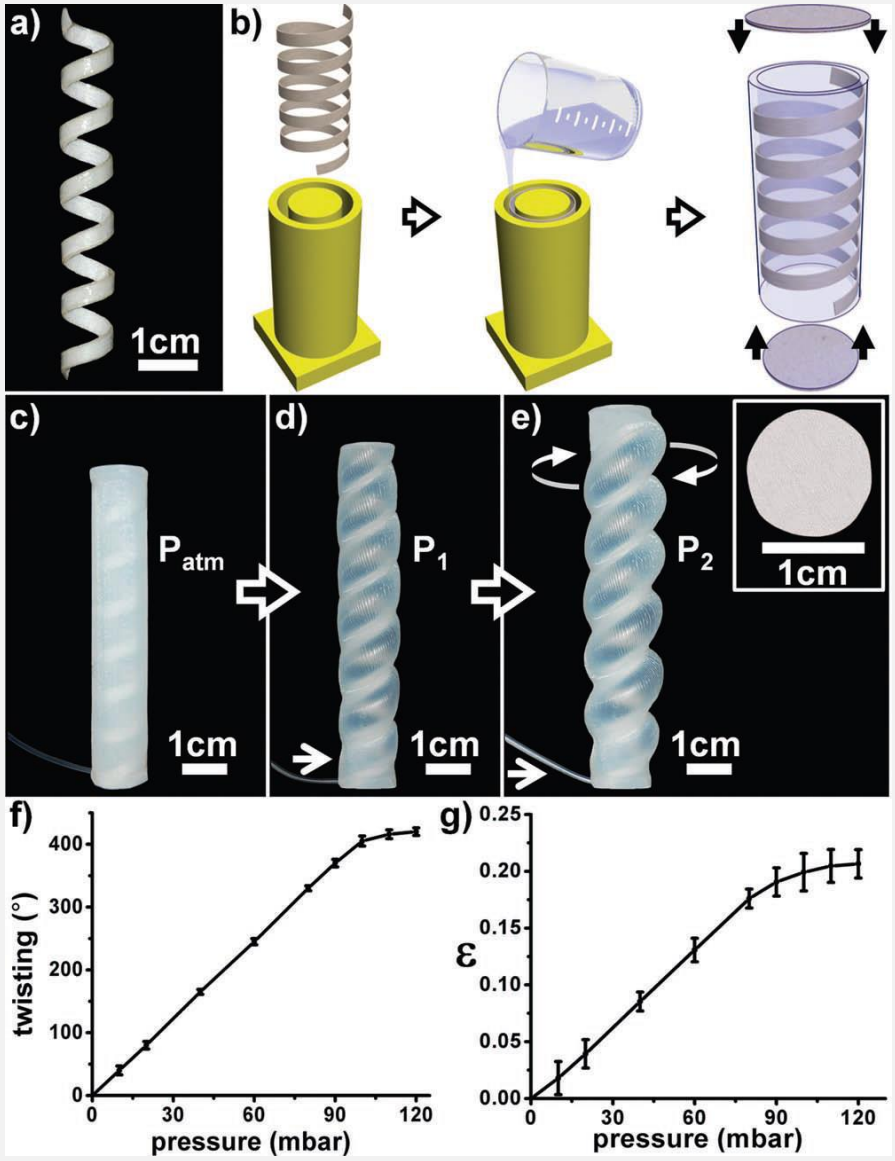




*Ilievski, et. al. (2011)

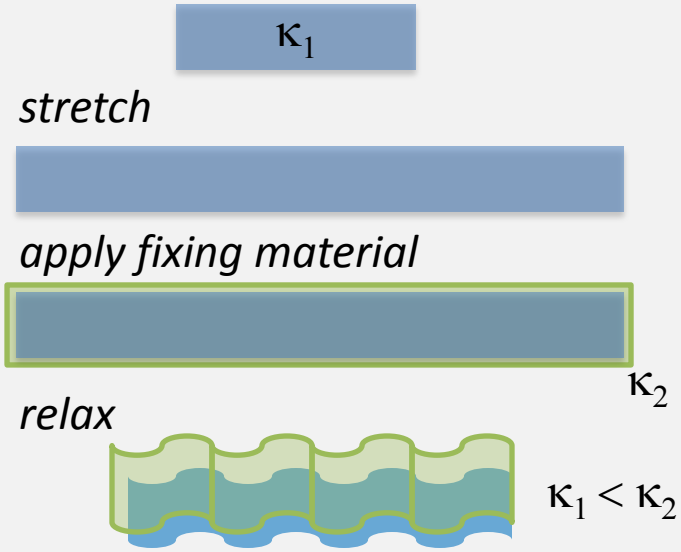
Other actuator geometries - paper



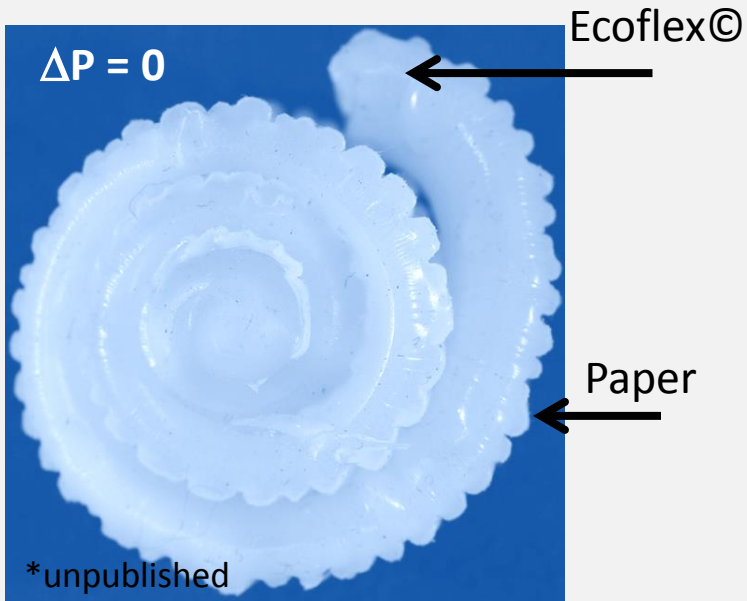


*Martinez, et. al. (2012)

‘Chameleon tong actuator’



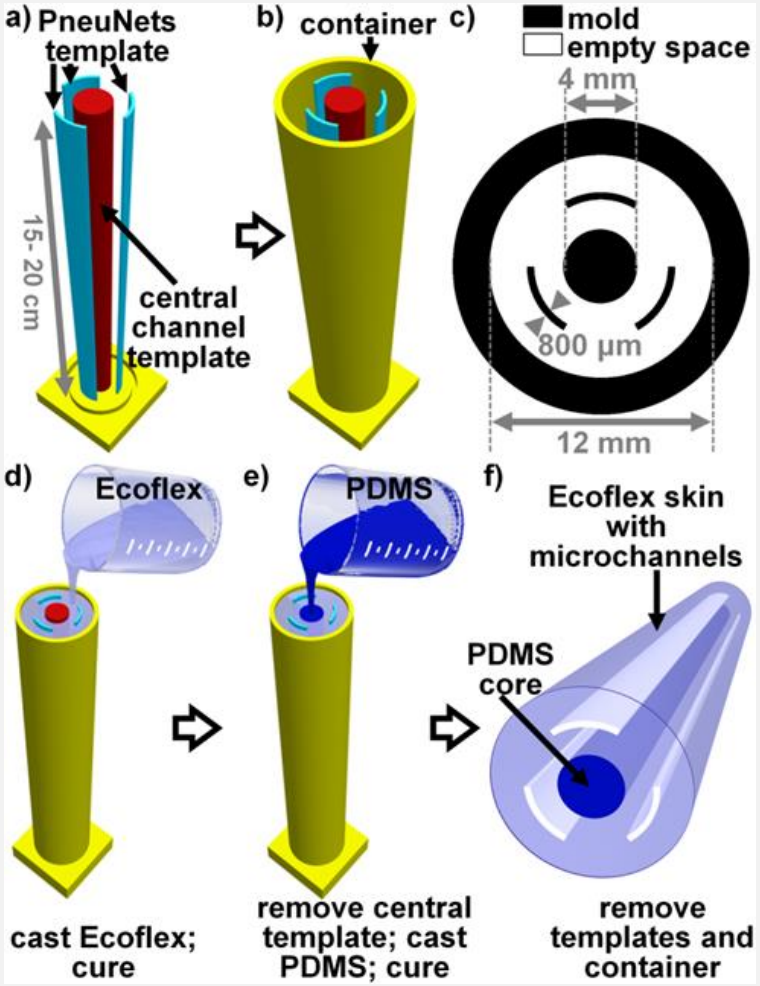
- Stretch a low stiffness material and constrain its stress distribution by adhesion of an unstrained material
  - —pdms, ecoflex, paper
- Relaxation induces buckling of the unstrained layer as the stretched layer attempts to return to its unstretched condition

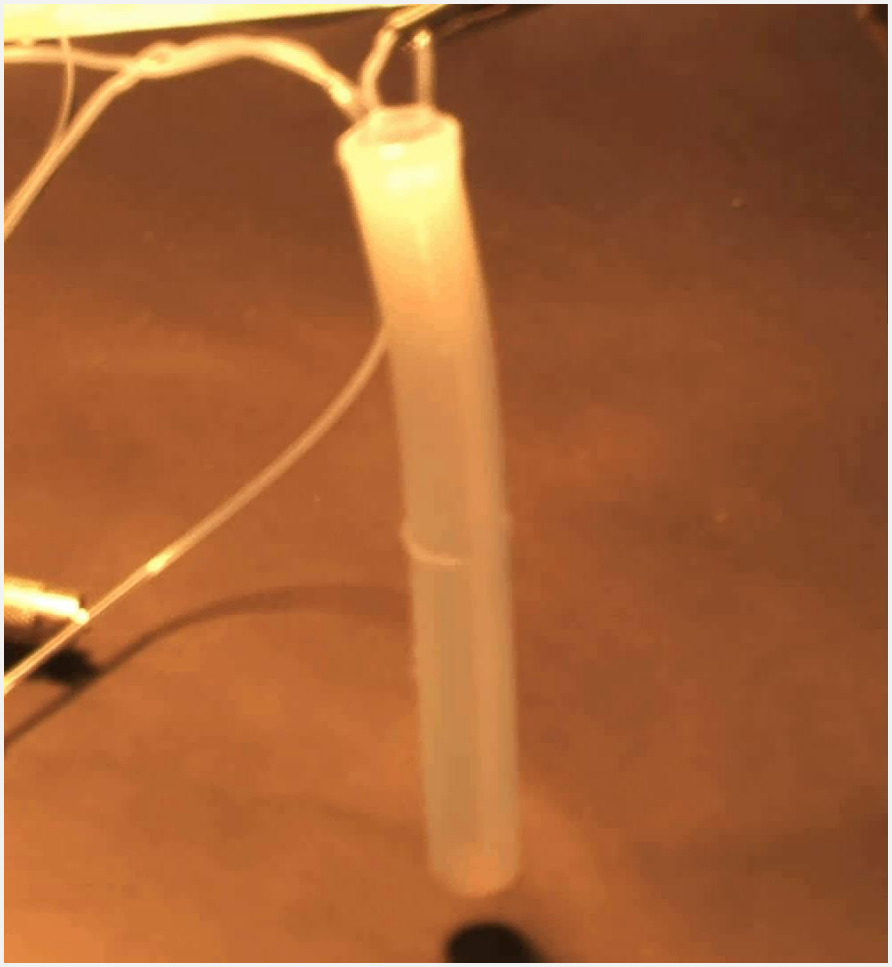


actuation of buckled component

Soft manipulators

Molding a tentacle (trimorph) actuator



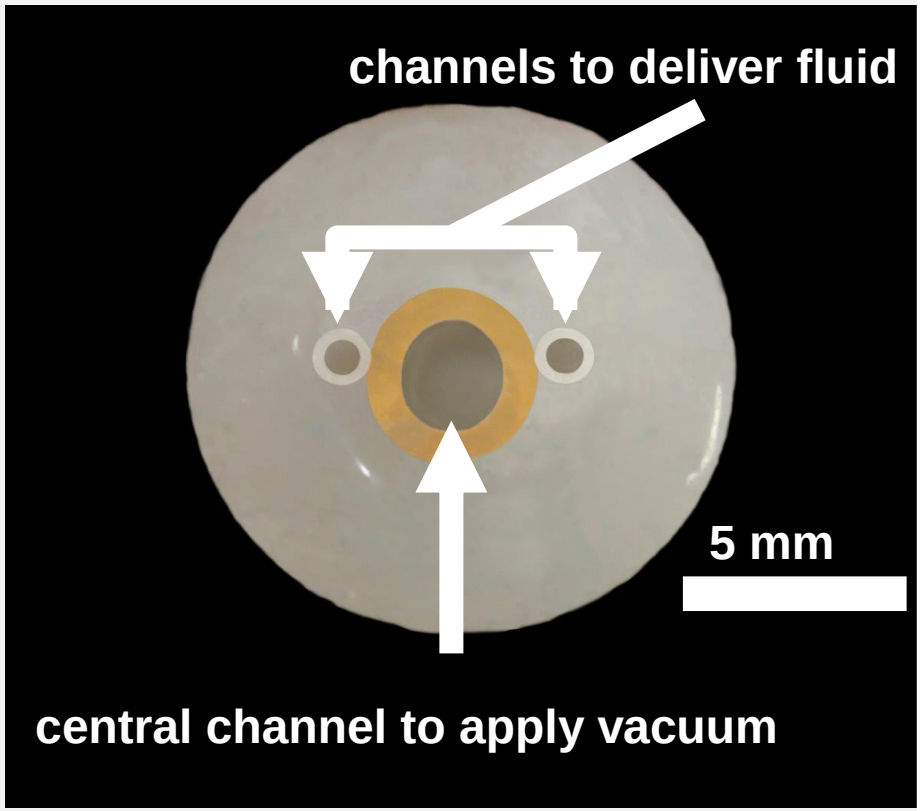


*Martinez, et. al. , Adv. Mat. (2012)

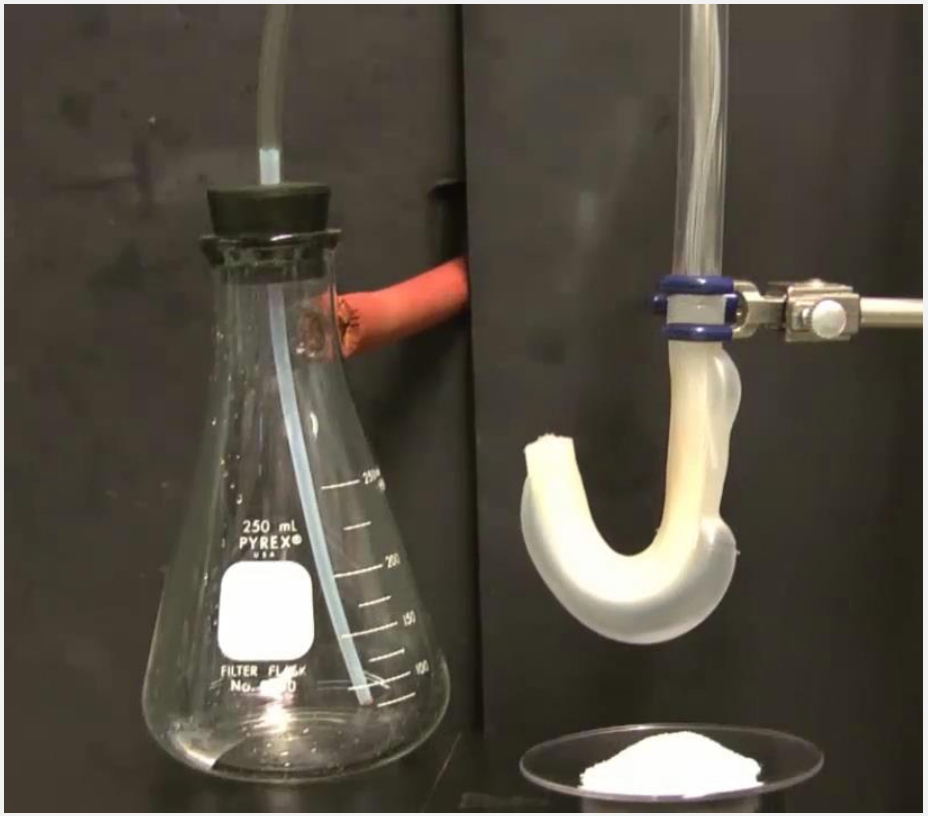
Using tentacles for mass delivery

Combine actuation (3 degrees of freedom) with materials collection/delivery capabilities.

schematic



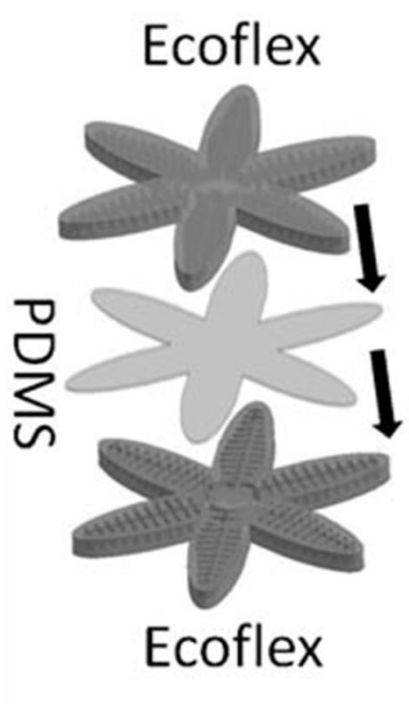
dissolution and collection of a salt



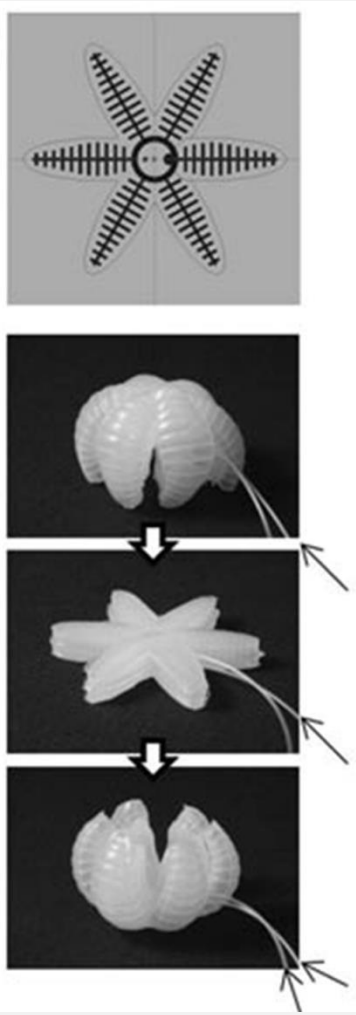
*Martinez, et. al. , Adv. Mat. (2012)

Compliant (bimorph) gripper

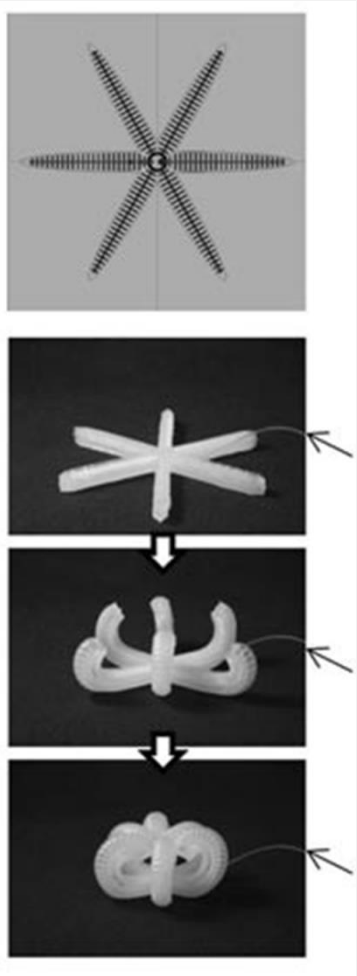
2 actuation layers

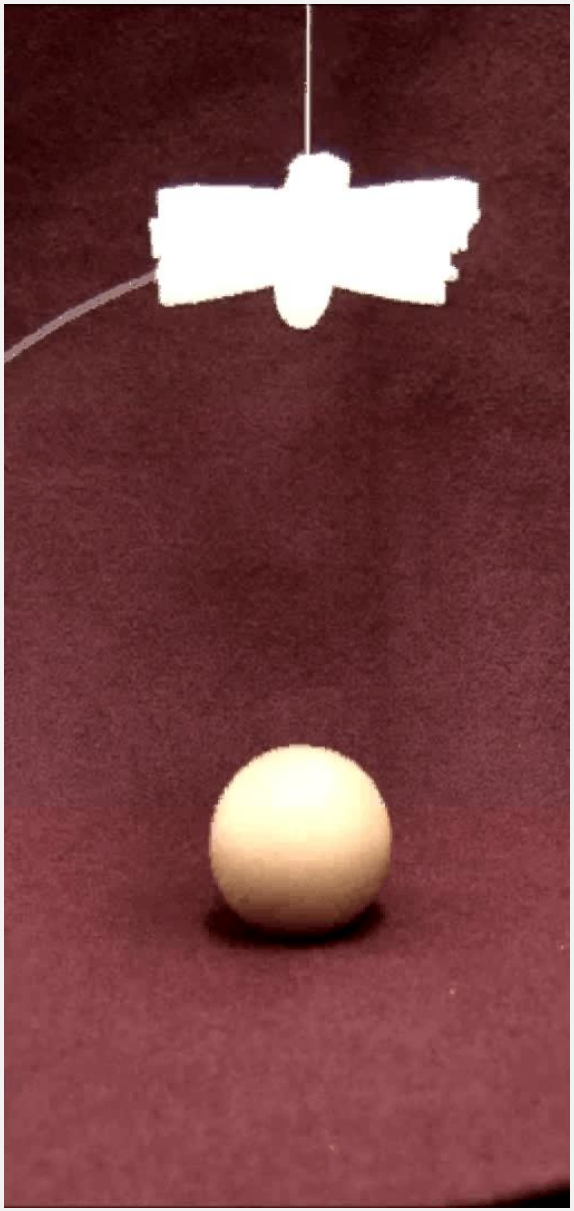


2 DOF



Longer fingers



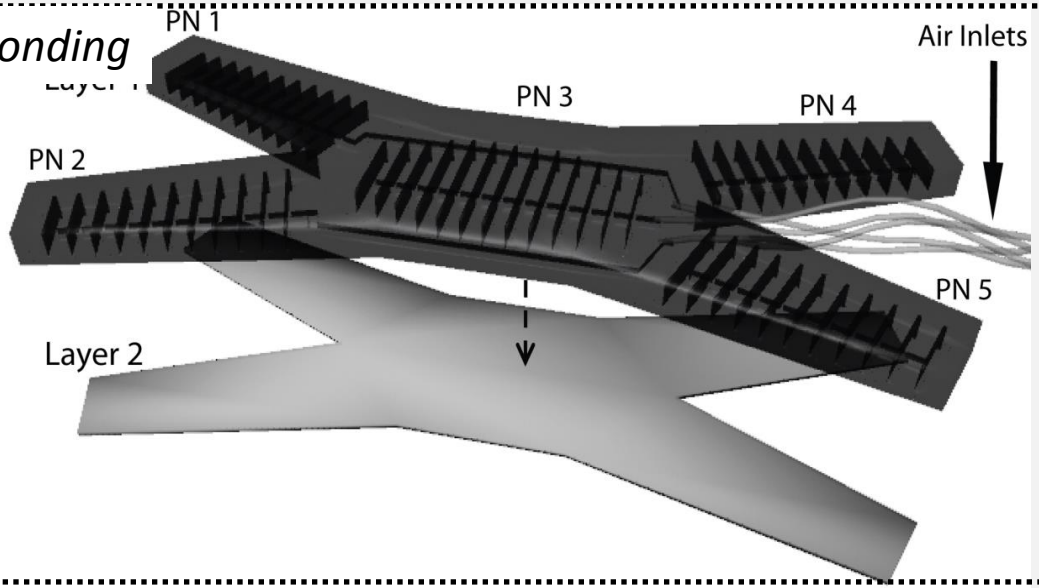


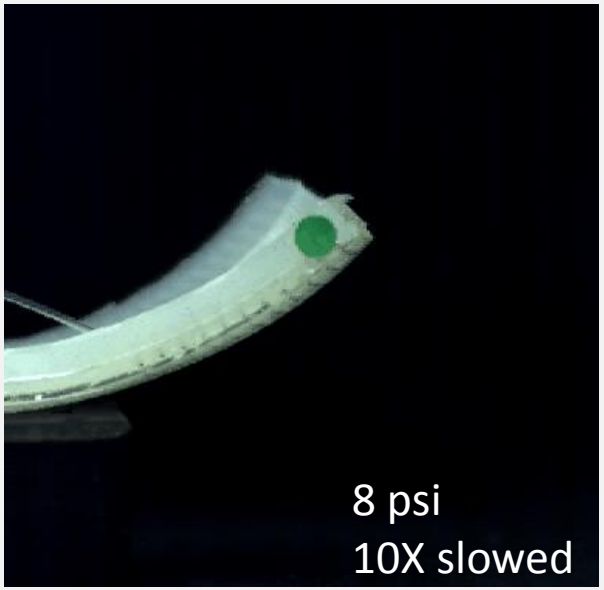
Ilievski et. al, *Ang. Chem. Int. Ed.* (2010)

Body morphing for locomotion

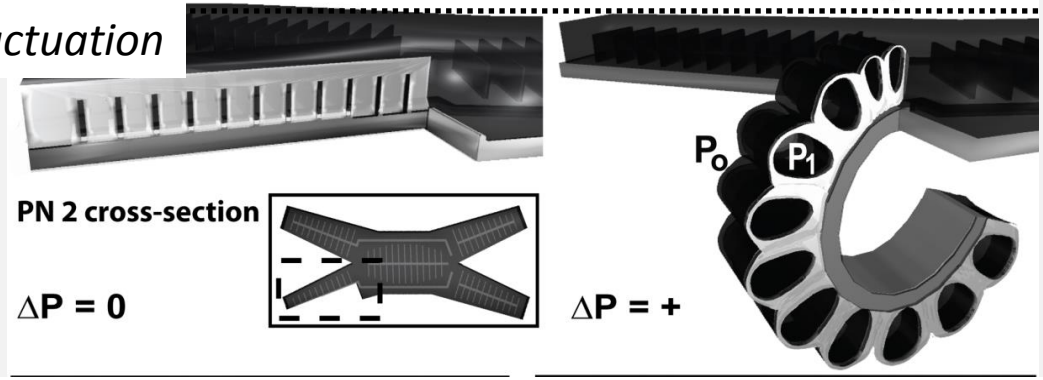
A mobile soft robot design

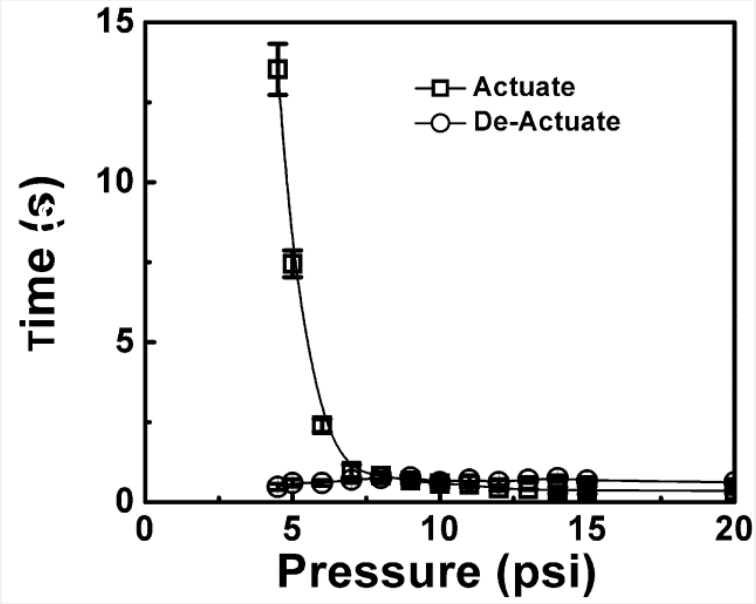
bonding





actuation





Shepherd et. al, *PNAS* (2011)

Multigait robot navigating an obstacle

Slithering up a soft hill

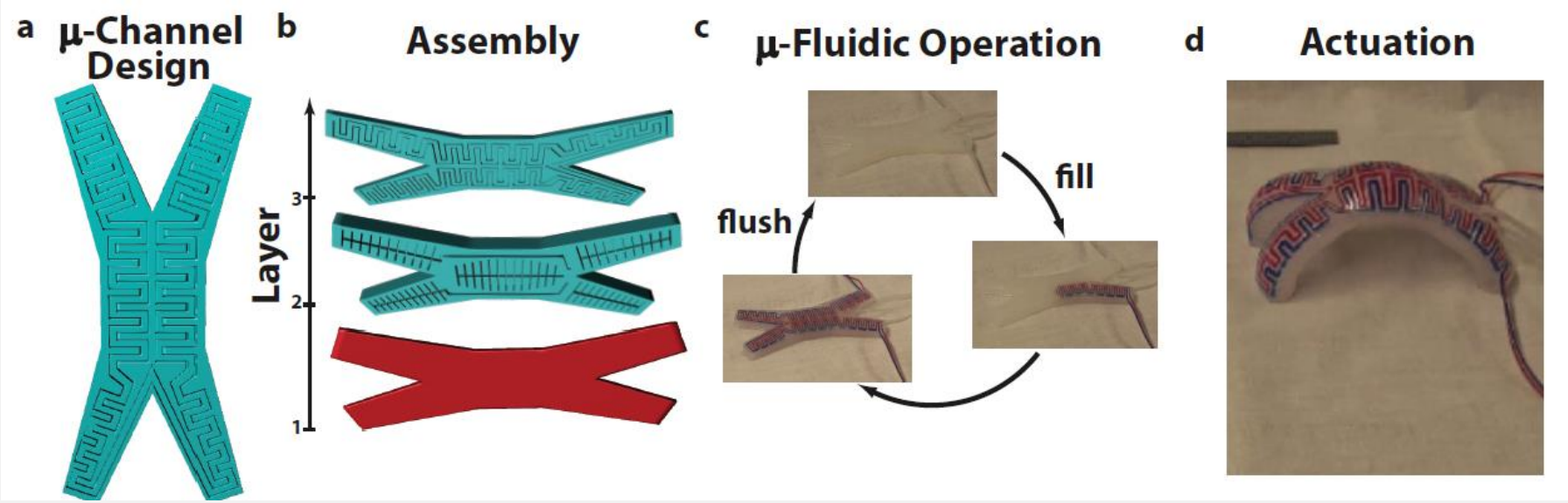
Shepherd et. al, *(unpublished)*

Low density is compatible with swimming

Shepherd et. al, *(unpublished)*

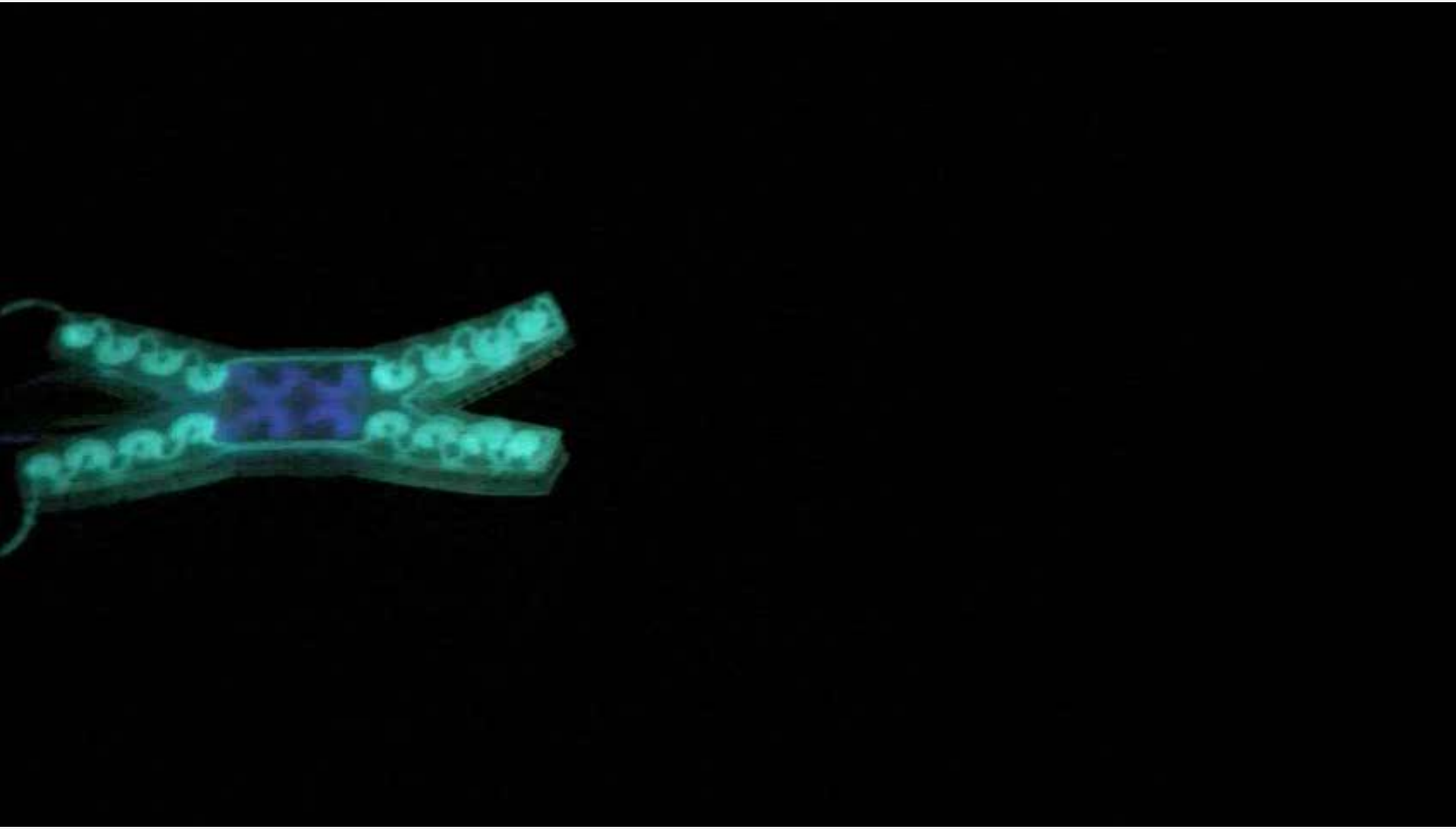
Translucent skins for color change

μ-Fluidic networks for display



Morin et. al, Science *(2012)*

Chemiluminescence

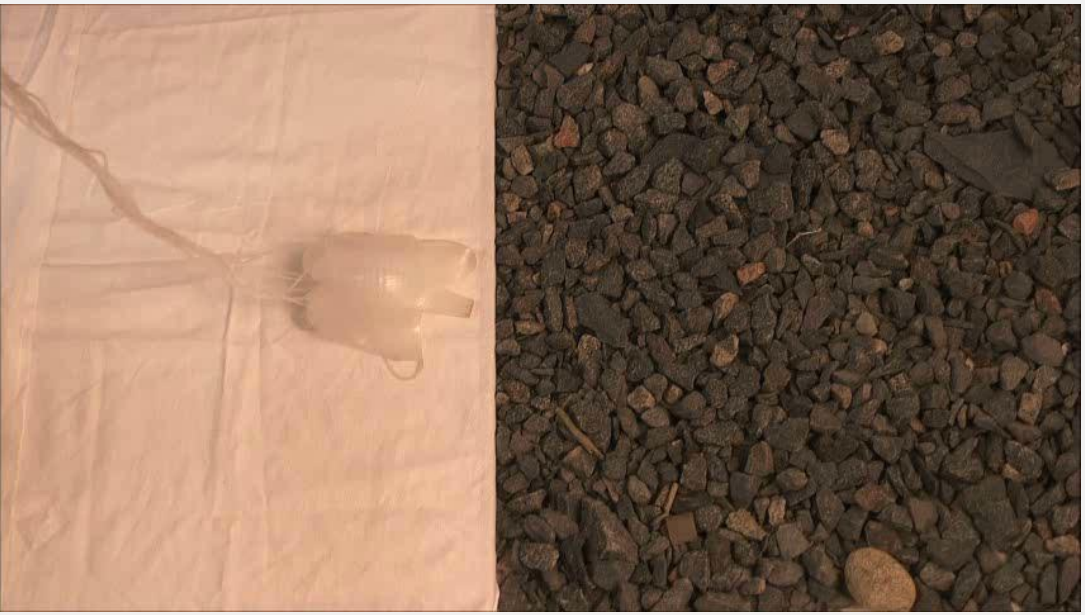


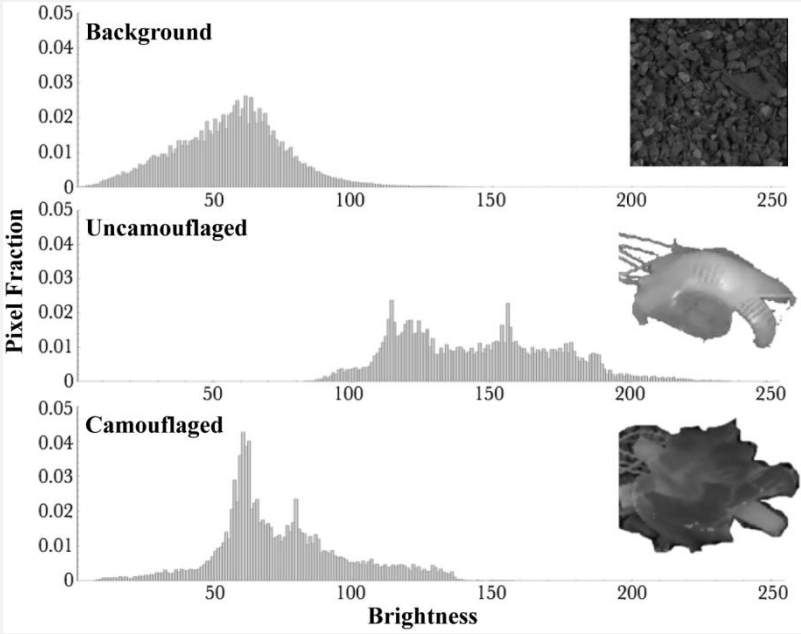
bis(2,4,6-trichlorophenyl) oxalate + fluorescent dye + hydrogen peroxide

(TCPO)

Morin et. al, Science *(2012)*

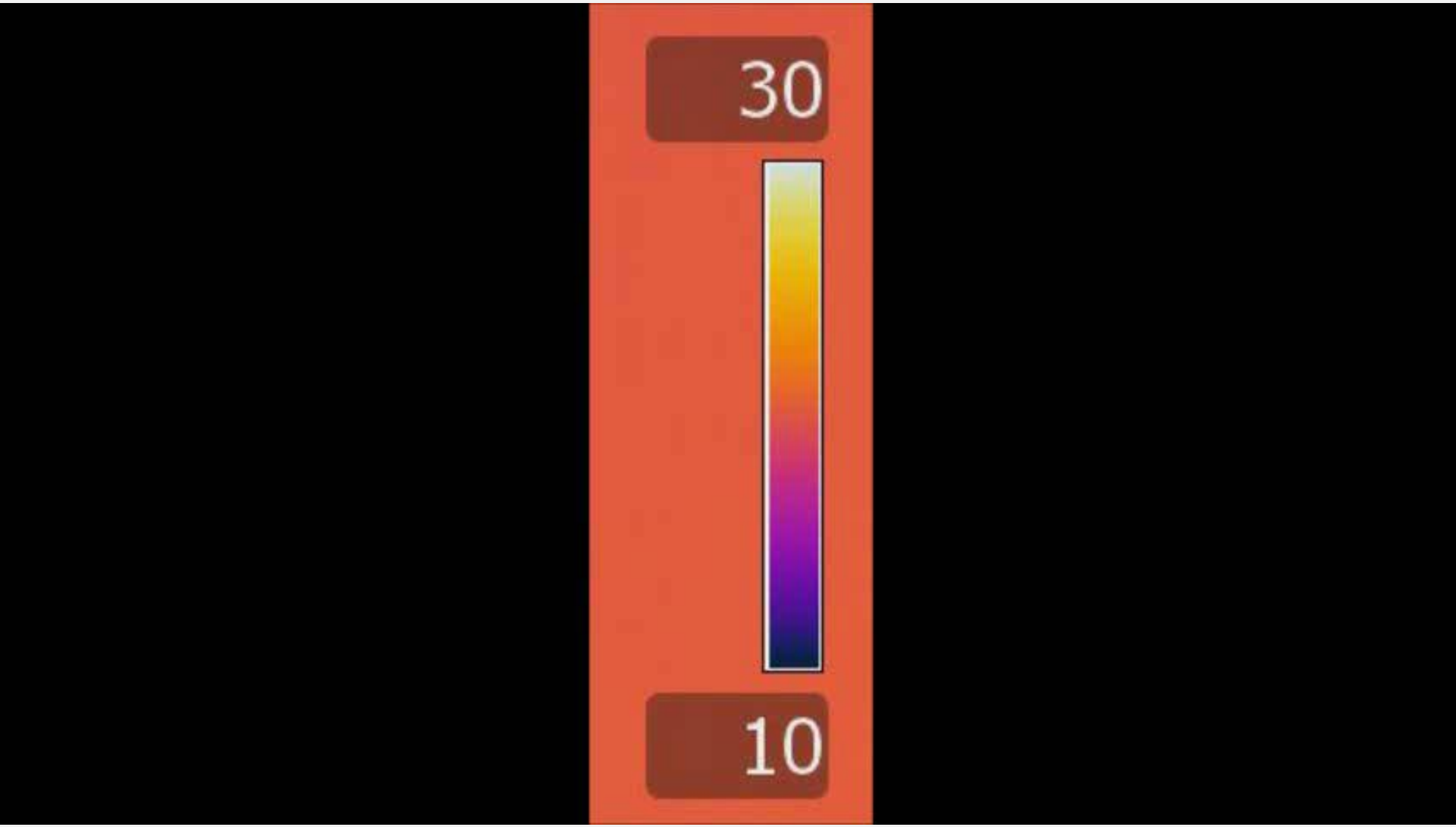
Disruptive coloration and patterning





Morin, Shepherd et. al, Science *(2012)*

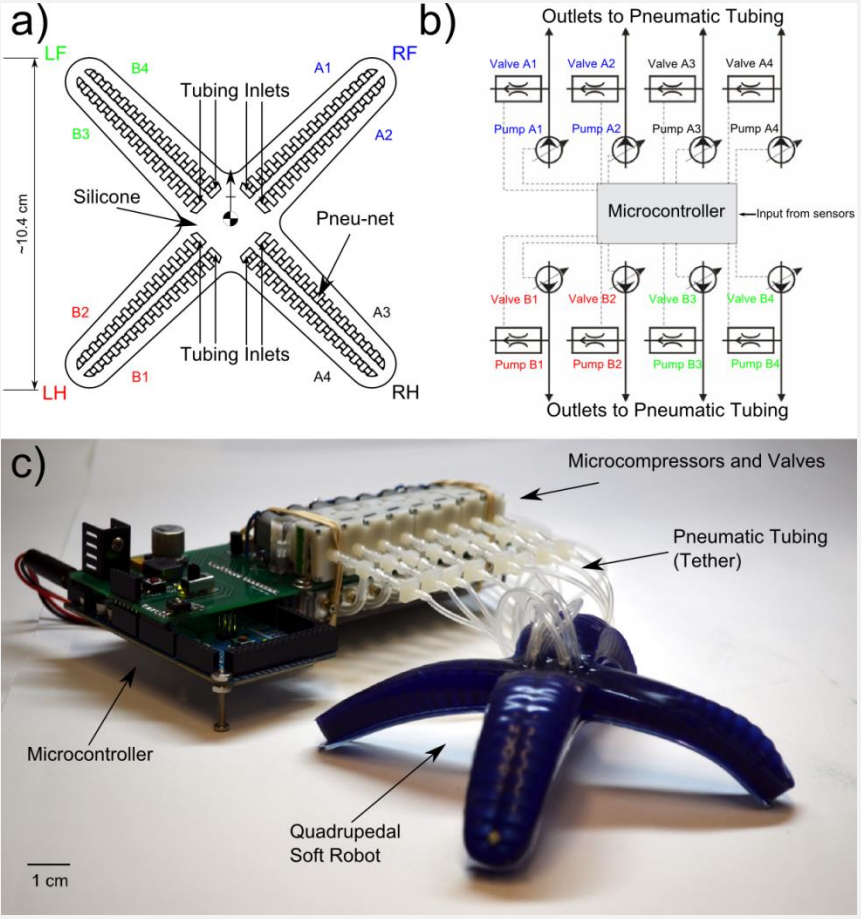
Infrared Display and Camouflage

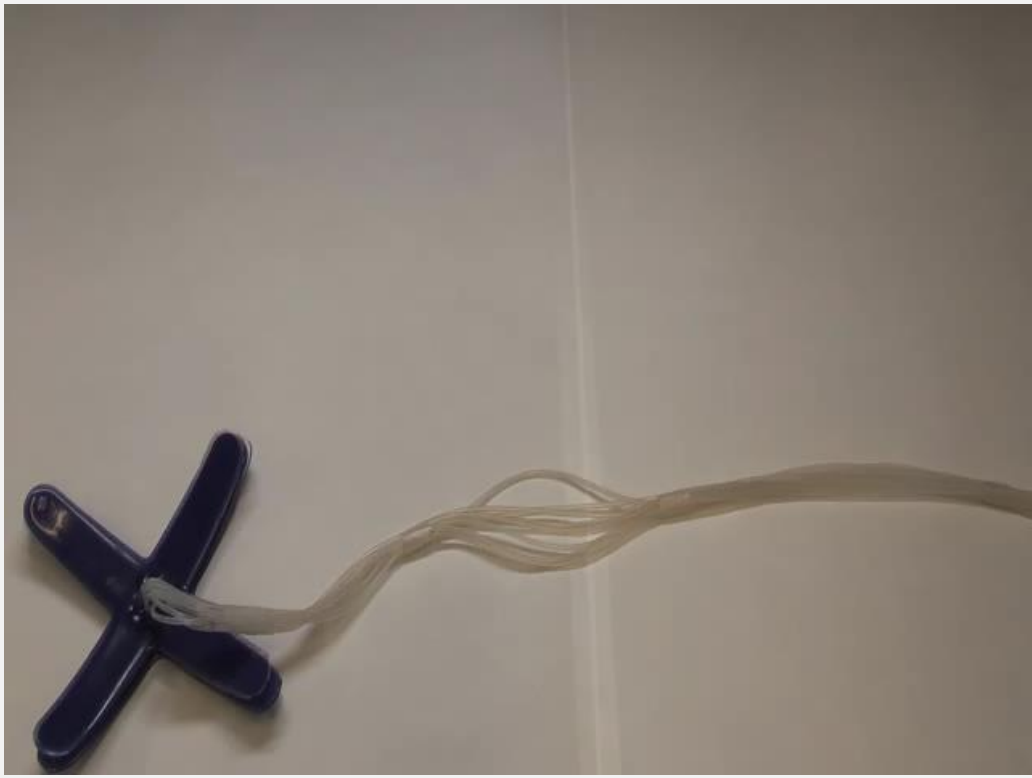


Morin et. al, Science *(2012)*

Body morphing for combining locomotion and manipulation

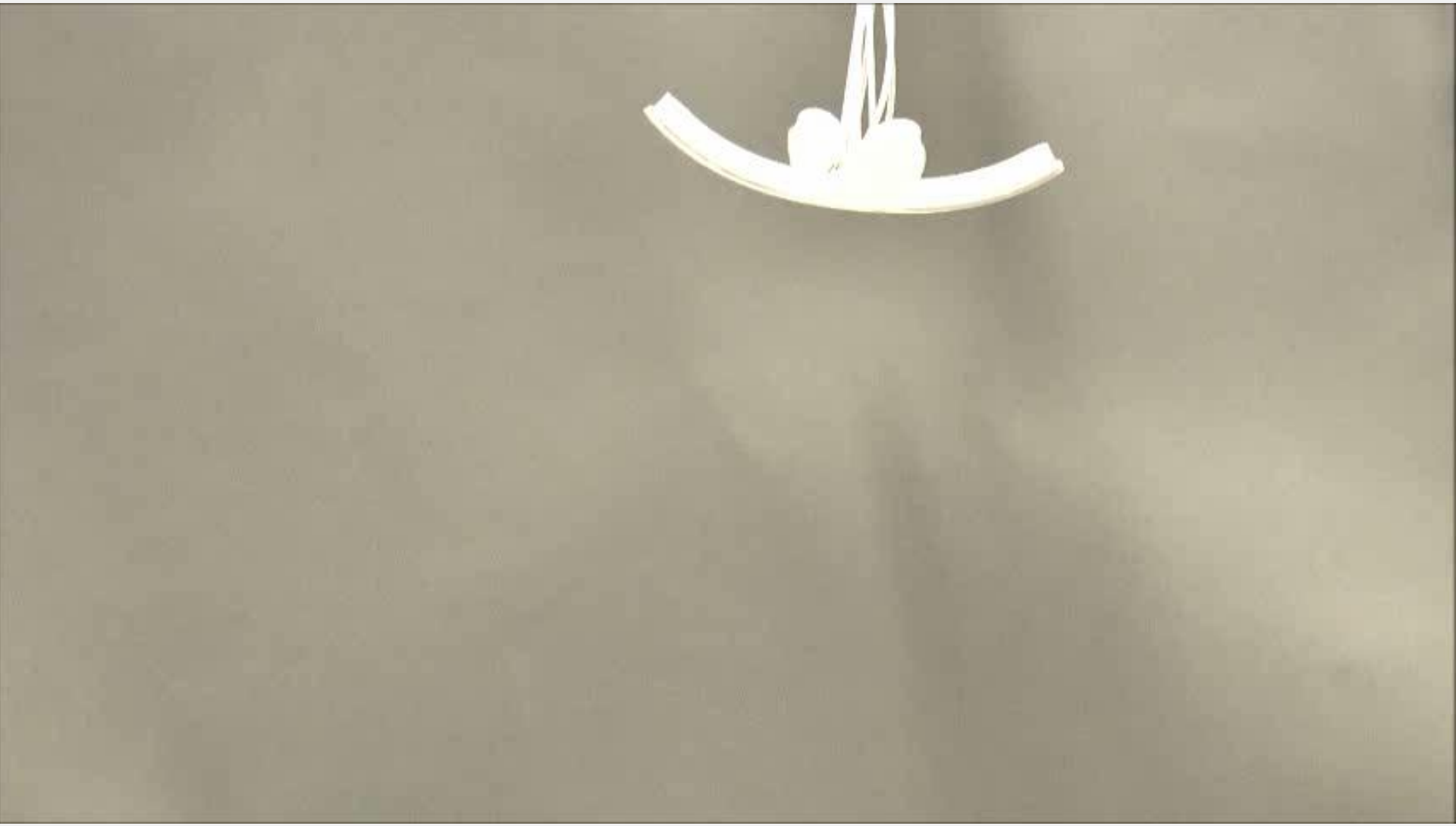
Walking in multiple directions





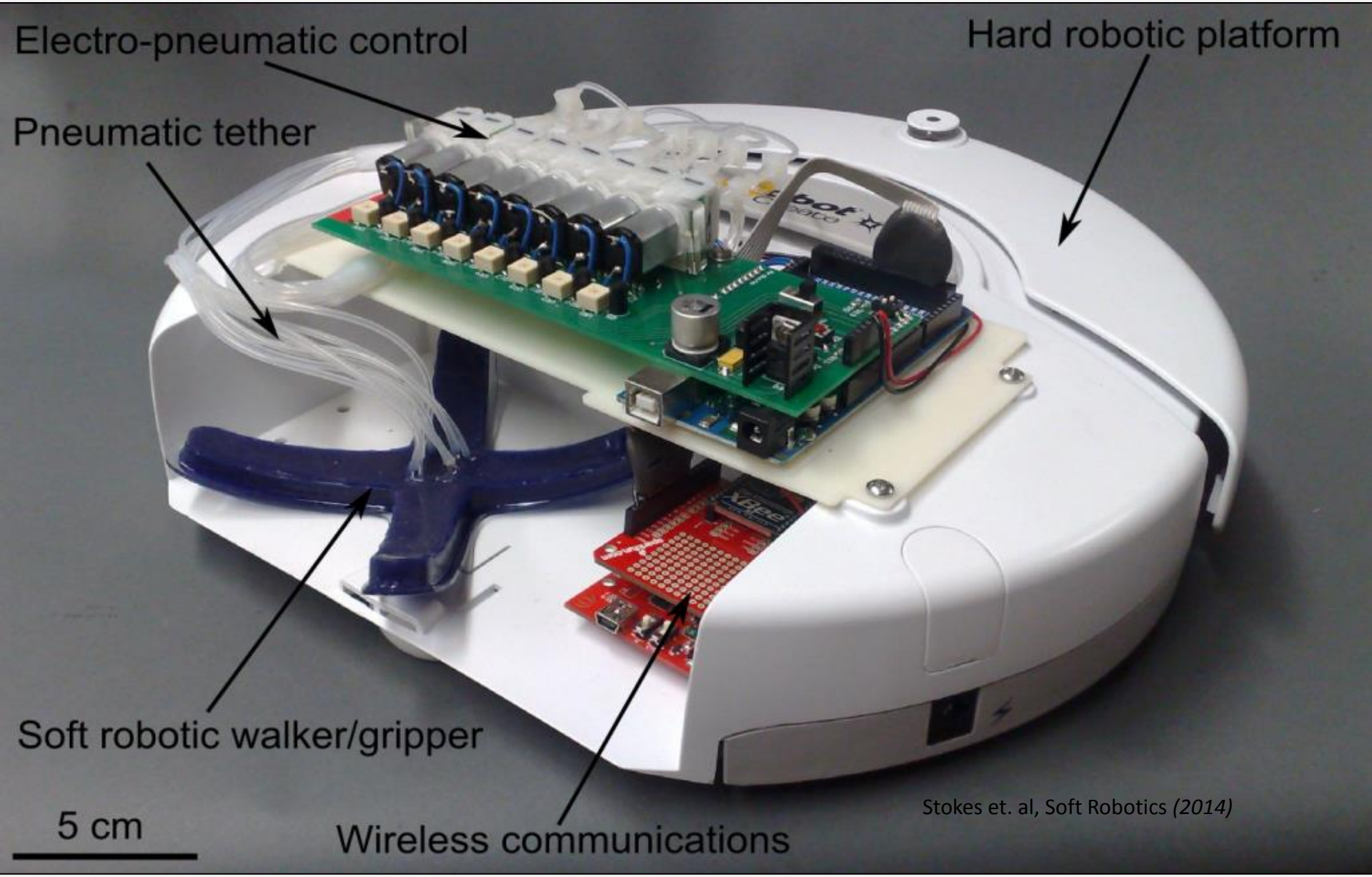
Stokes, Shepherd, et. al, *Soft Robotics* **1** 1 (2014)

Multimodal function: it is also a gripper



Stokes et. al, Soft Robotics *(2014)*

Marsupial robot to eliminate tethers

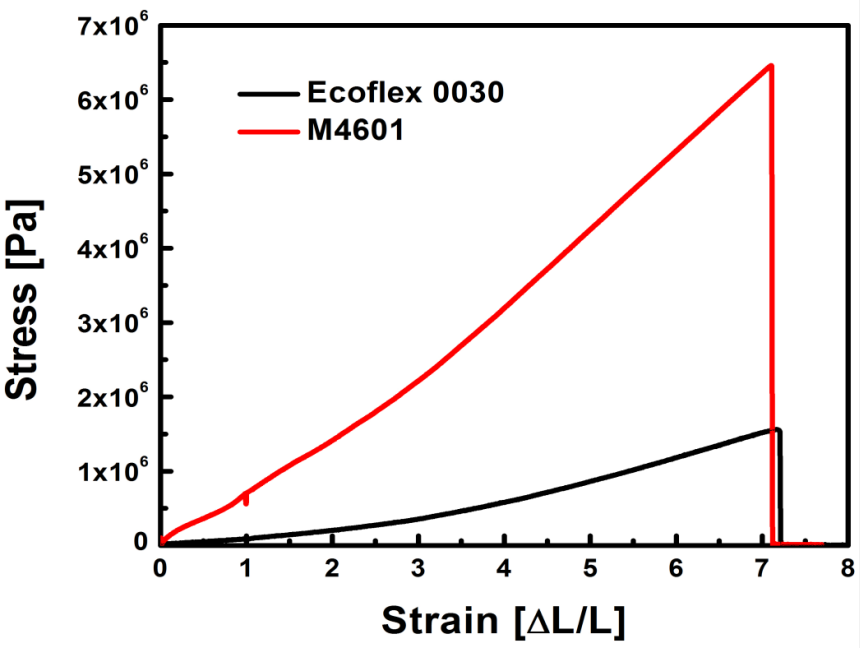


Stokes et. al, Soft Robotics *(2014)*

Marsupial robot to eliminate tethers

Stokes et. al, Soft Robotics *(2014)*

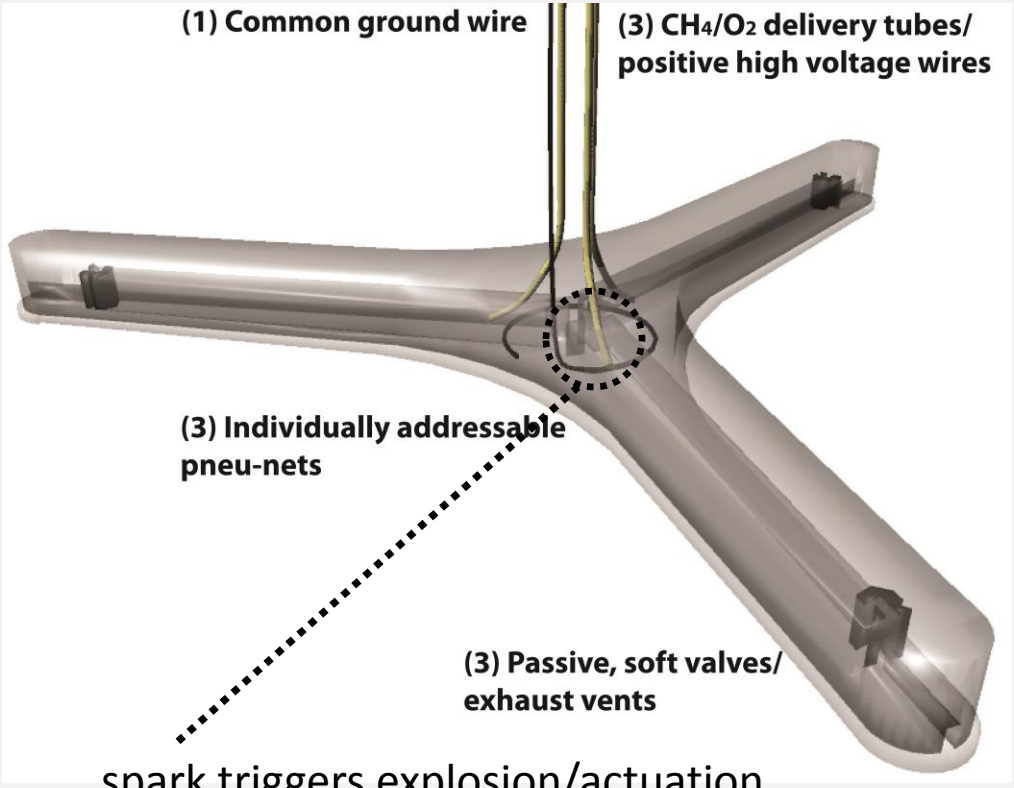
Tougher silicones for greater loads



Material Properties	M4601	Ecoflex 0030
Ultimate Strain	700%	720%
Tensile Strength	7 MPa	1.5 MPa
Energy to fracture/toughness	270 MJ/cm^3	100 MJ/cm3
Elastic Modulus	1 MPa	100 kPa

Improving the speed of actuation

Combustion for high speed actuation

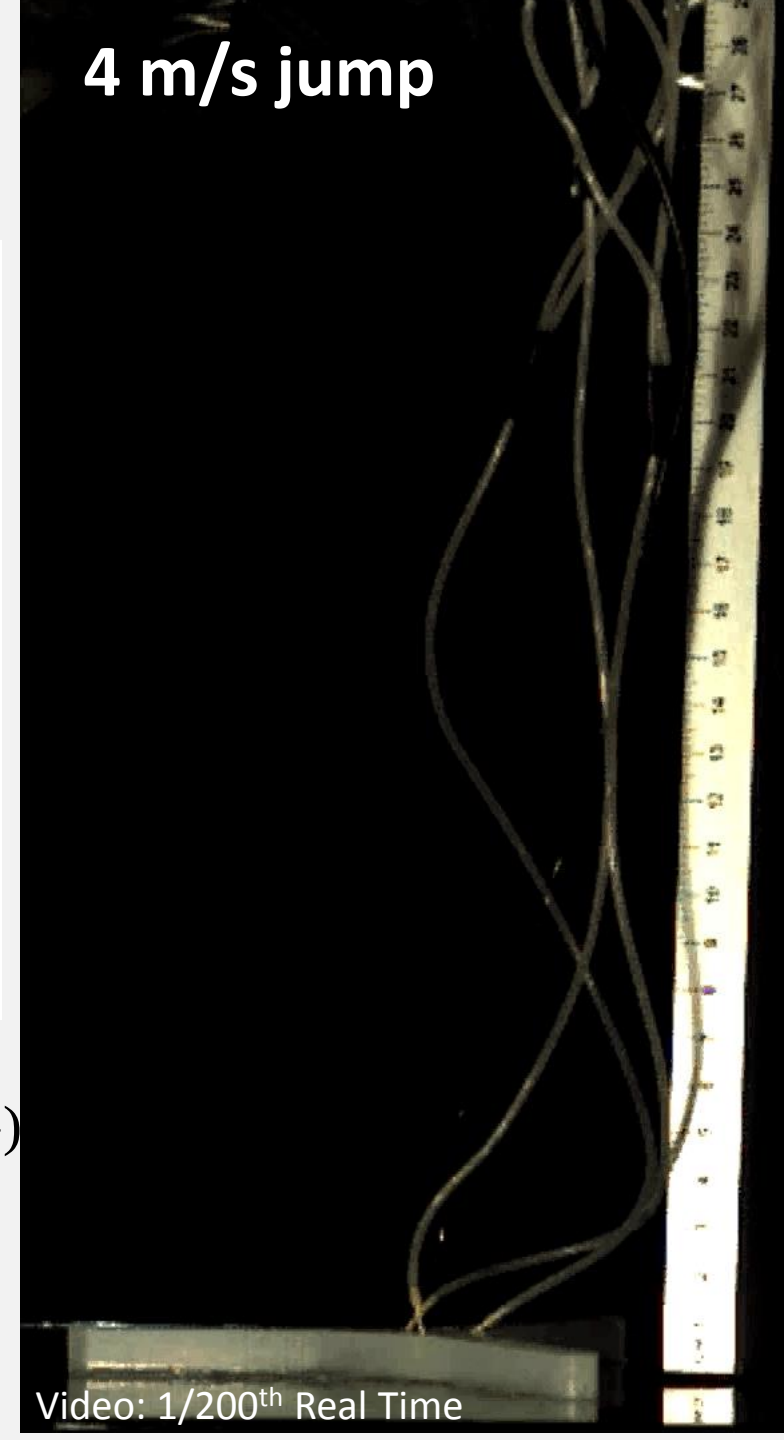


spark triggers explosion/actuation

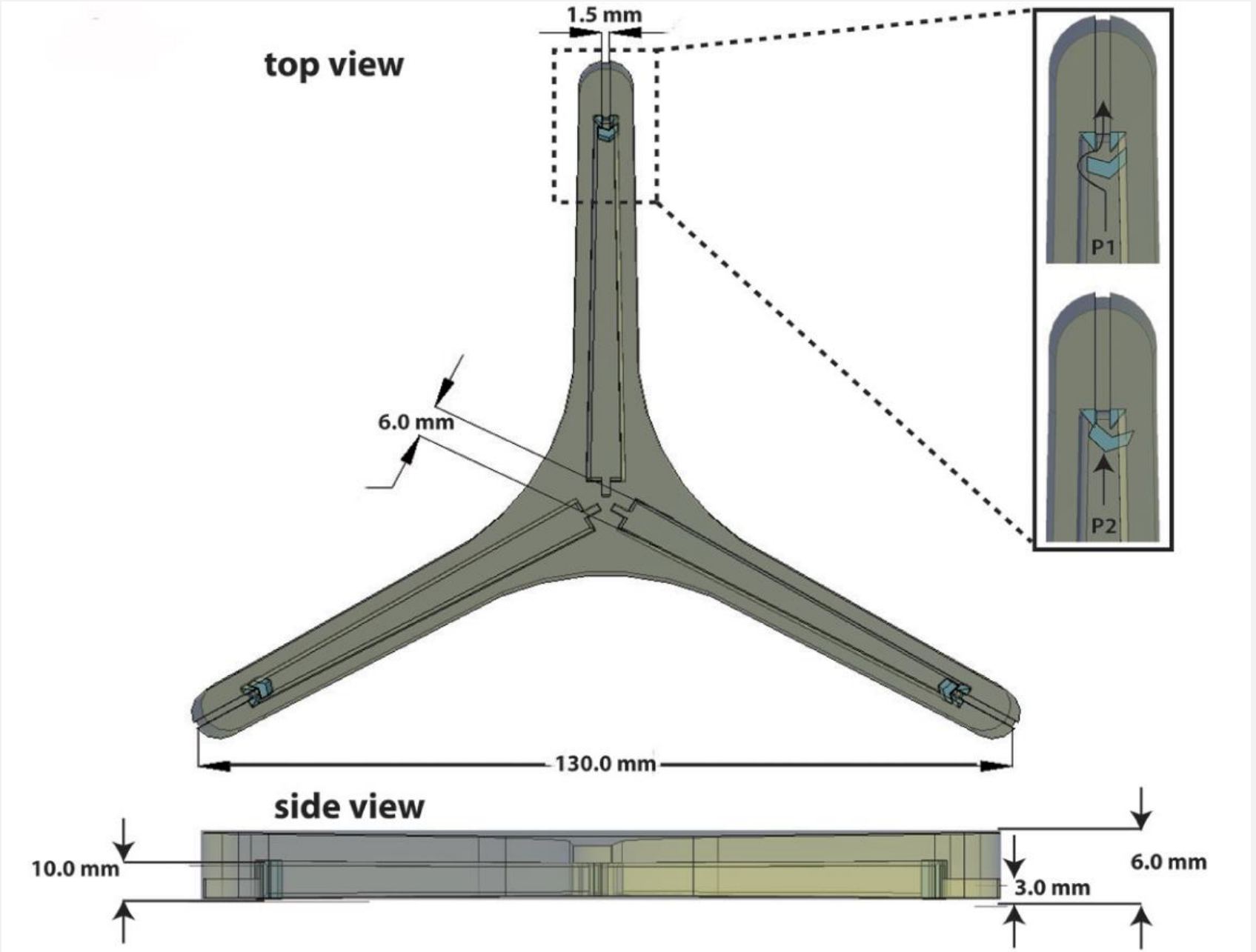
$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(l)} + \Delta H(891\frac{kJ}{mol})$$

Heat from reaction expands gas, causes actuation

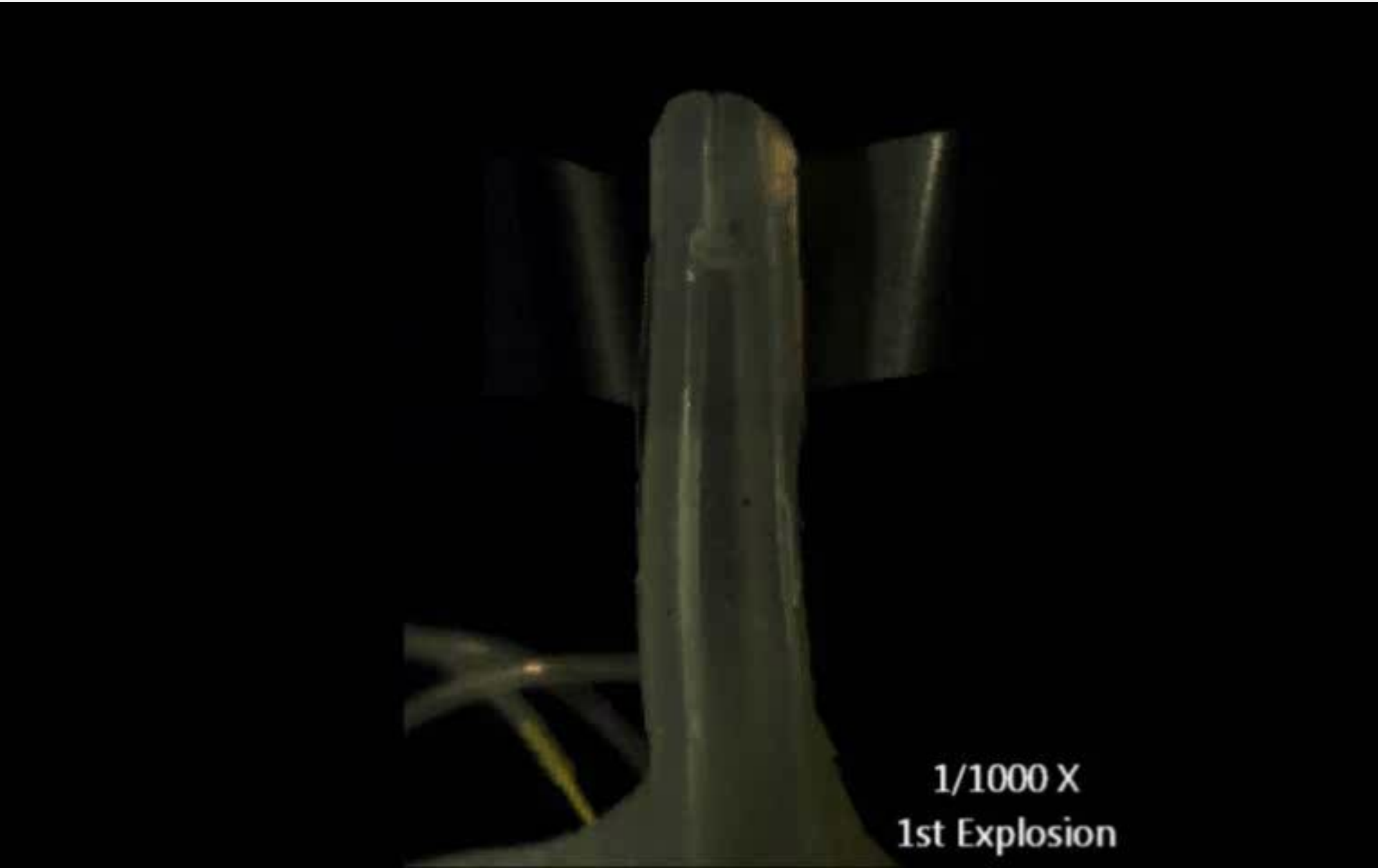
Shepherd et. al, *Ang. Chem. Int.* (2013)



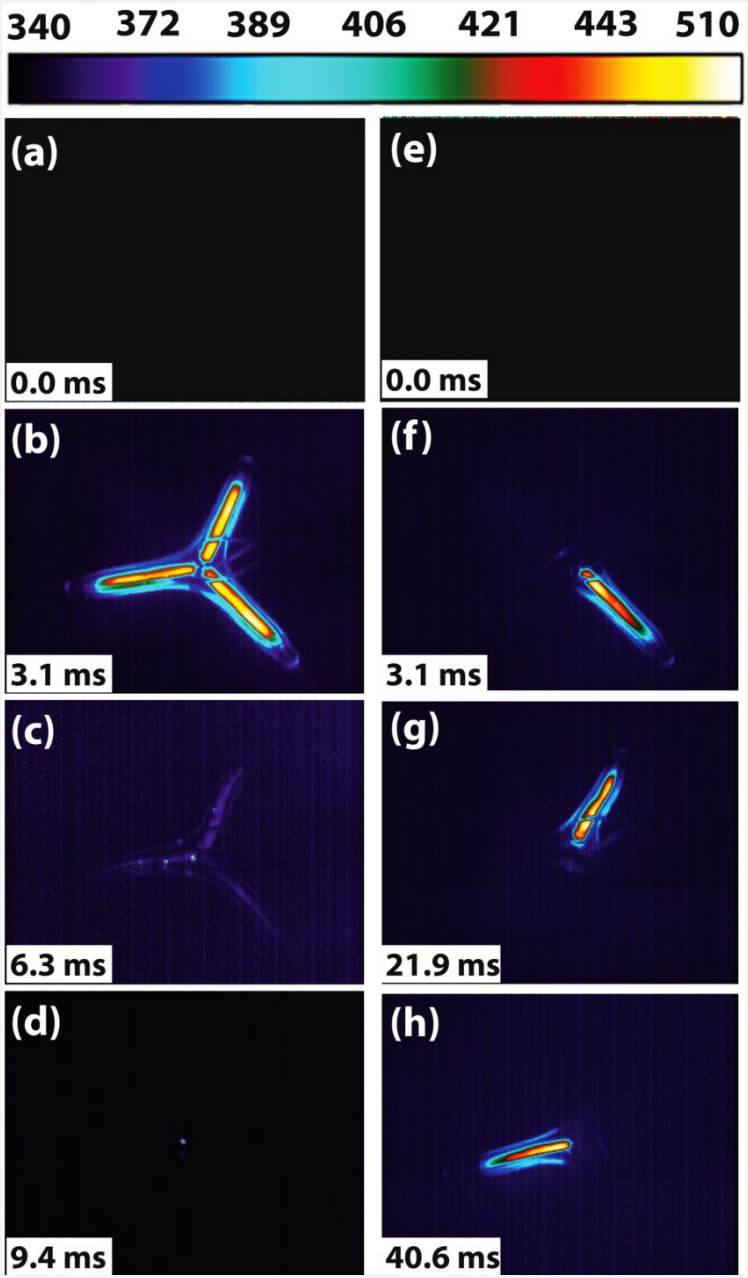
Soft flap acts as a pressure valve

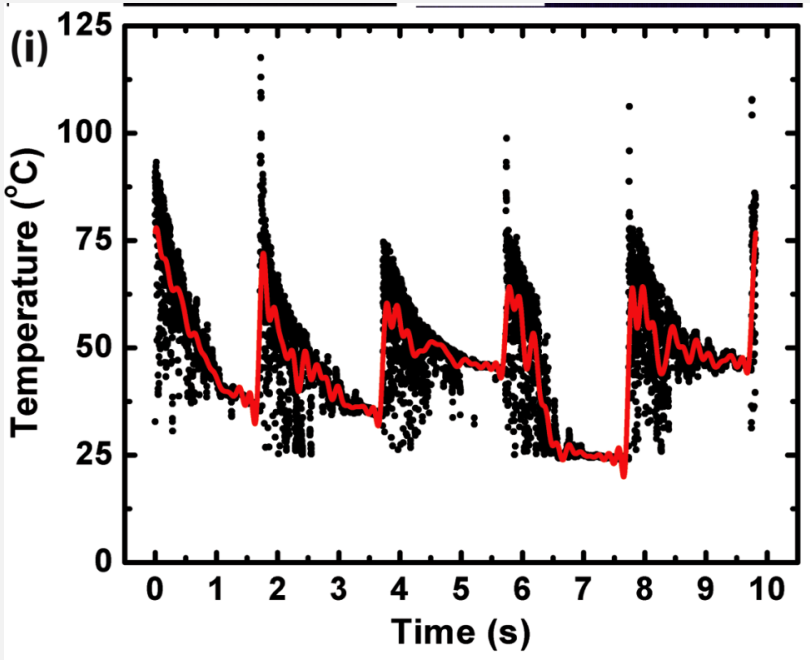


Soft flaps act as a passive valve

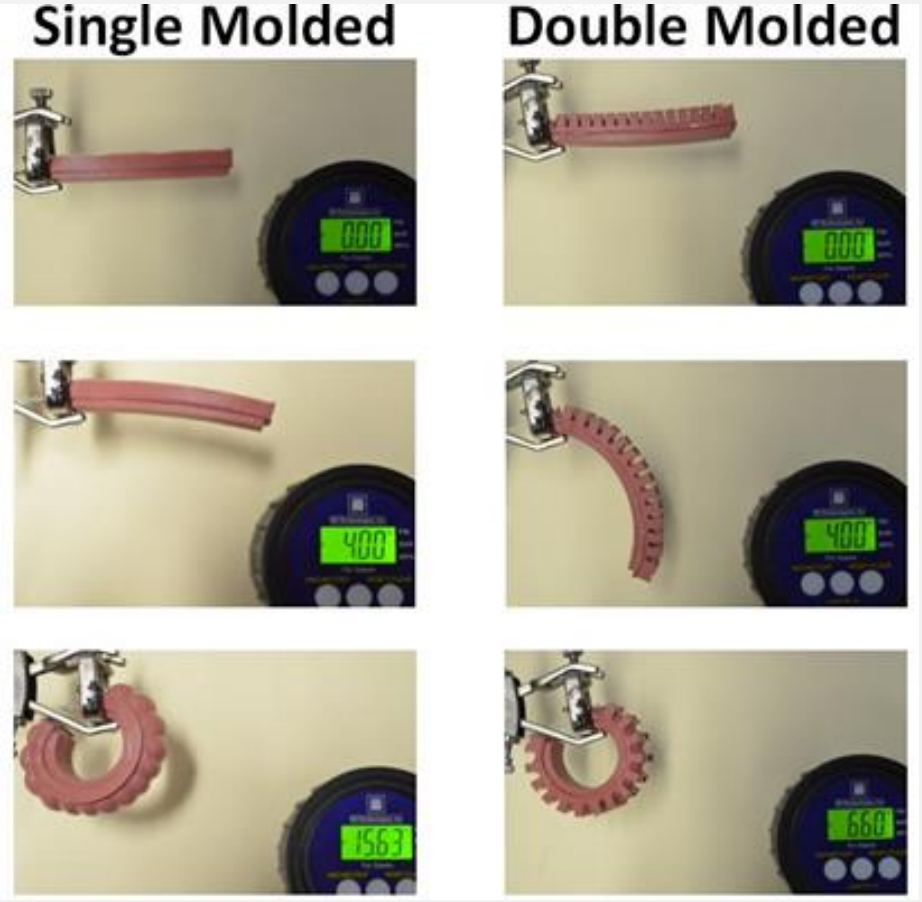


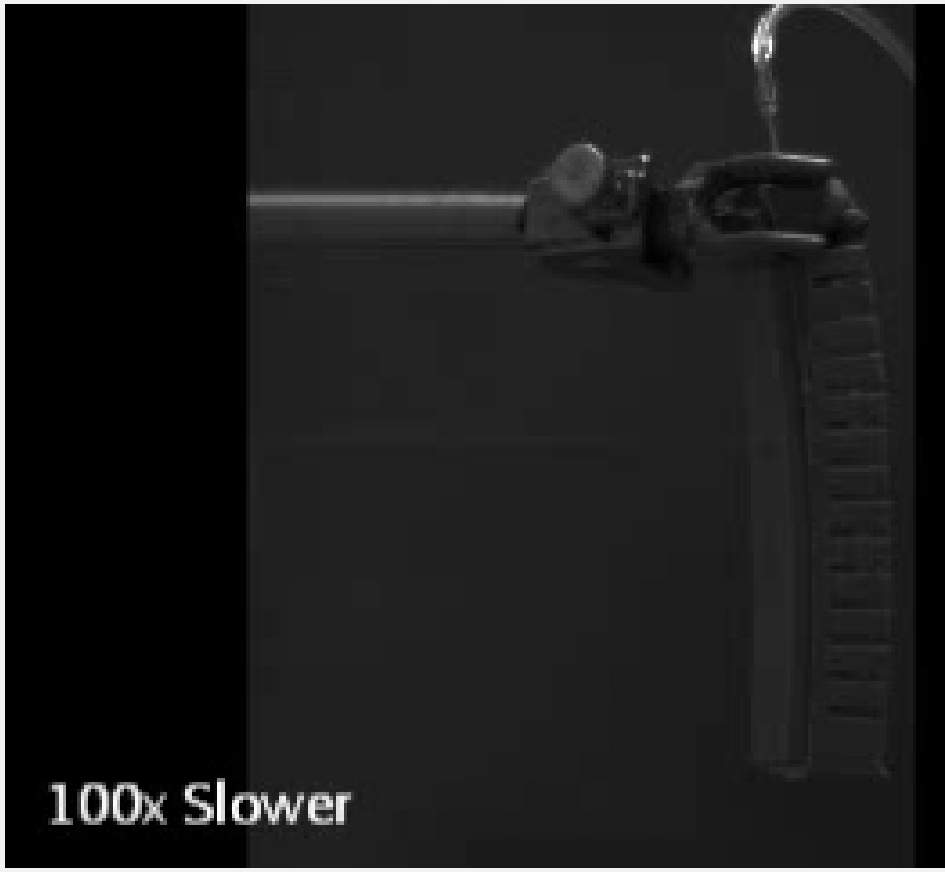
Temperatures compatible with silicone





Reticulated pneu-net design for fast actuation





Strain directed more towards the active degree of freedom than single molded

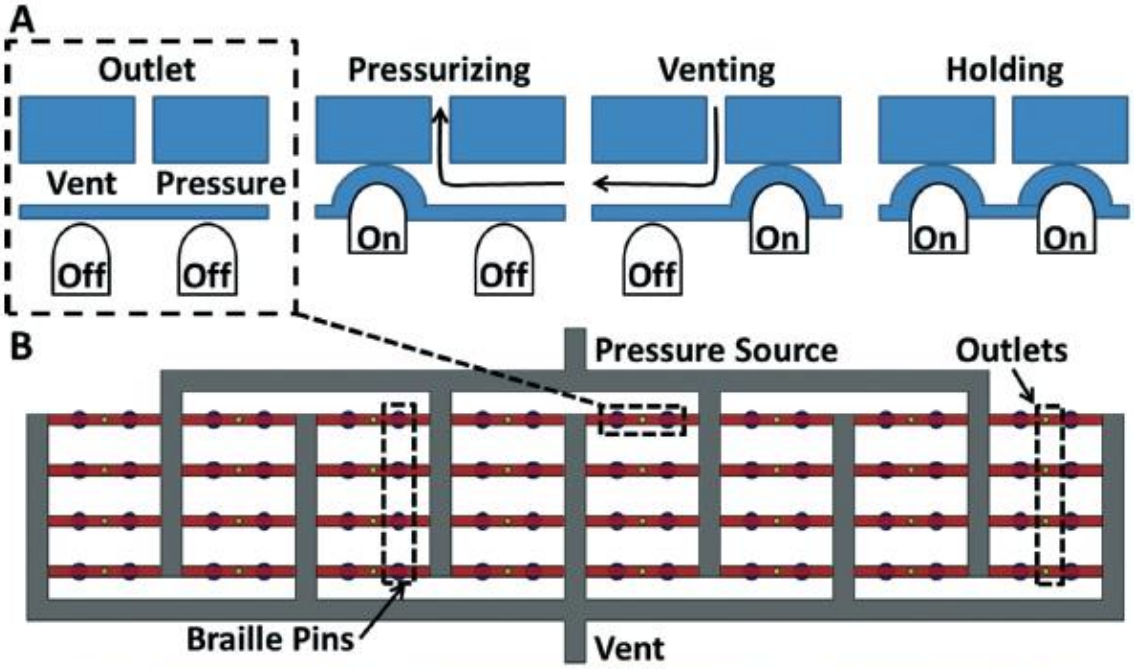
More efficient and rapid actuation

Mosadegh et. al Adv. Fun. Mat. (2014)

Reticulated pneu-net design, slide 2

Mosadegh et. al Adv. Fun. Mat. (2014)

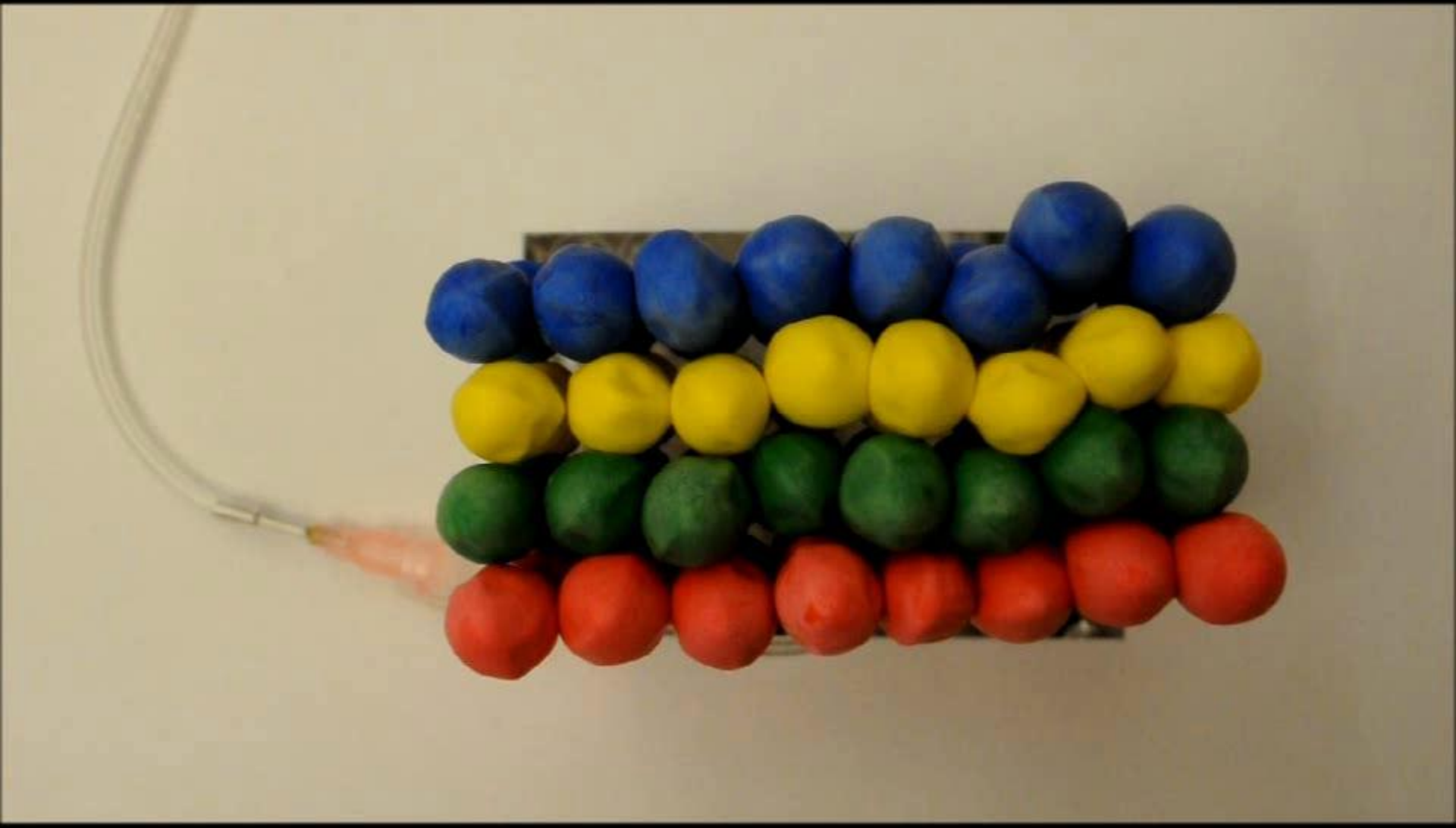
Multiplexed Pressure Inputs



A single pressure input can control 32 actuators via Braille display

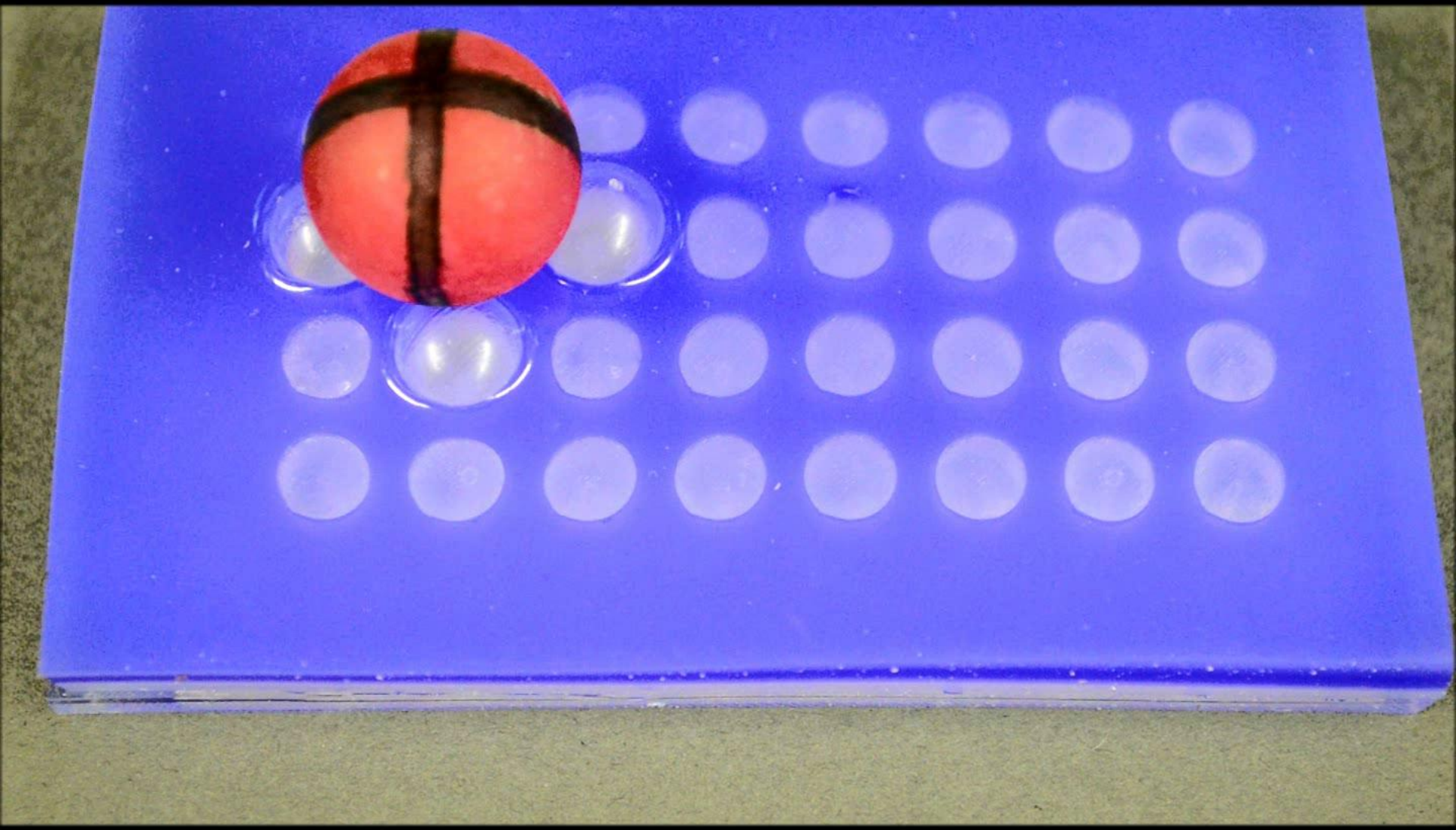
Mosadegh, et. al, Lab on a Chip *(2013)*

Multiplexed Pressure Inputs



Mosadegh, et. al, Lab on a Chip *(2013)*

Multiplexed Pressure Inputs

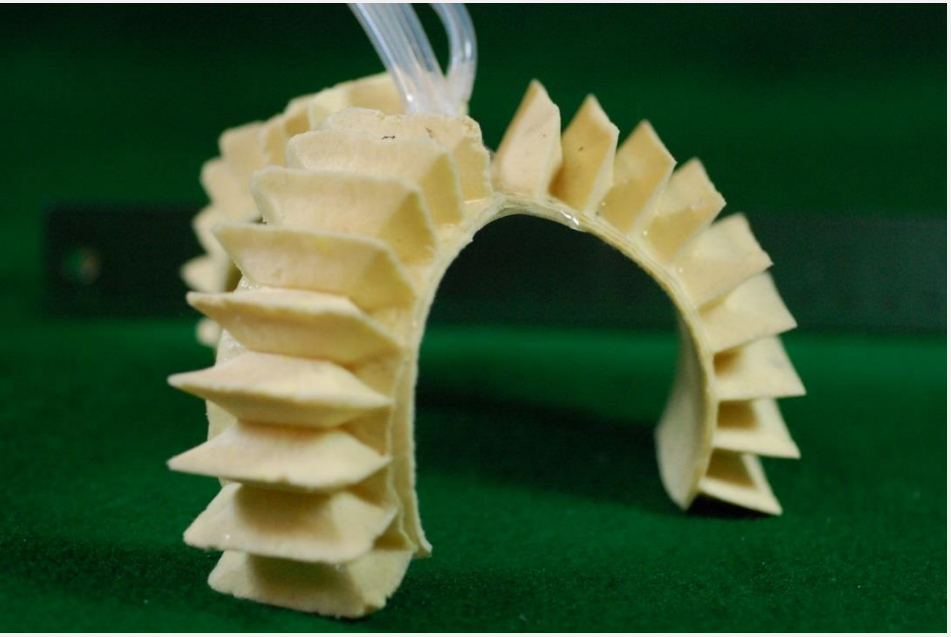


Mosadegh, et. al, Lab on a Chip *(2013)*

Improving the sensitivity to

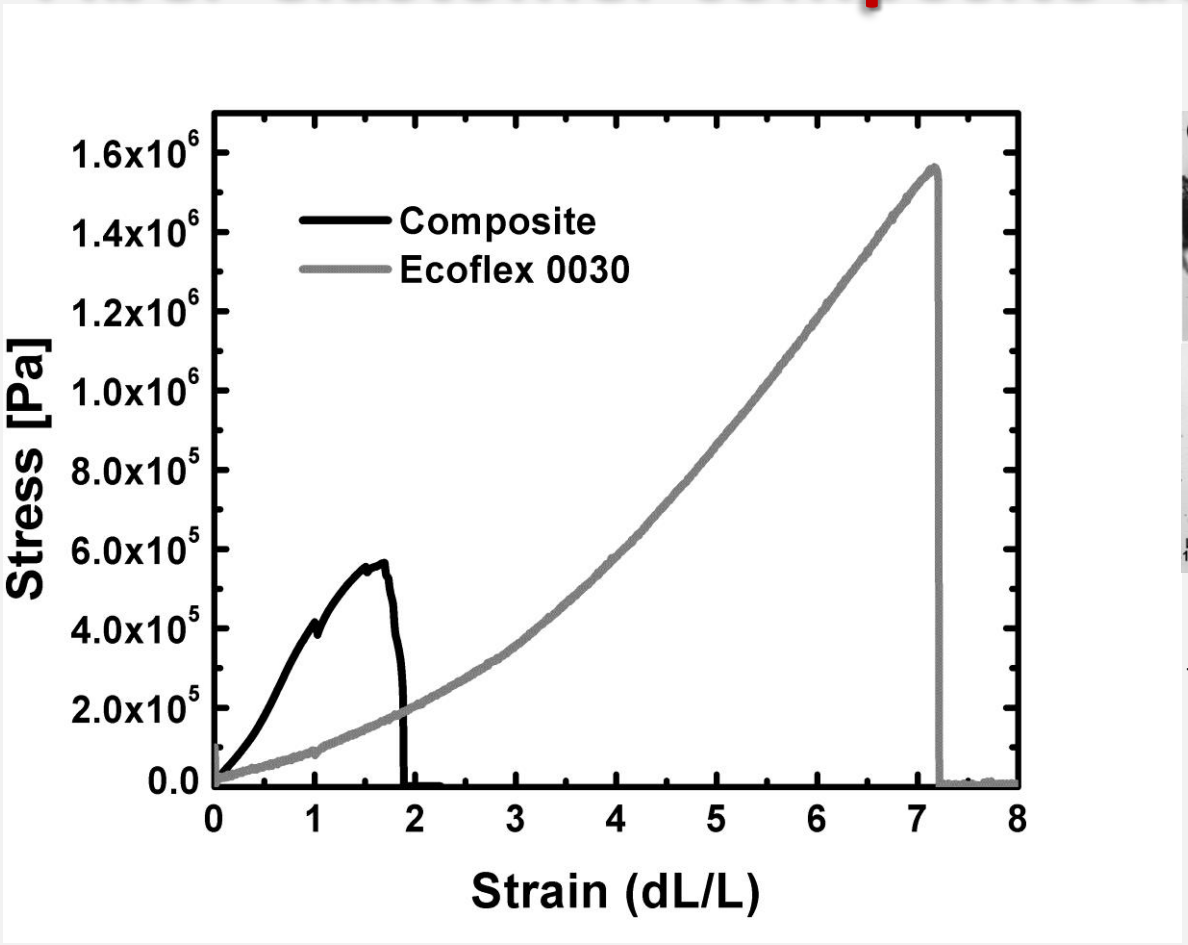
puncture from sharp objects

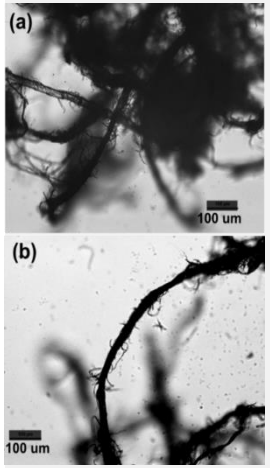
Puncture resistance & self sealing



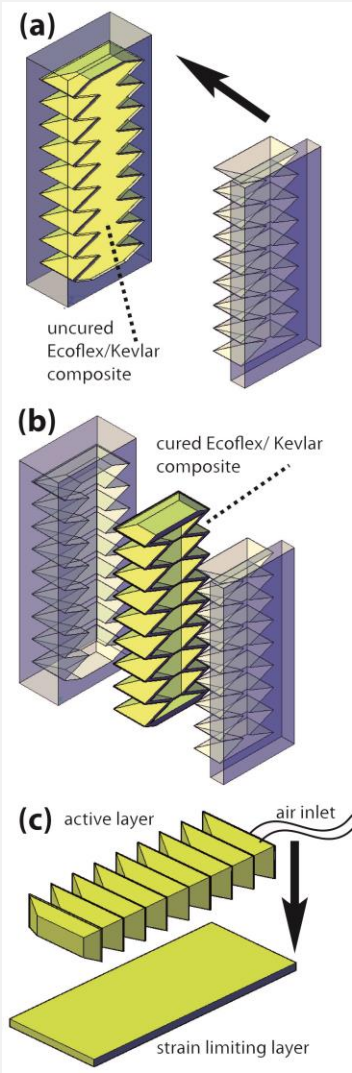
Shepherd et. al, *Adv. Mat.* (2014)

Fiber-elastomer composite actuators

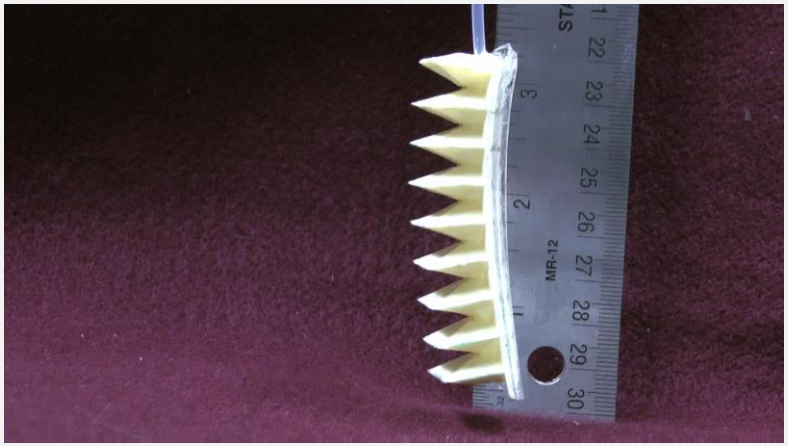


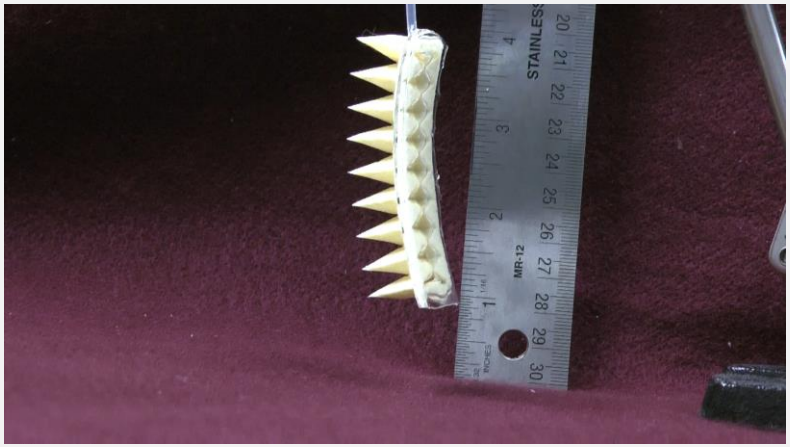


Polyaramid fibers



Bimorphic actuation from single input

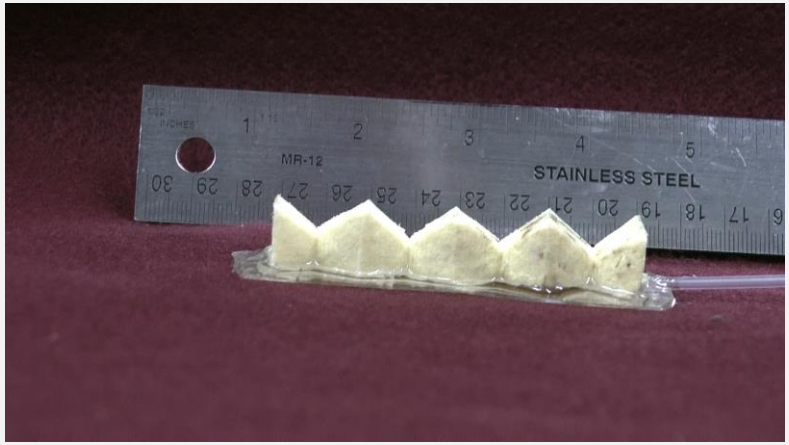




Positive curvature with positive pressure

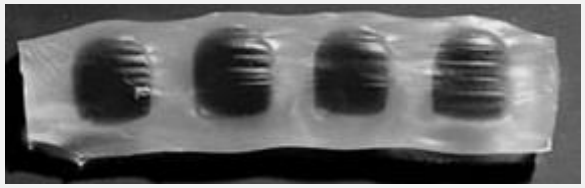
Negative curvature with vacuum

Increasing number of pleats increases curvature

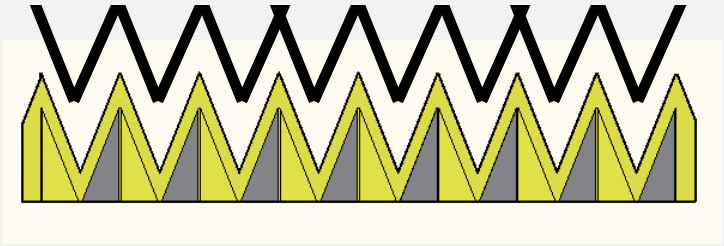


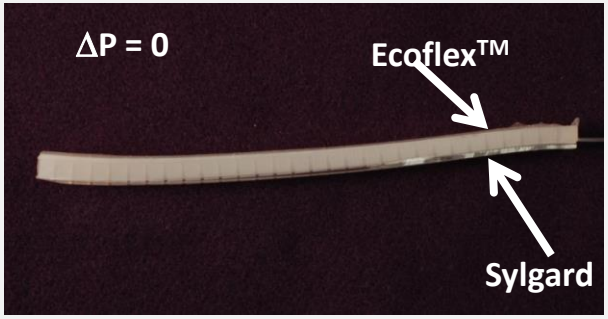
ACTUATOR GEOMETRY'S CONTRIBUTION TO CURVATURE

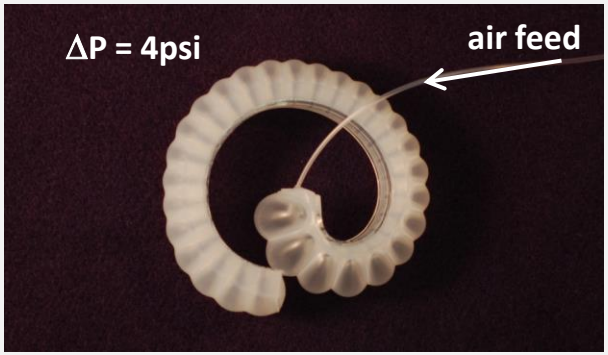
active volume

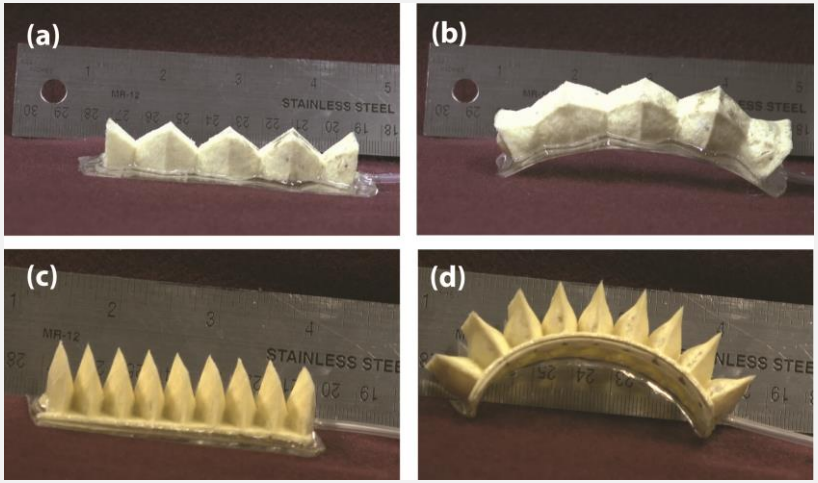


active volume



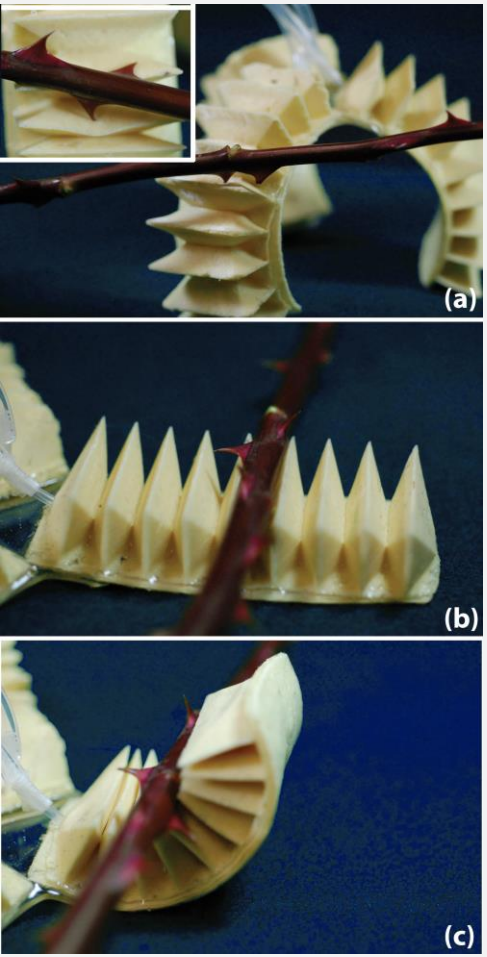


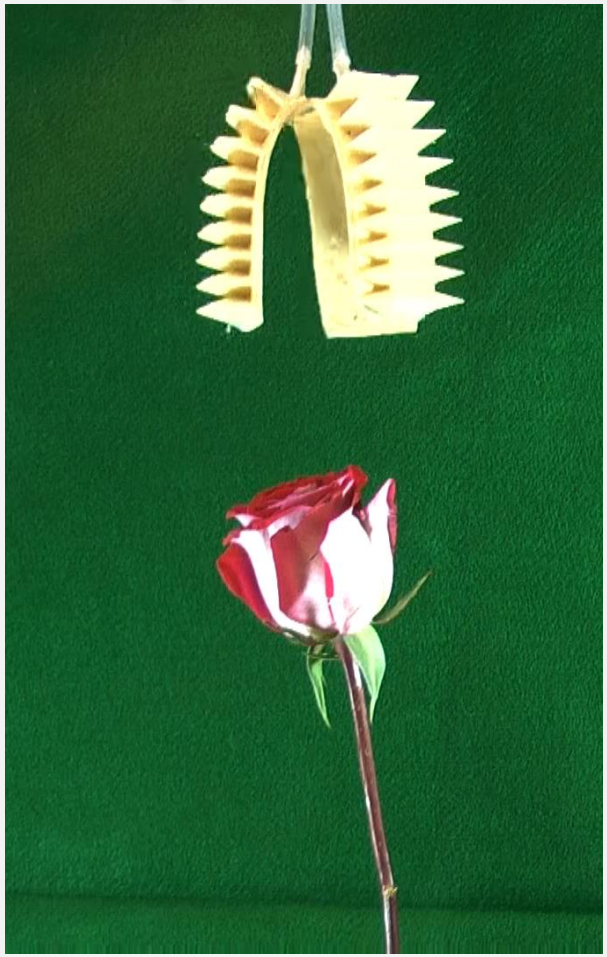


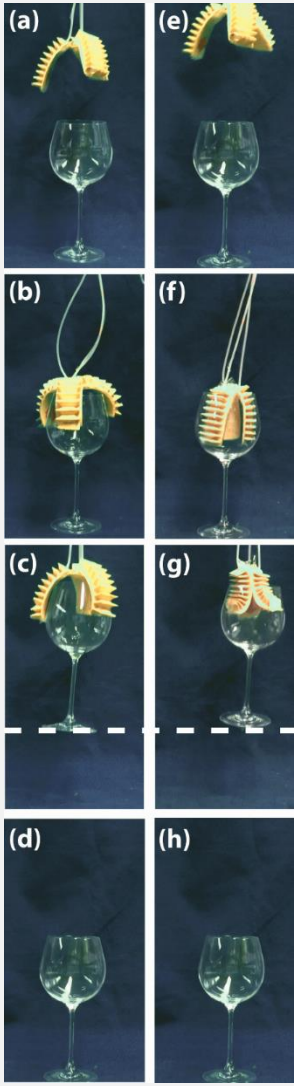


The curvature depends on the volume of material that is available to stretch

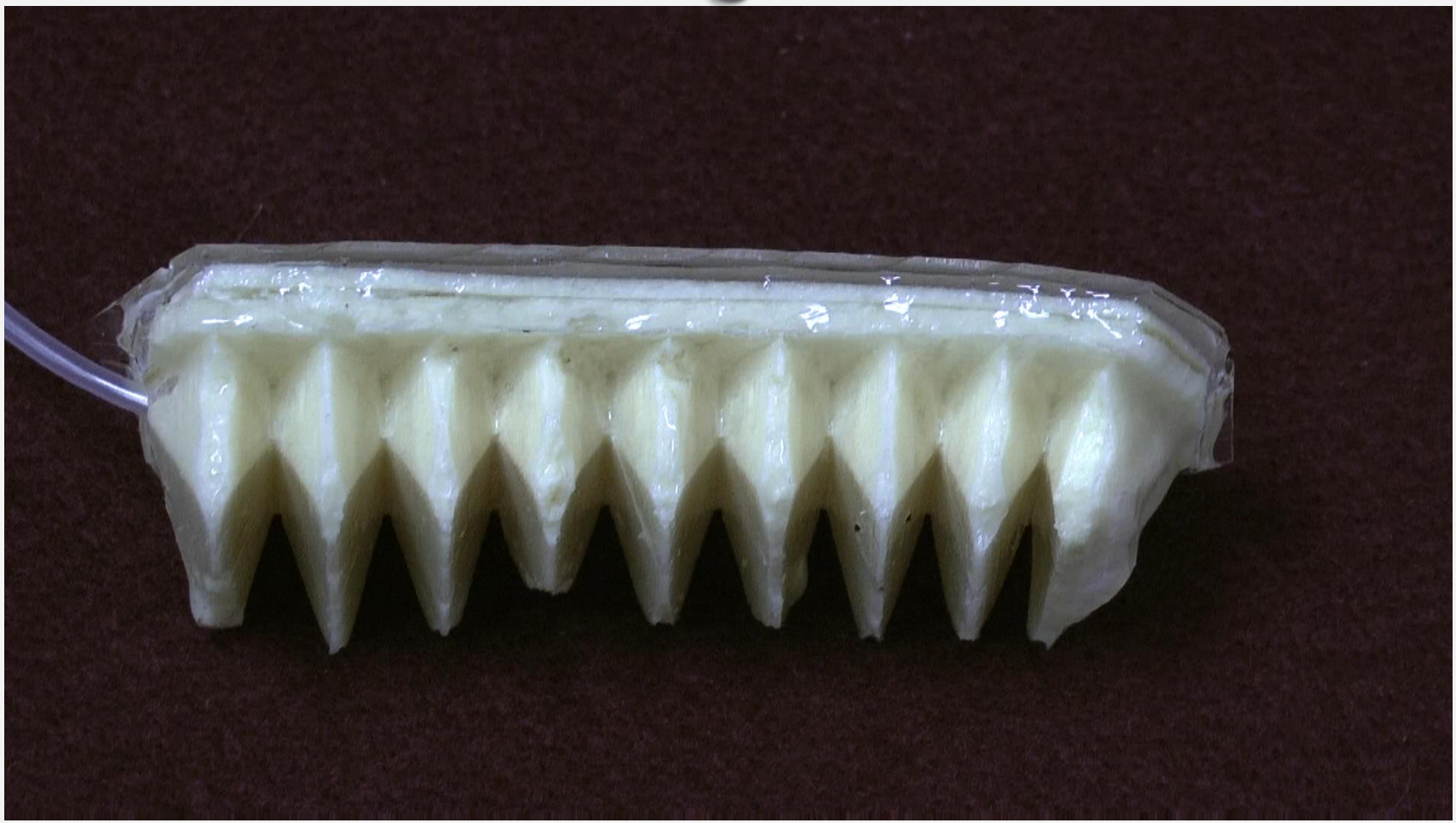
Fiber-elastomer composite actuators







Self sealing actuators



Highly collaborative effort

Collaborators:

George Whitesides, Adam Stokes, Steve Morin, Filip Ilievski, Aaron Mazzeo, Ramses Martinez

Rob Wood, Mike Tolley, Kevin Galloway, Mike Karpelson

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DARPA (W911NF-11-1-0094; W911NF-08-1-0143)