ME 23N: Soft Robots for Humanity
Autumn 2019

Week 1:
Introduction to soft robotics, compliance, and bio-inspiration

Allison M. Okamura
Stanford University

What is a soft robot?

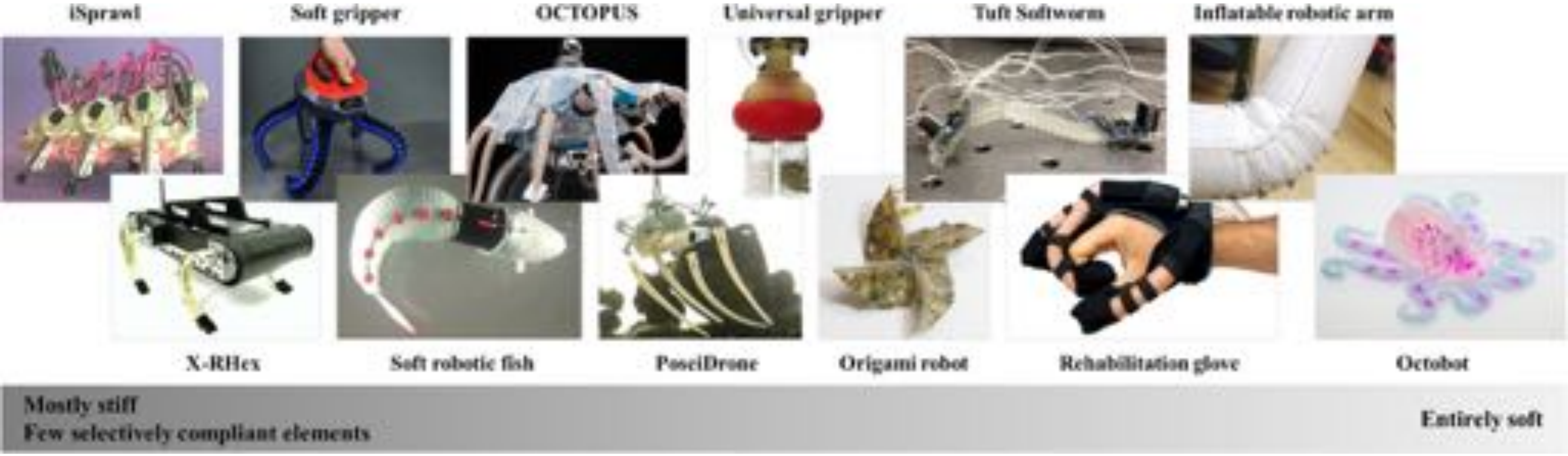


Image reproduced from a review article by Laschi, Mazzolai, and Cianchetti:
"Soft robotics: Technologies and systems pushing the boundaries of robot abilities", *Science Robotics* 2016

- Soft robots are soft by material, structure, or control
- Soft materials are flexible and/or stretchable

Teaching Team

Allison Okamura

Ari Brown

Laura Blumenschein

Tita Kanjanapas

Introductions

- Name (and nickname if you have one!)
- Hometown (or where you grew up)
- One thing about yourself that you probably **share** with a lot of people in this room
- One thing about yourself that might be **unique** in this room
- What **major(s)** are you thinking about?
- What do you hope to get out of this class?

What is this class about?

We will discuss what makes a robot soft, the tools and design approaches for creating soft robots, and what advantages and challenges result from using soft materials and compliant structures.

Students will get hands-on experience building soft robots using various materials, actuators, and programming to create robots that perform different tasks.

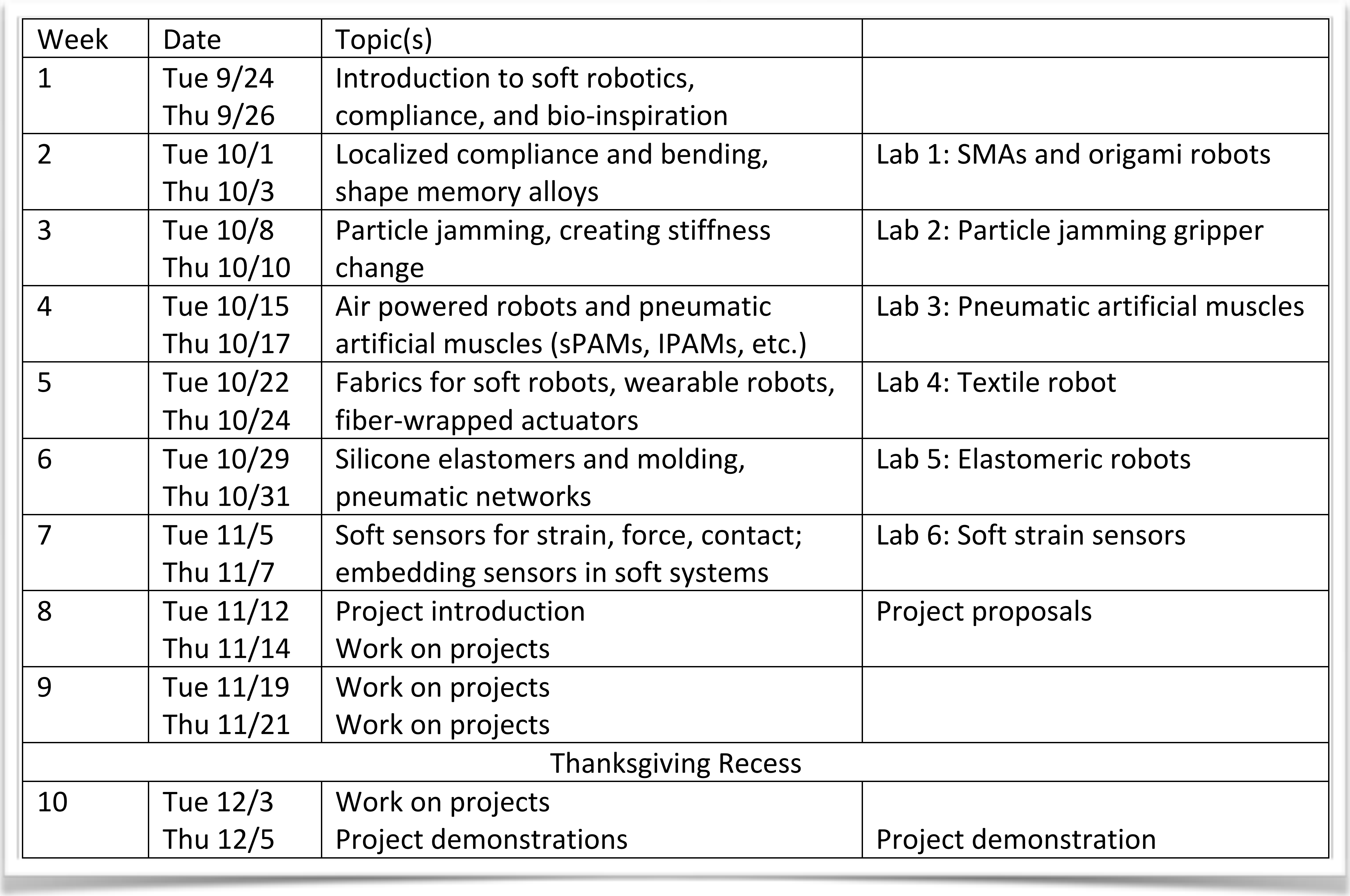
Through this process, students will gain an appreciation for the capabilities and limitations of bio-inspired systems, use design thinking to create novel robotic solutions, and gain practical interdisciplinary engineering skills related to robotics, mechanical engineering, and bioengineering.

Objectives

By the end of this class, you will:

1. Be familiar with the growing field of soft robotics
2. Understand the design concepts behind compliant design and bio-inspired design
3. Develop designing and prototyping skills to create and control soft robotic systems
4. Design and build a new soft robotic system that accomplishes a beneficial task

Schedule



Week	Date	Topic(s)	
1	Tue 9/24 Thu 9/26	Introduction to soft robotics, compliance, and bio-inspiration	
2	Tue 10/1 Thu 10/3	Localized compliance and bending, shape memory alloys	Lab 1: SMAs and origami robots
3	Tue 10/8 Thu 10/10	Particle jamming, creating stiffness change	Lab 2: Particle jamming gripper
4	Tue 10/15 Thu 10/17	Air powered robots and pneumatic artificial muscles (sPAMs, IPAMs, etc.)	Lab 3: Pneumatic artificial muscles
5	Tue 10/22 Thu 10/24	Fabrics for soft robots, wearable robots, fiber-wrapped actuators	Lab 4: Textile robot
6	Tue 10/29 Thu 10/31	Silicone elastomers and molding, pneumatic networks	Lab 5: Elastomeric robots
7	Tue 11/5 Thu 11/7	Soft sensors for strain, force, contact; embedding sensors in soft systems	Lab 6: Soft strain sensors
8	Tue 11/12 Thu 11/14	Project introduction Work on projects	Project proposals
9	Tue 11/19 Thu 11/21	Work on projects Work on projects	
Thanksgiving Recess			
10	Tue 12/3 Thu 12/5	Work on projects Project demonstrations	Project demonstration

me23n.stanford.edu

d’Arbeloff Lab Rules

- You can enter the room any time another class is not in session https://meintranet.stanford.edu/faculty-intranet/d-arbeloff-undergraduate-research-and-teaching-lab
- Respect other students’ projects, activities of other classes, etc.
- Never leave your items on the benches when you are not in the room (put them on a labeled shelf)
- Leave the room better than you found it
- Note that this room is not very secure

To Do

- Pick your **favorite robot** from fiction or media. I will send a link for where you can enter your robot name and upload a picture. No repeats, please — so check the list of robot names before you enter your robot.

- Before class on Thursday, think about and be prepared to discuss:
  - How does/could this robot function? What mechanisms might be involved?
  - What are the implications of this robot for humanity?

charmlab

tour

(If we are not running a user study!)

To Do

- Pick your **favorite robot** from fiction or media. I will send a link for where you can enter your robot name and upload a picture. No repeats, please — so check the list of robot names before you enter your robot.

- Before class on Thursday, think about and be prepared to discuss:
  - How does/could this robot function? What mechanisms might be involved?
  - What are the implications of this robot for humanity?

Groups of Two

1	Leena	Youngju
2	Caroline	Angelo
3	Brian	Alana
4	Tomas	Huy
5	Sochima	Emma
6	Cherié	Josue
7	Nick	Ellie
8	Senkai	Nadin

For 10 minutes:

Make
something with an
8.5” x 11” piece of paper

you can use tape and scissors
10 minutes

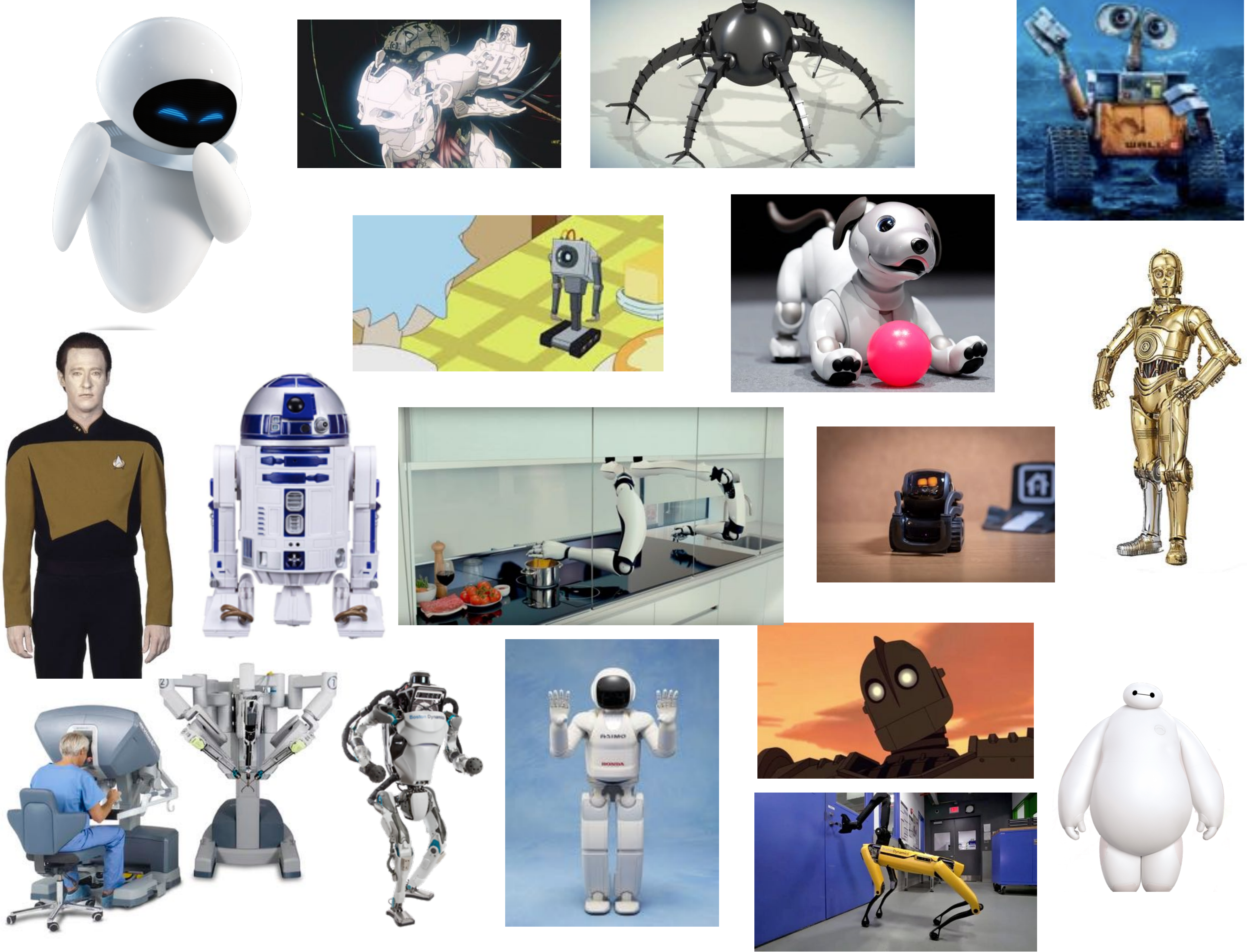
For 10 minutes:

Reflect
on what you made
in your lab notebook

Report

to the class
(if desired)

Favorite Robots


ASIMO
HONDA
Boston Dynamics

Groups of Three-ish

1	Leena	Caroline	Brian	
2	Tomas	Sochima	Cherié	
3	Nick	Senkai	Youngju	
4	Angelo	Alana	Huy	
5	Emma	Josue	Ellie	Nadin

Favorite Robots

- Discuss:
  - How does/could each of your robots function? What mechanisms might be involved?
  - What are the implications of this robot for humanity?

- Report:
  - Pick one of your robots and report to the class
  - (If you want to talk about your robot with me after class, great!)

Soft Robotics Examples

Hands-on
Haptic Medical
Simulation

Flexible
Patient-Specific
Medical Robots

Biologically
Inspired Robot
Growth

Hands-on Haptic Medical Simulation

Medical Simulation

Laerdal's SimMan

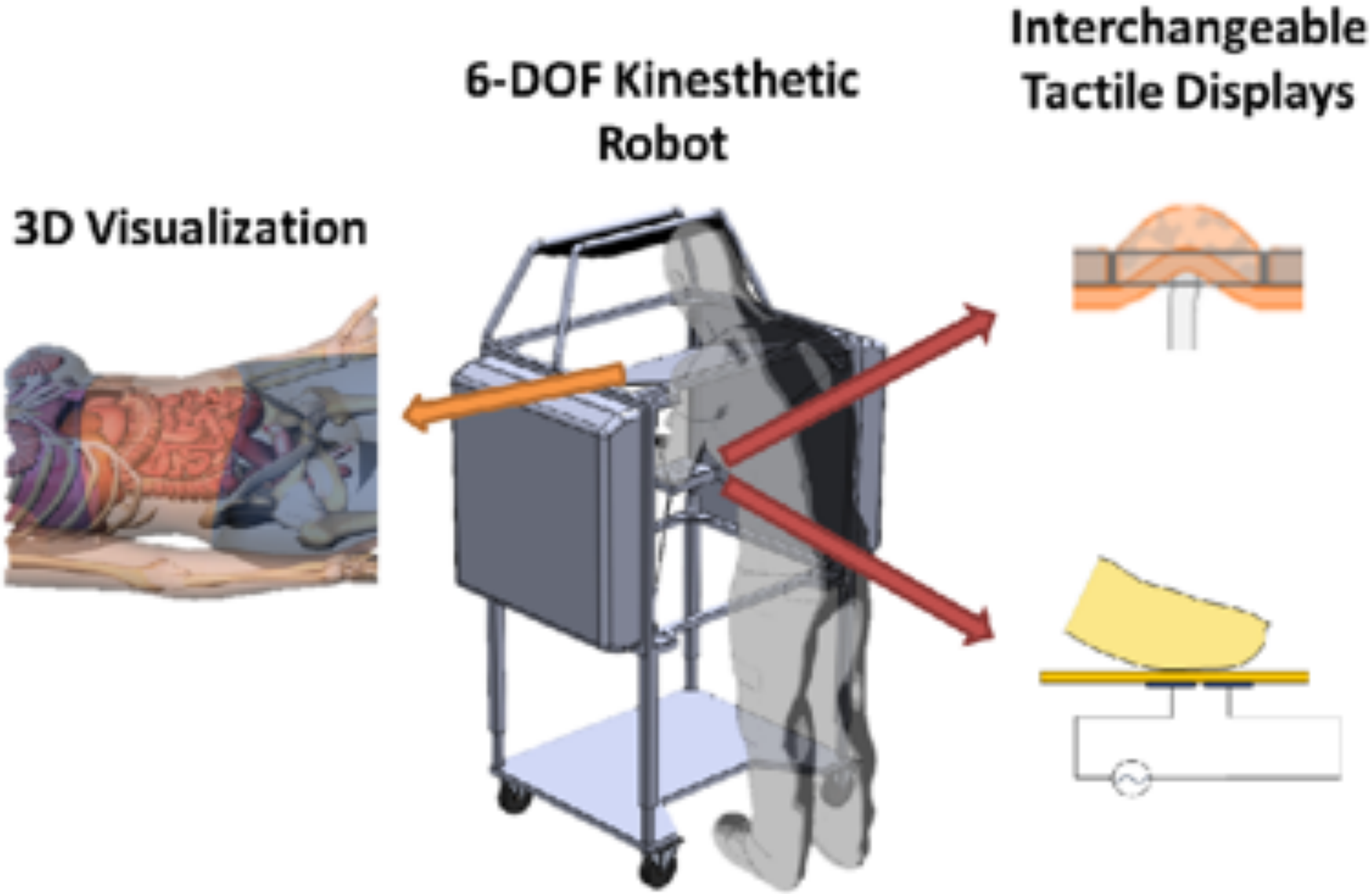
Phantom Desktop

Mannequins:
mostly passive,
tactile, multi-contact

Tool-based
interaction: active,
programmable forces

Can we have the best of both worlds?

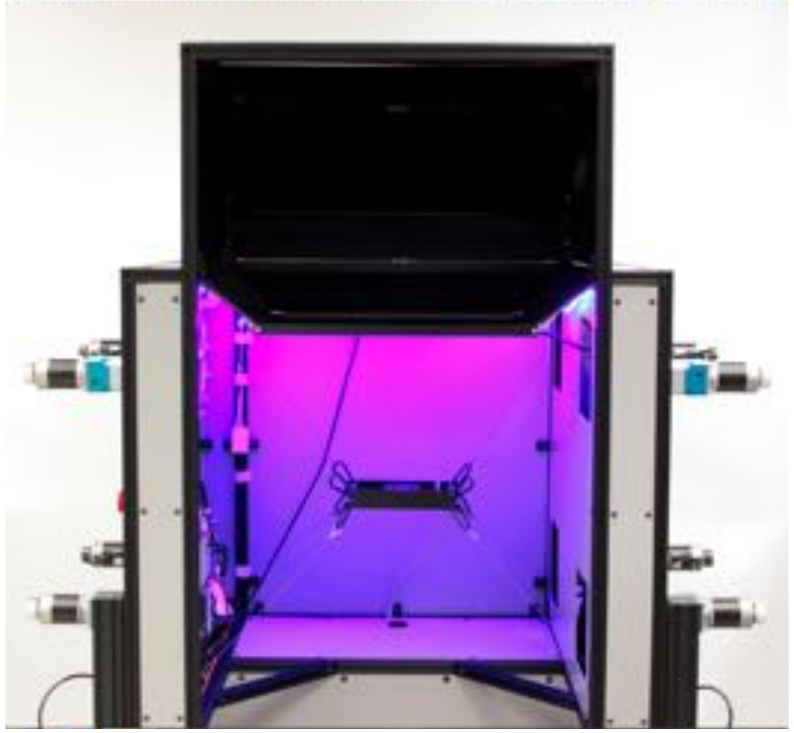
Encountered-Type Medical Simulator



3D Visualization

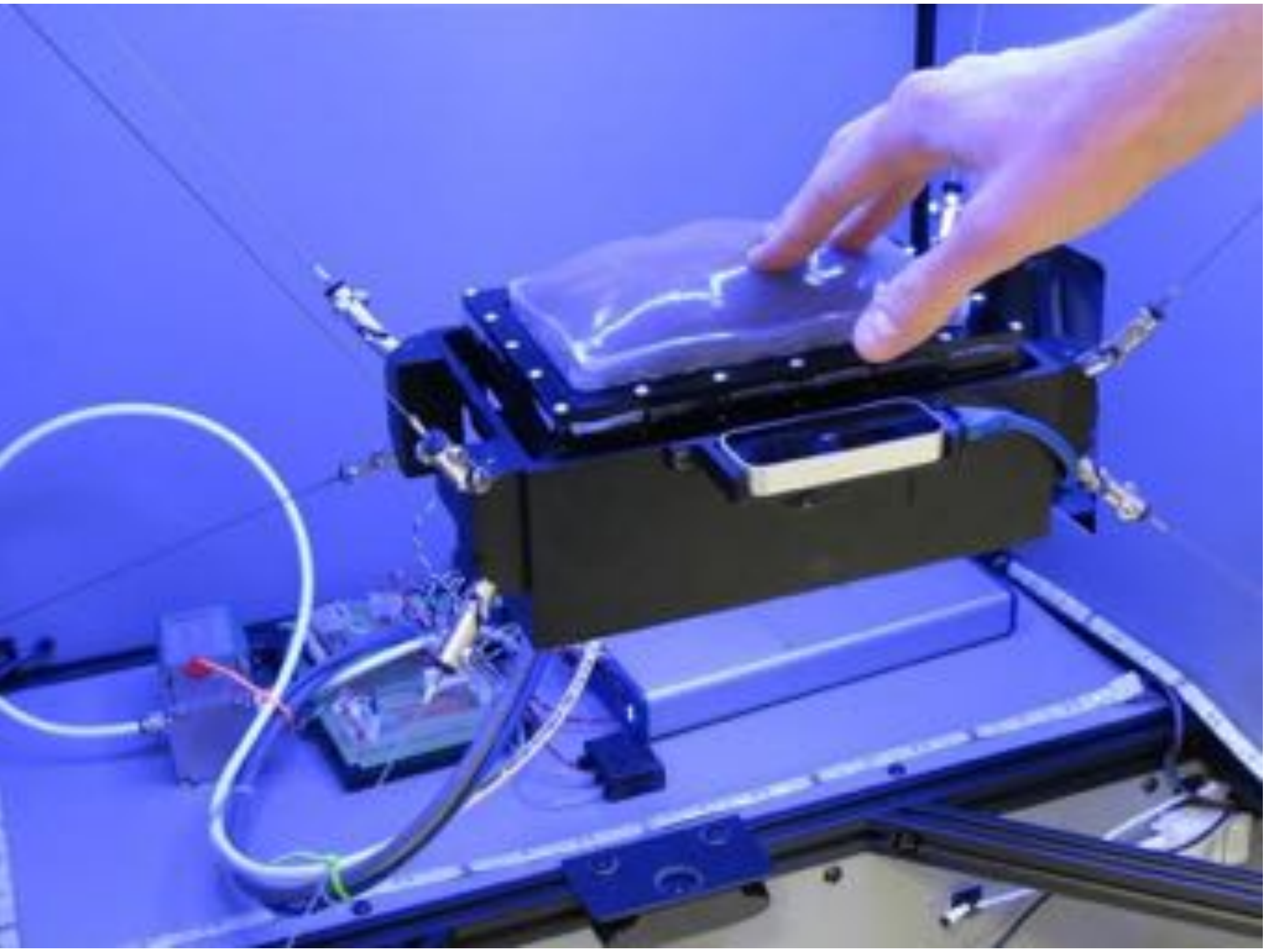
6-DOF Kinesthetic Robot

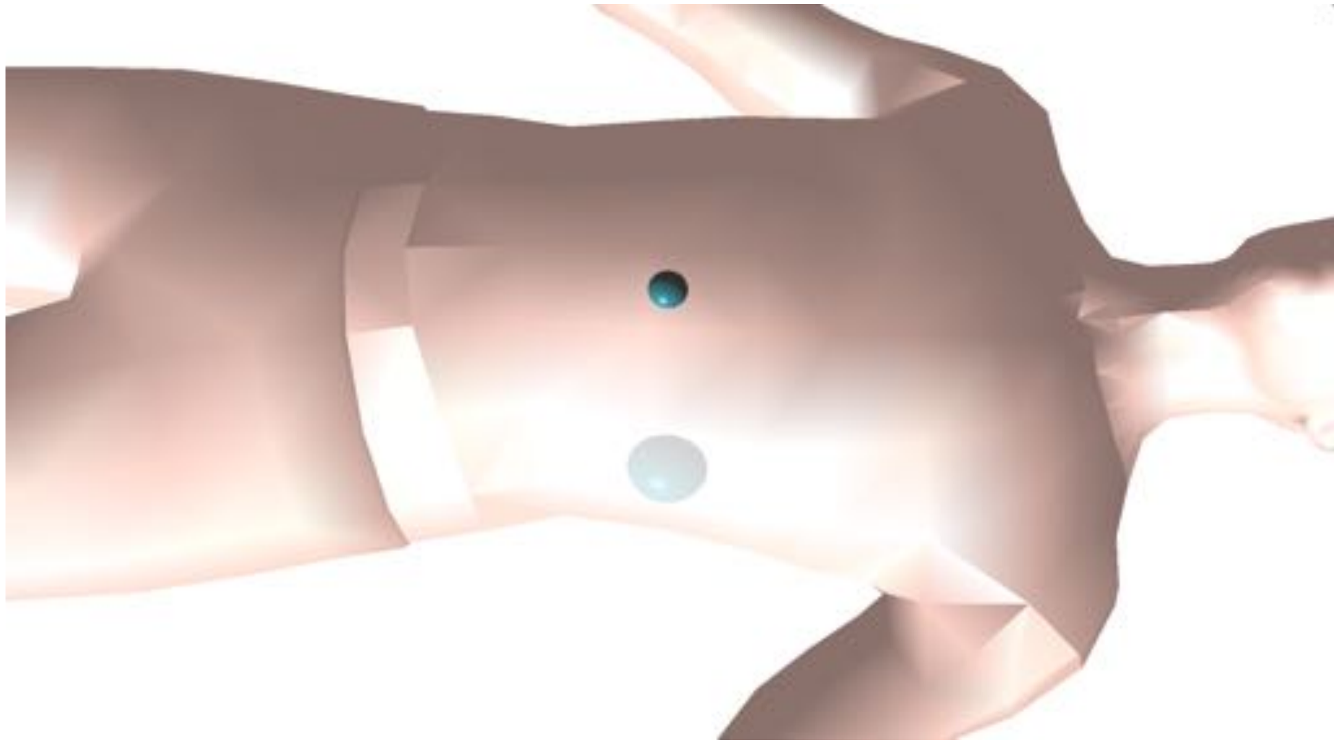
Interchangeable Tactile Displays



In collaboration with Intelligent Automation, Inc. and Tanvas, Inc.

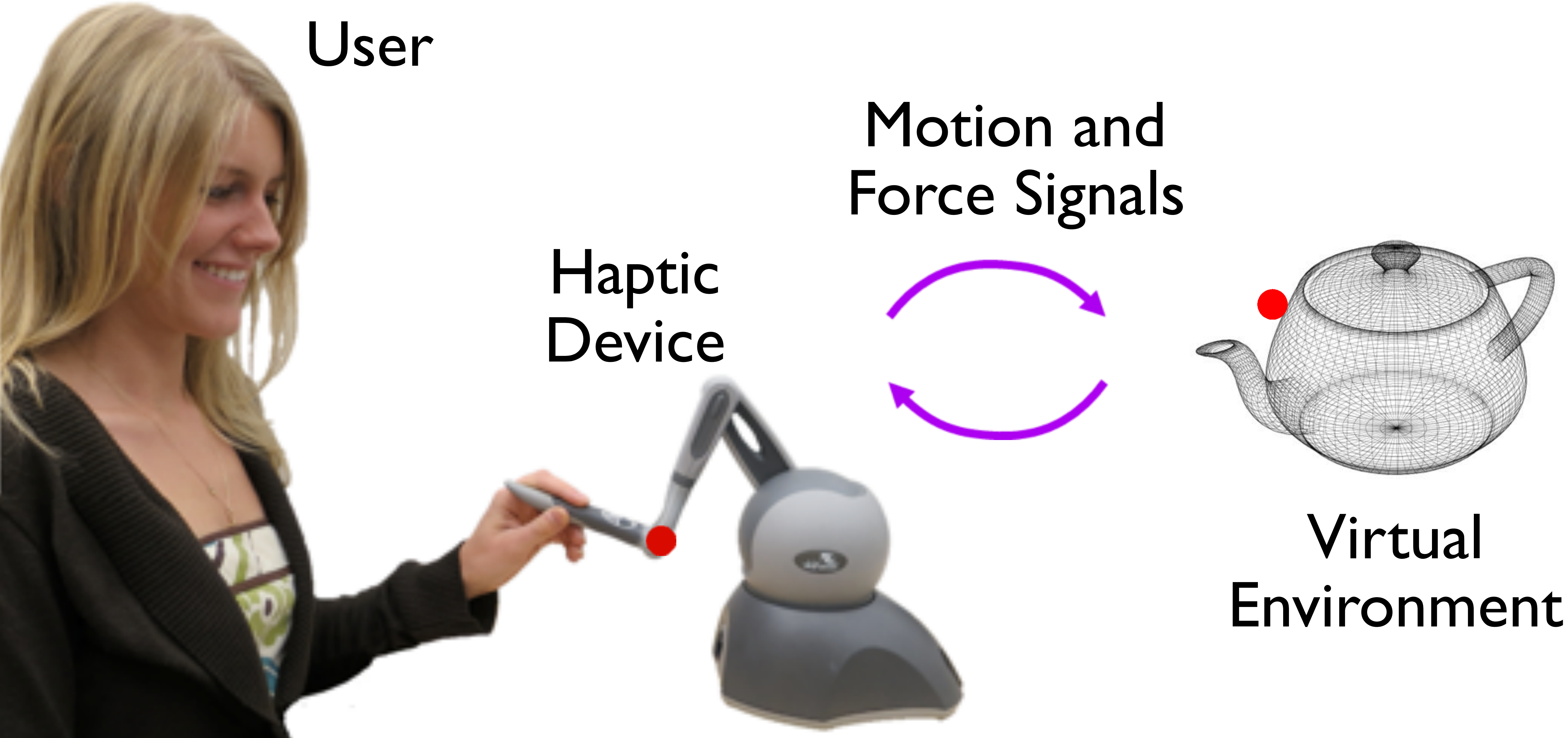
Encountered-Type Medical Simulator





Stanley & Okamura Eurohaptics 2014

Typical Force Feedback Devices



User

Haptic Device

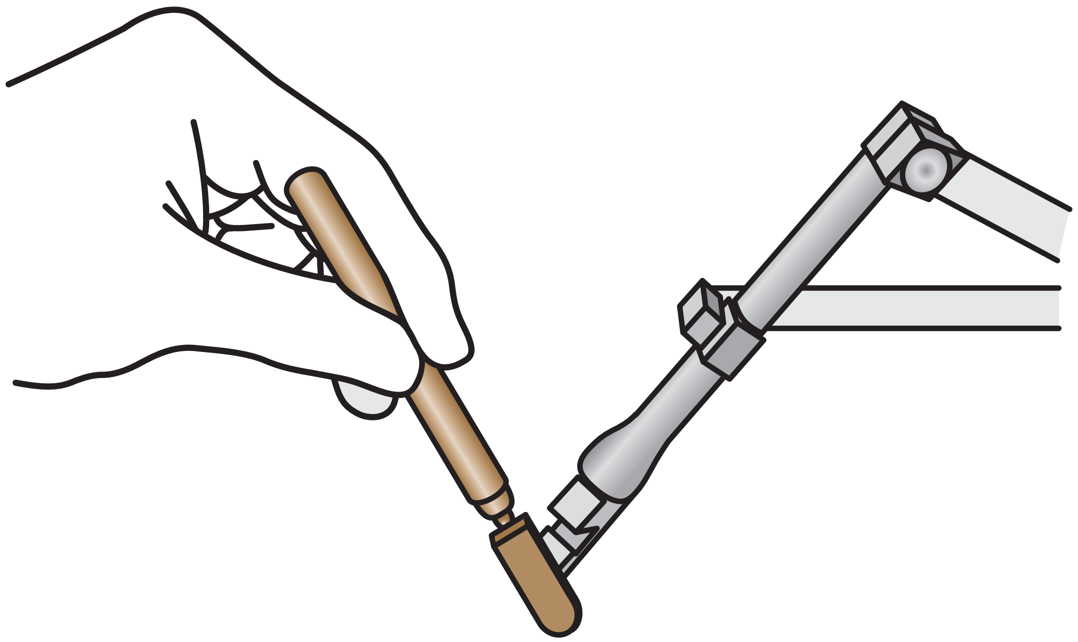
Motion and Force Signals

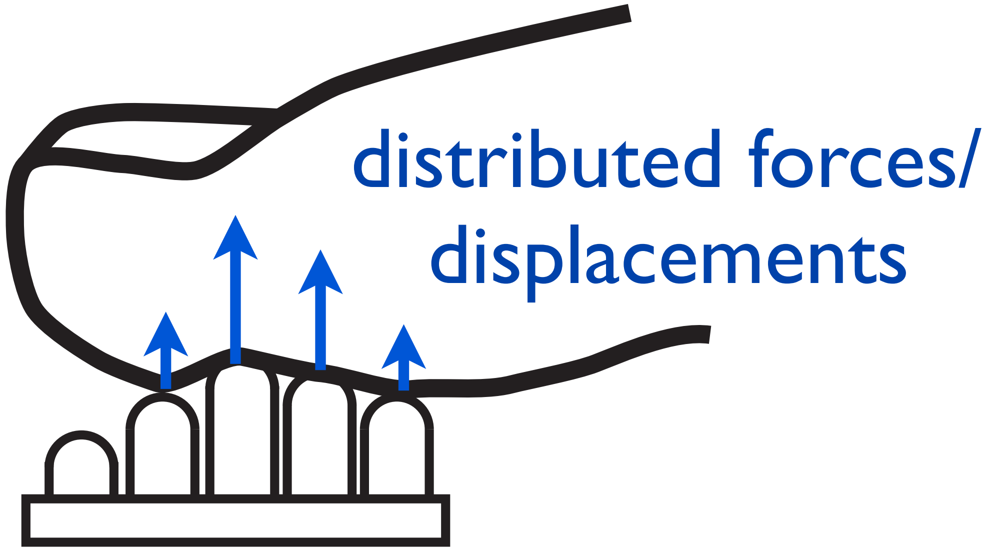
Virtual Environment

Kinesthetic vs. Cutaneous Devices

Kinesthetic (force feedback) haptic devices display forces or motions, typically through a tool

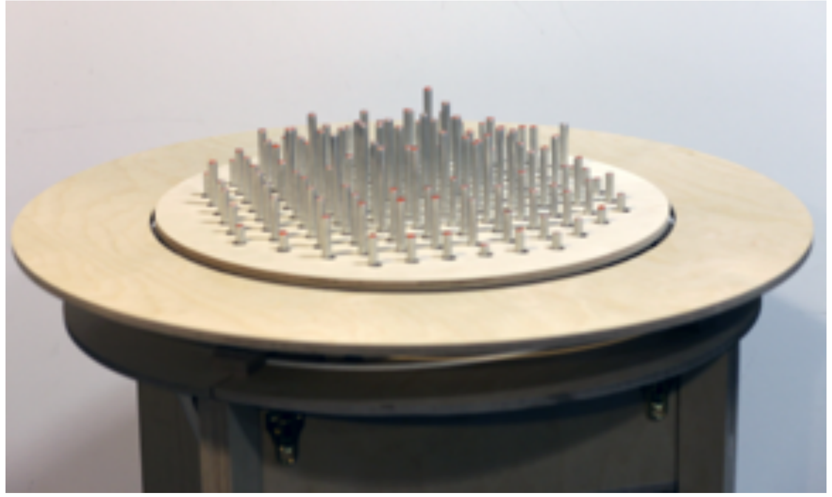
Cutaneous (tactile) haptic devices stimulate the skin



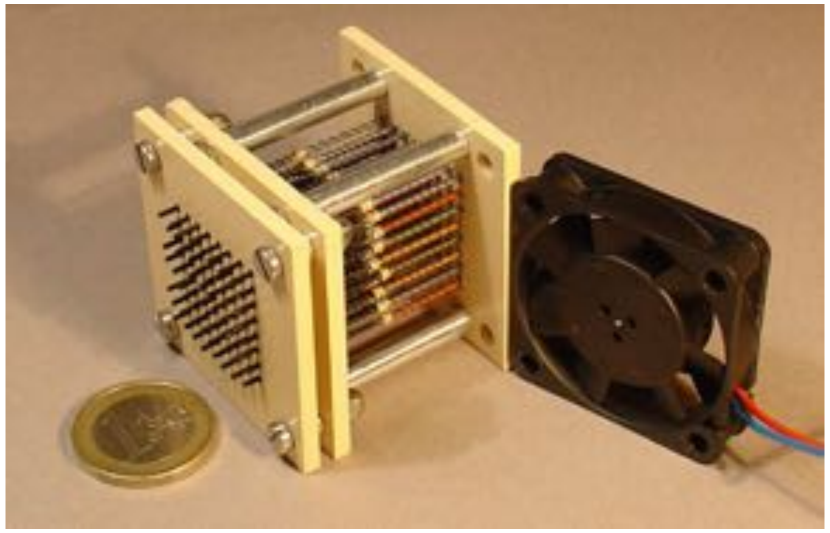


Active Surfaces do both!

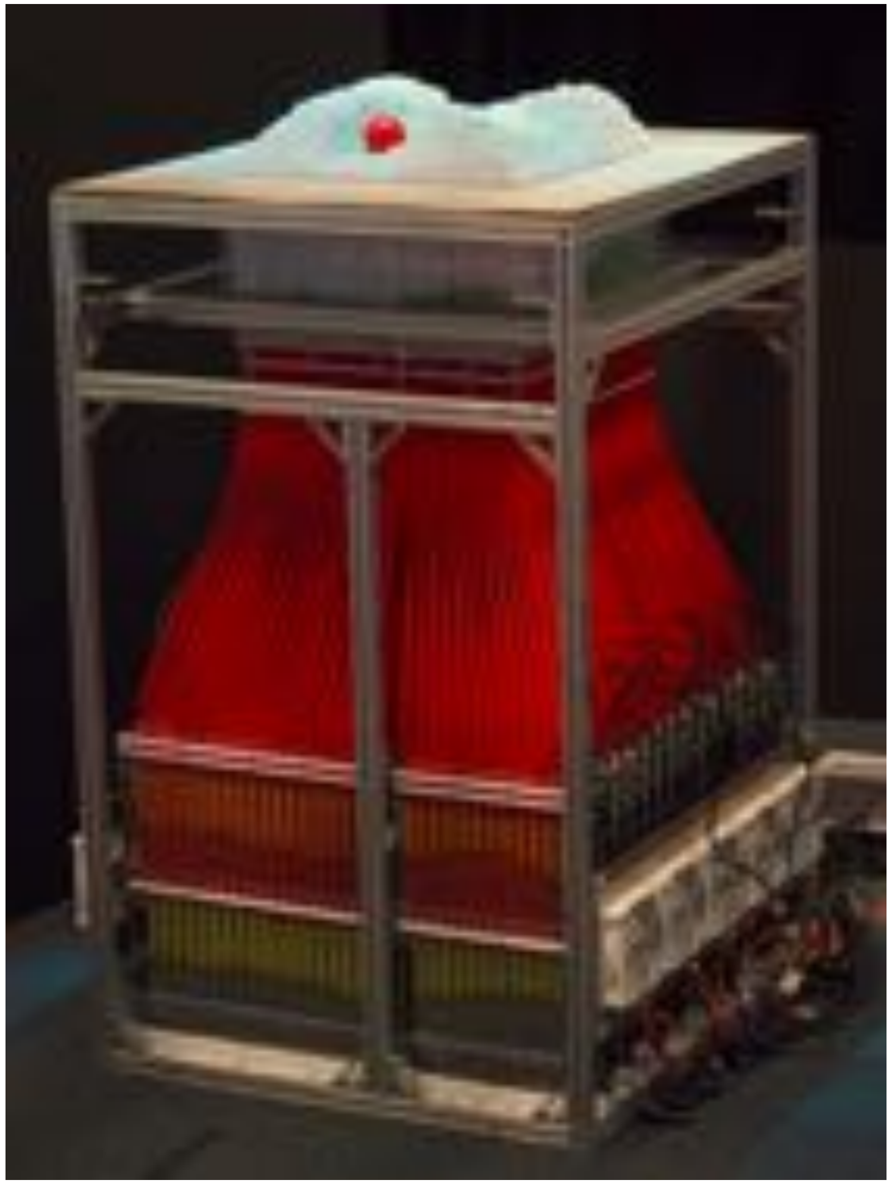
Pin Arrays and Crusts



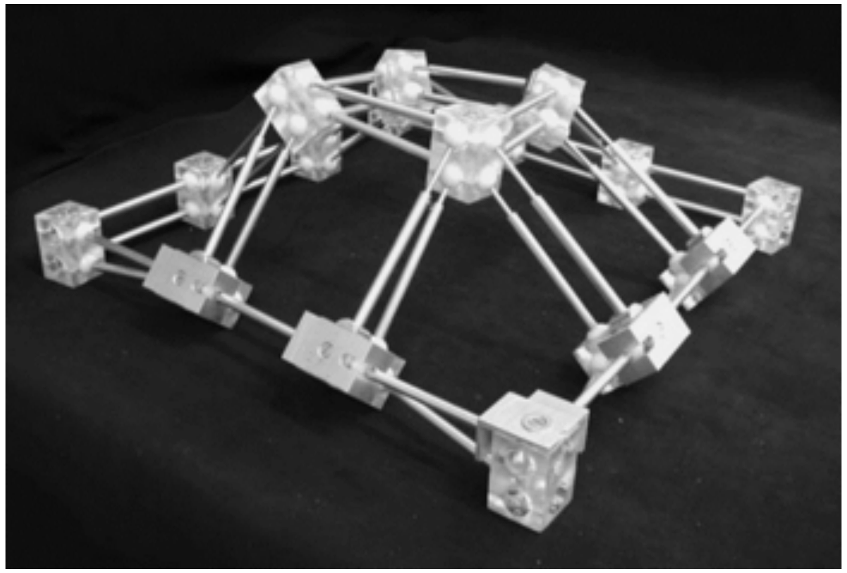
Leithinger et al. 2010



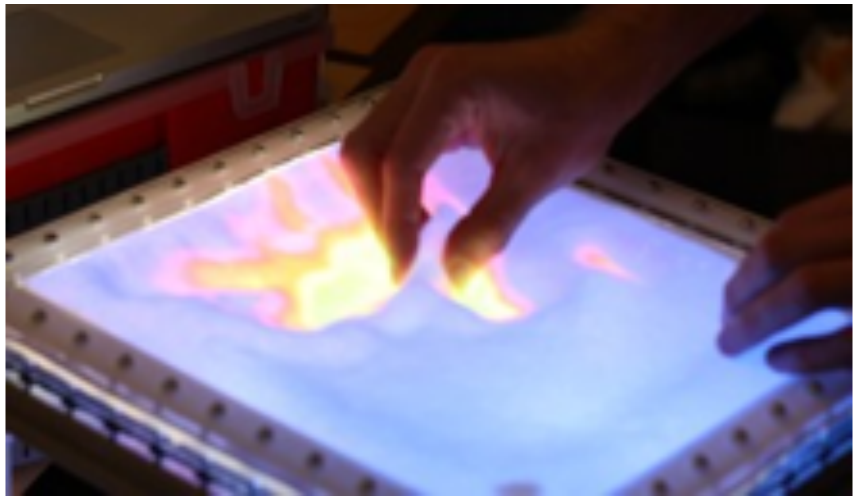
Velazquez et al. 2005



Follmer et al. 2013

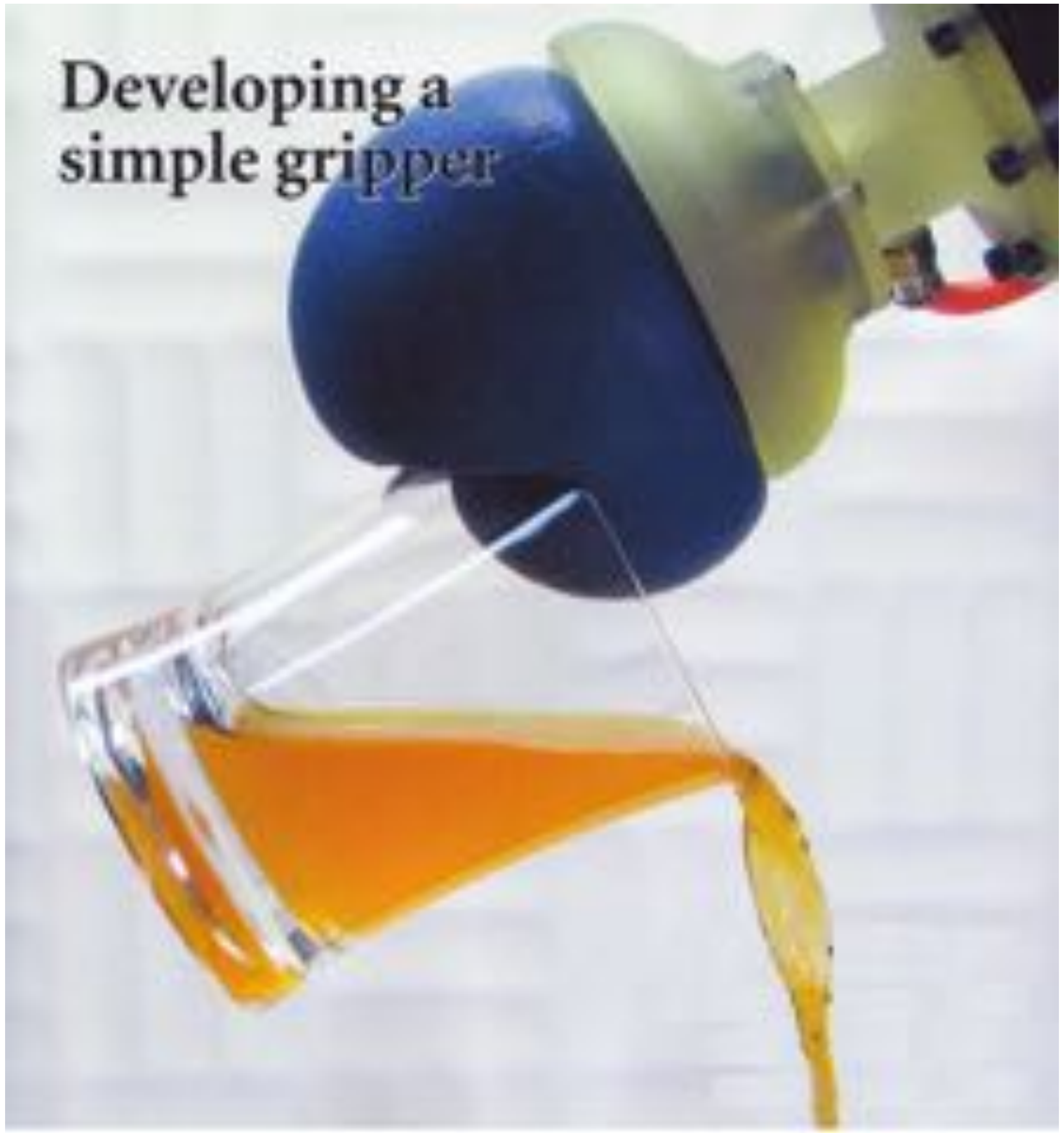


Mazzone et al. 2003



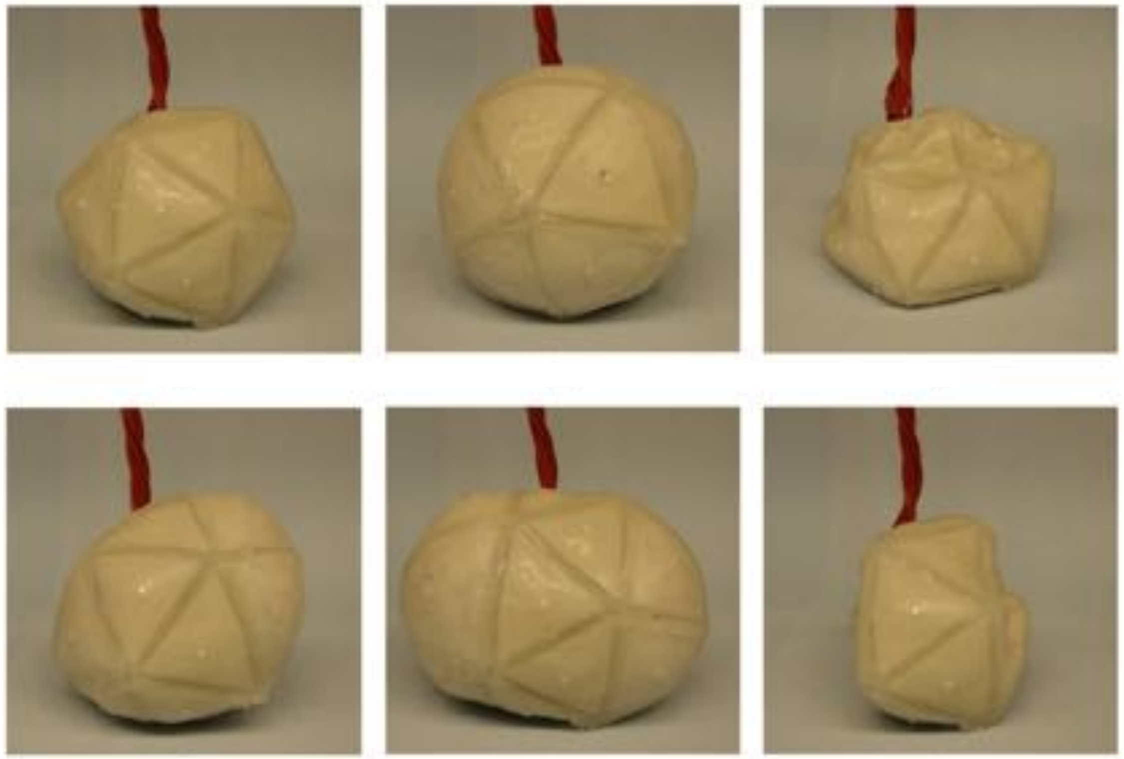
Follmer et al. 2012

Particle Jamming



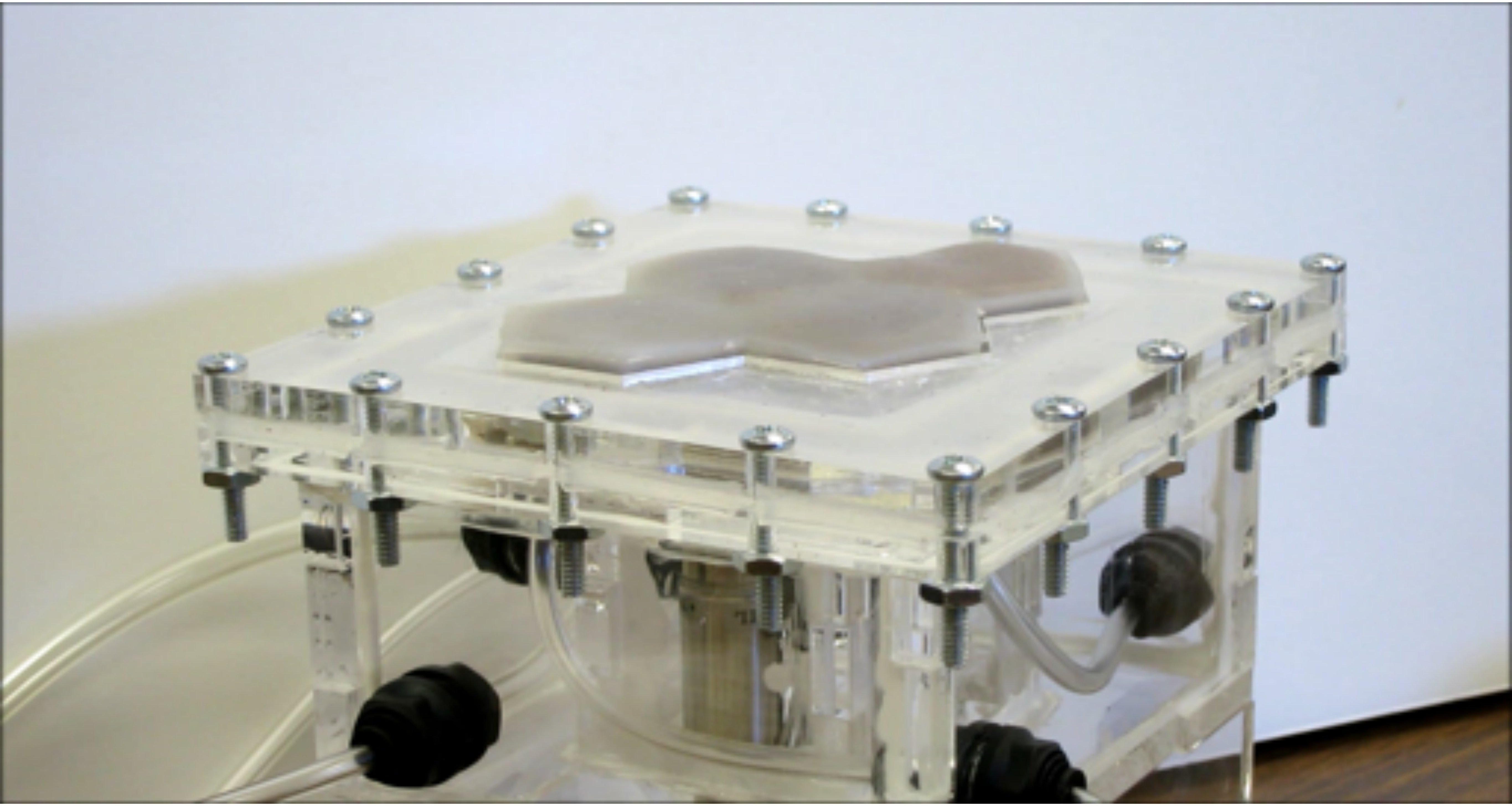
Brown et al. 2010

Cheng et al. 2012



Steltz et al. 2009

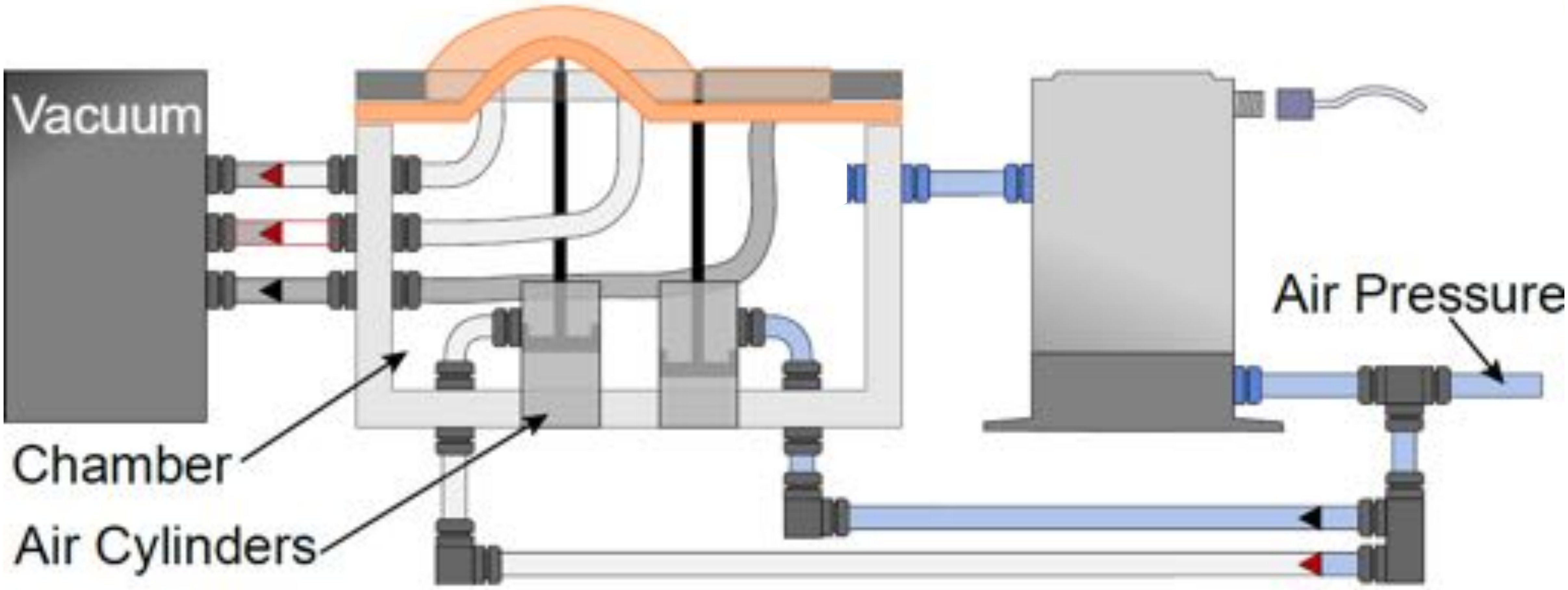
Haptic Jamming: Four-Cell Surface



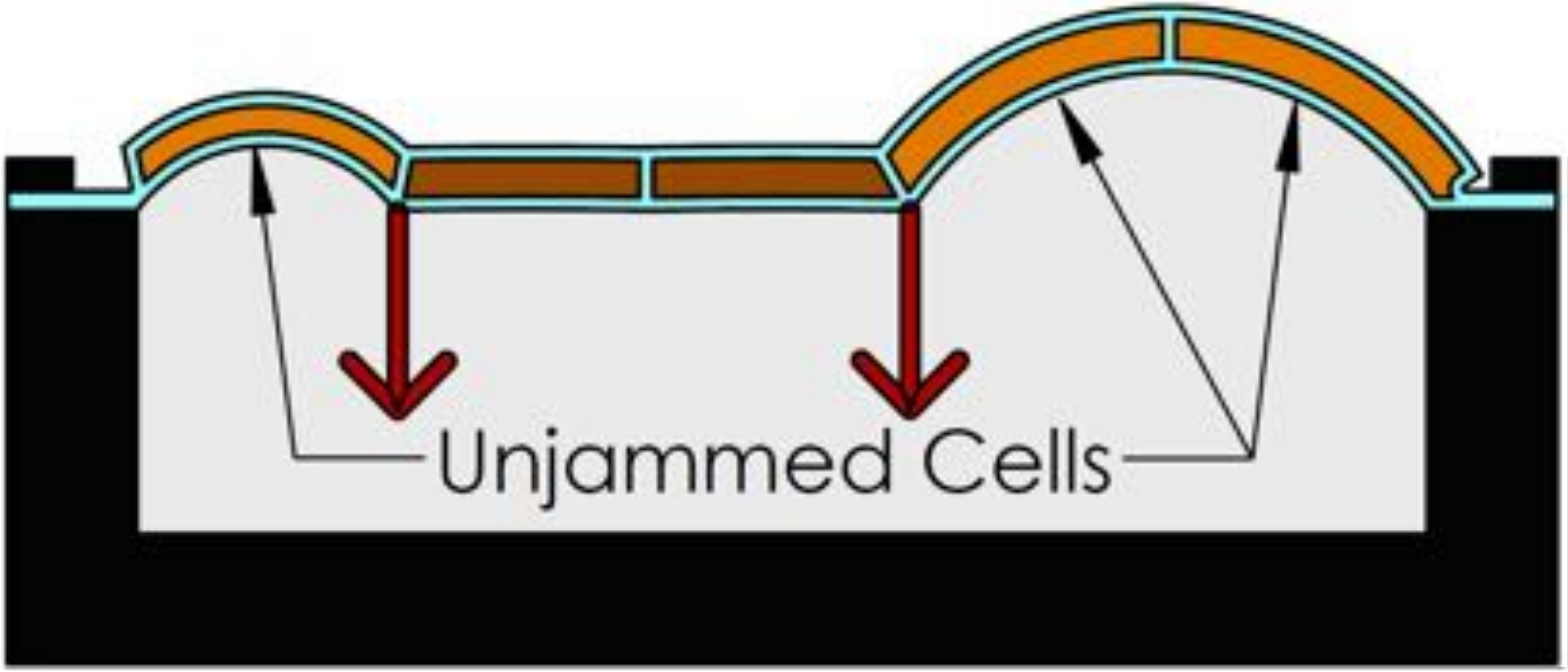
Video is real time

Stanley et al. MMVR 2013

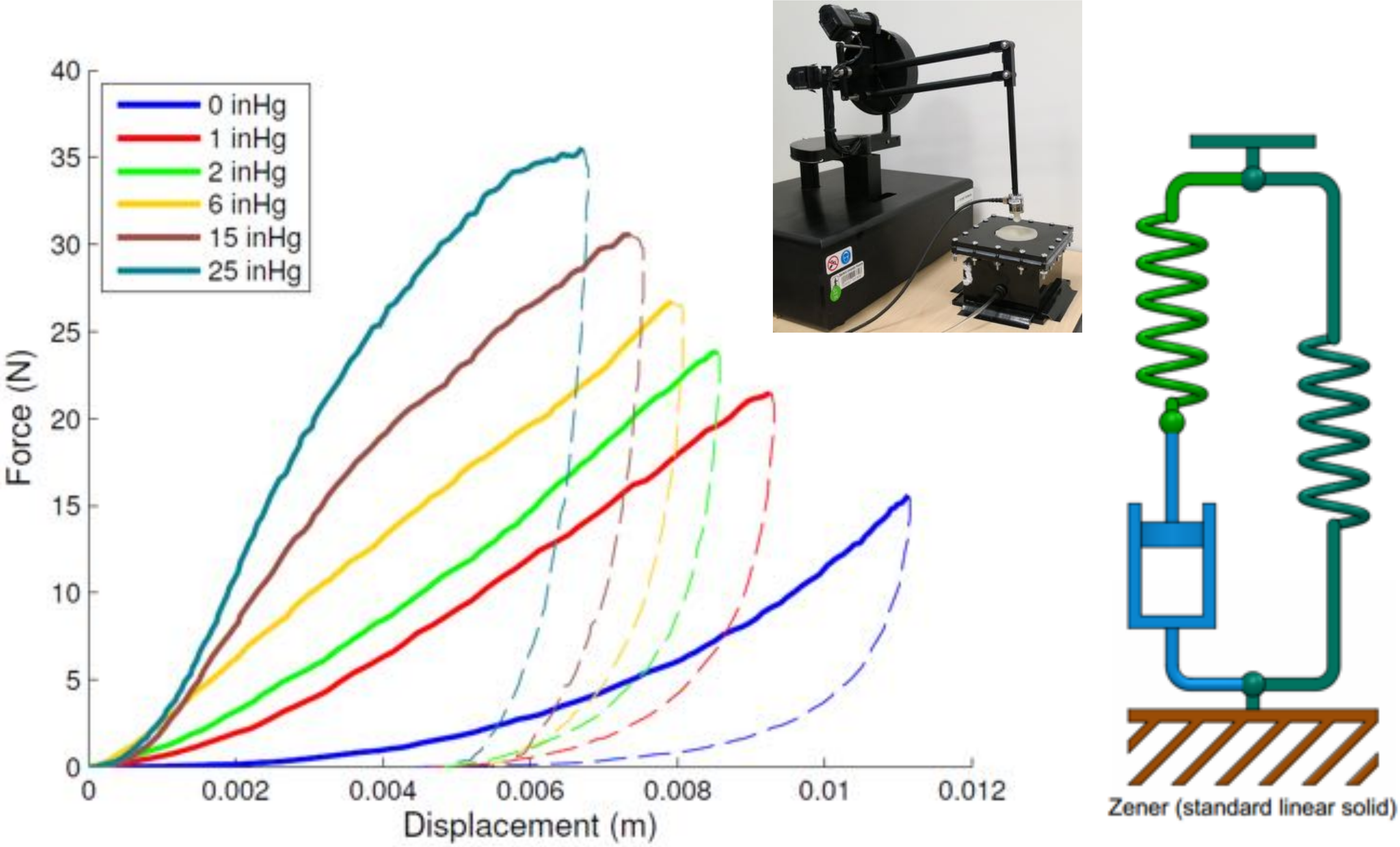
Haptic Jamming Actuation



Haptic Jamming Actuation

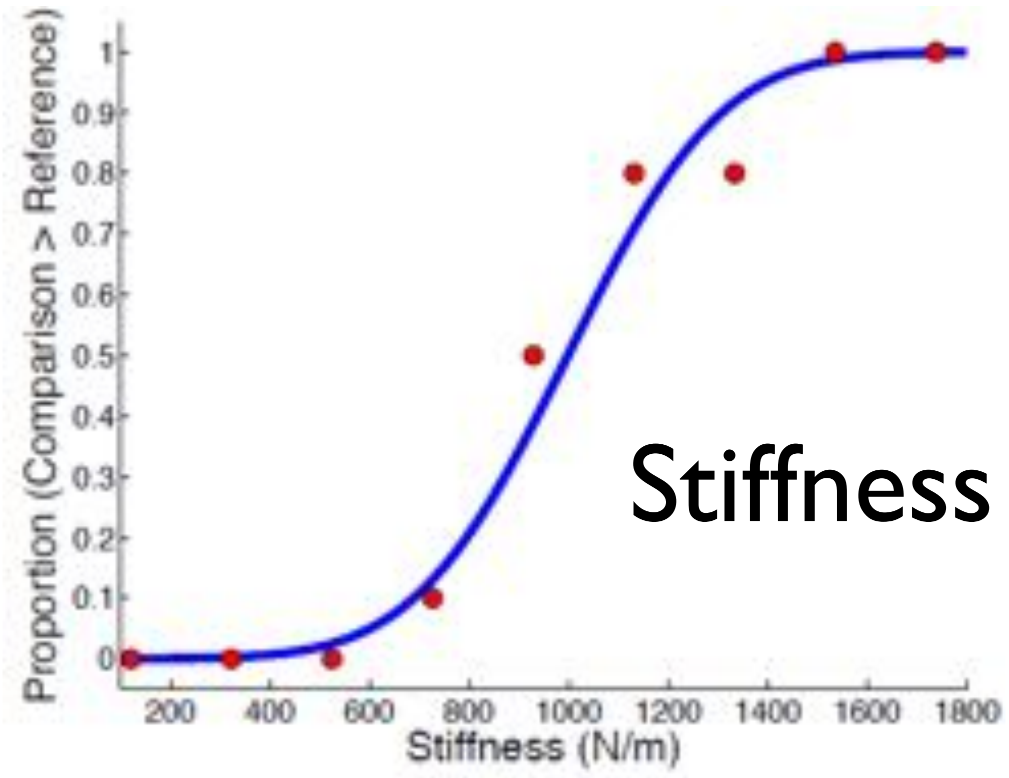


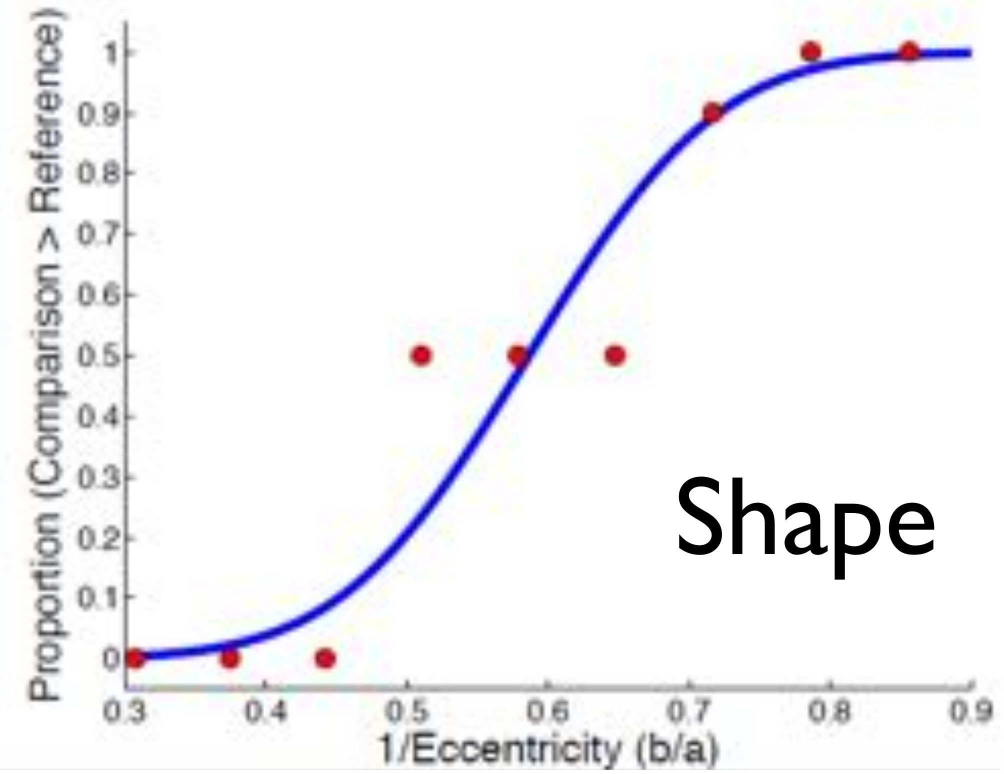
Mechanical Properties



Stanley & Okamura ToH 2014

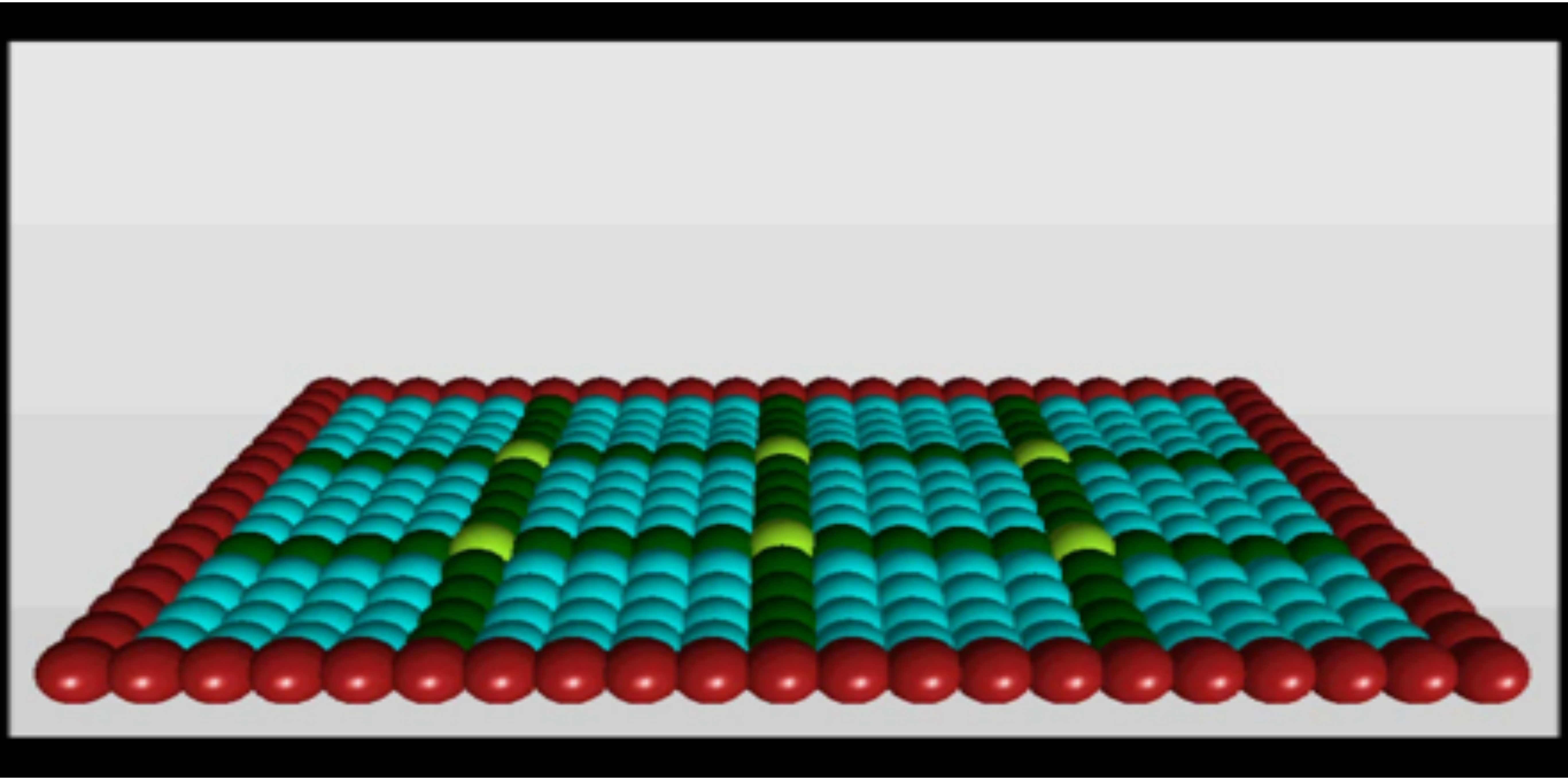
Perception





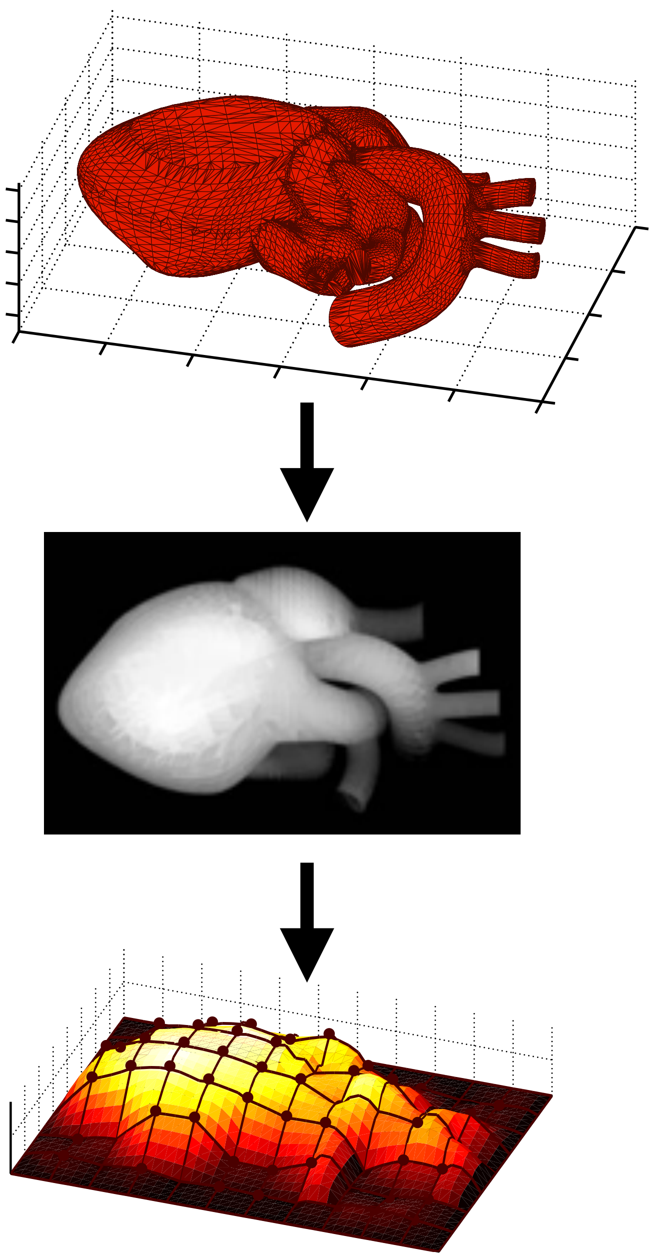
Genecov et al. Haptics Symp 2014

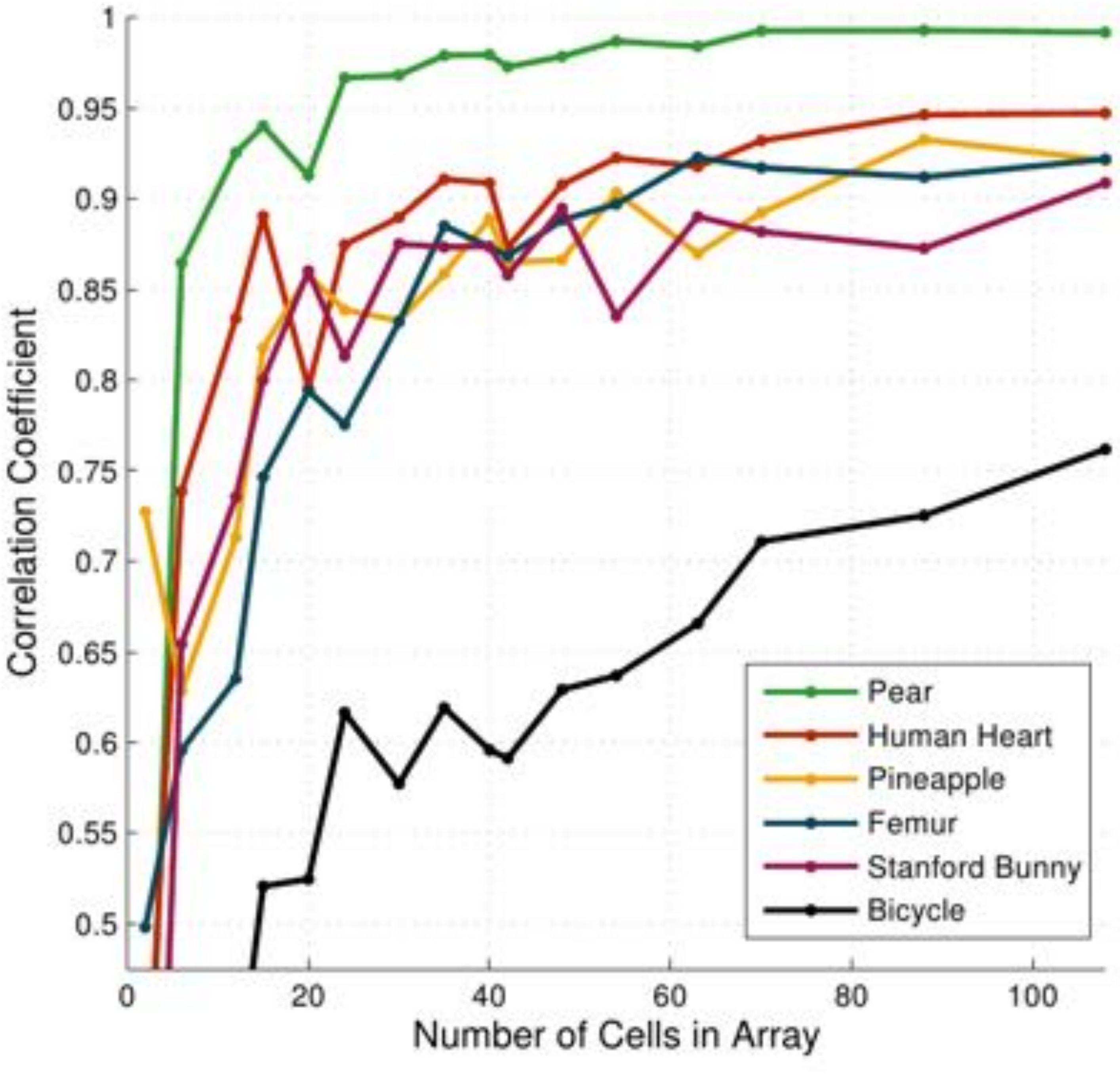
Shape Simulation



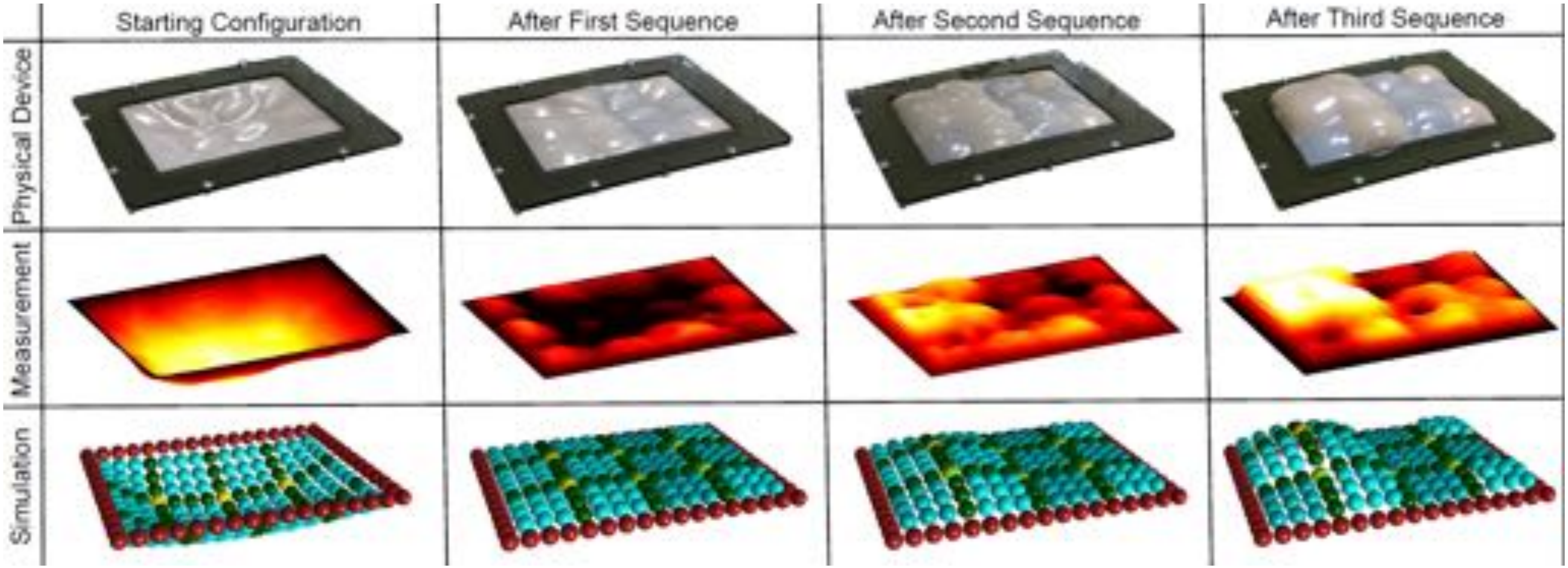
Shape Simulation

Which shapes will render well?



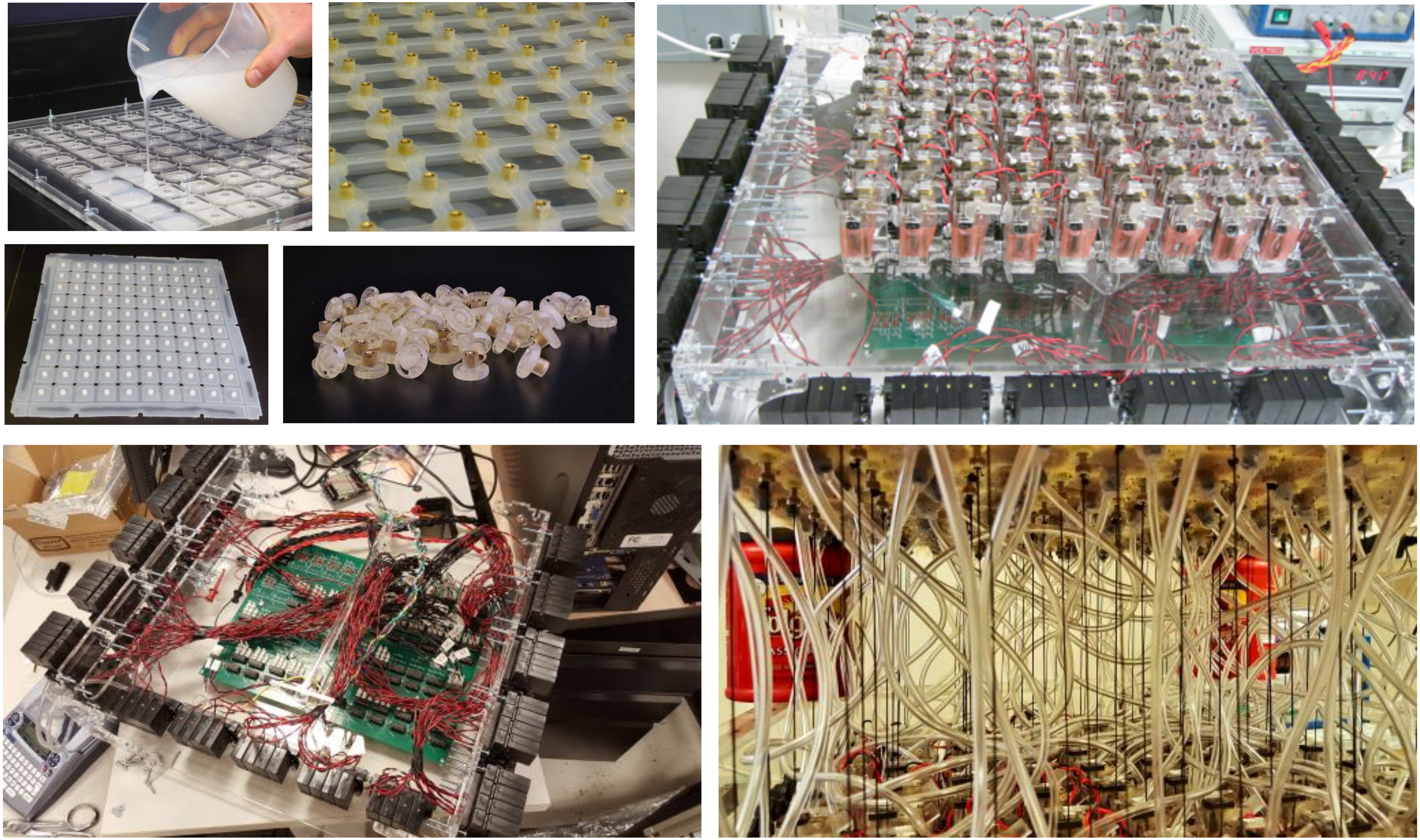


Closed-Loop Control



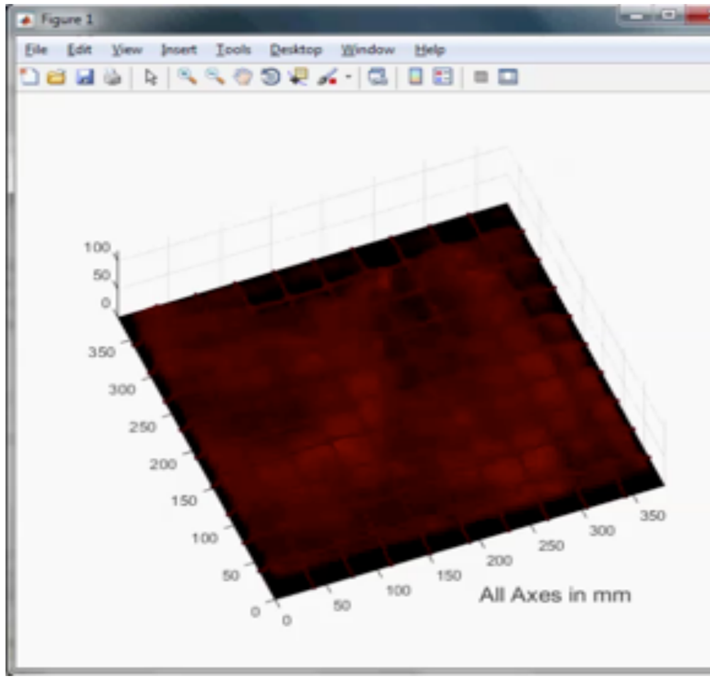
Stanley & Okamura ICRA 2016

100-Cell Array

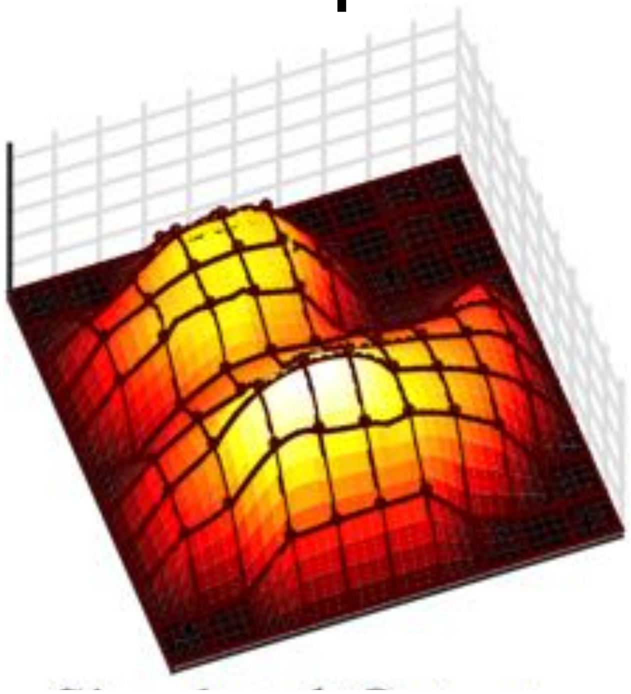


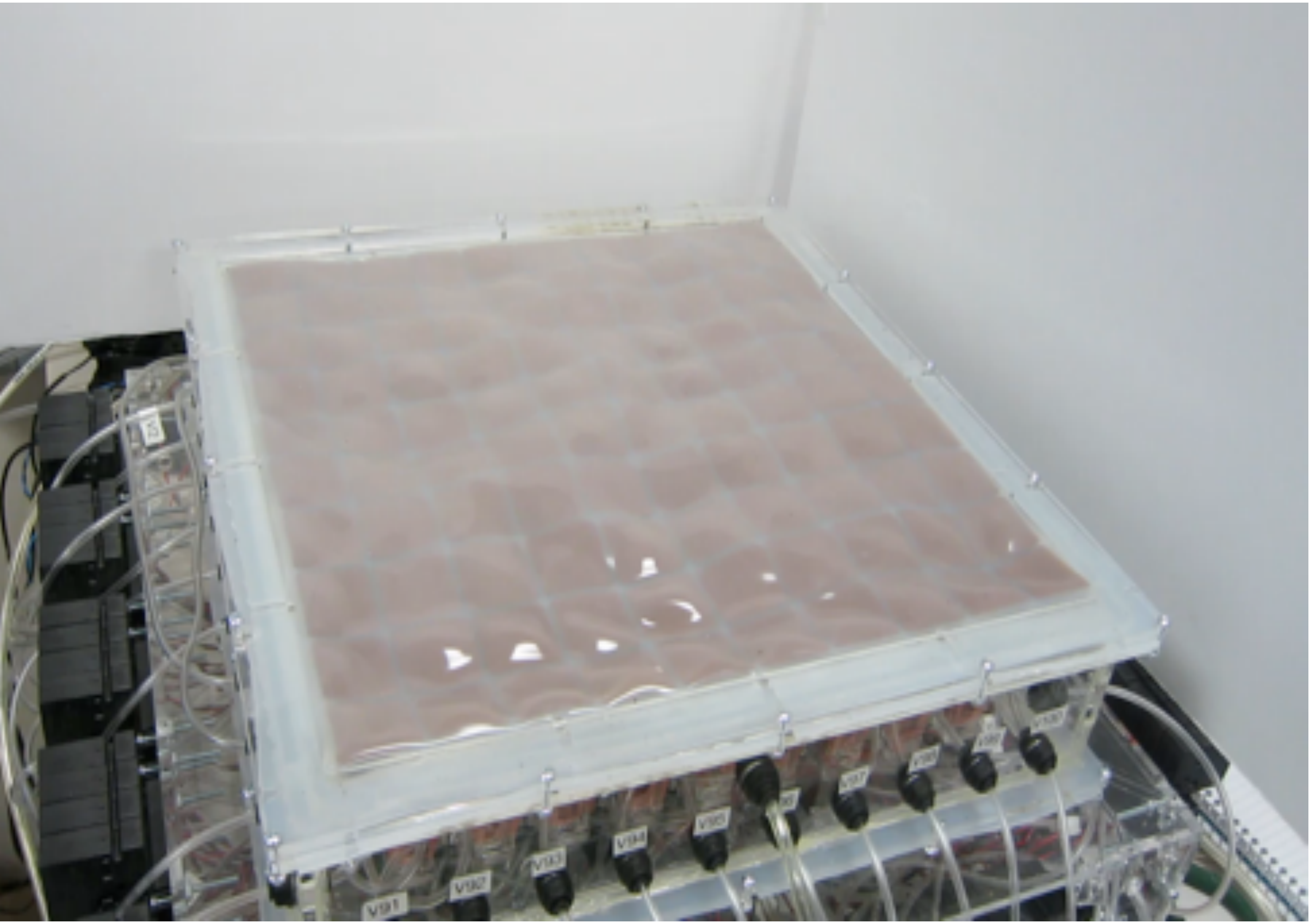
Closed-Loop Control

Measured Output



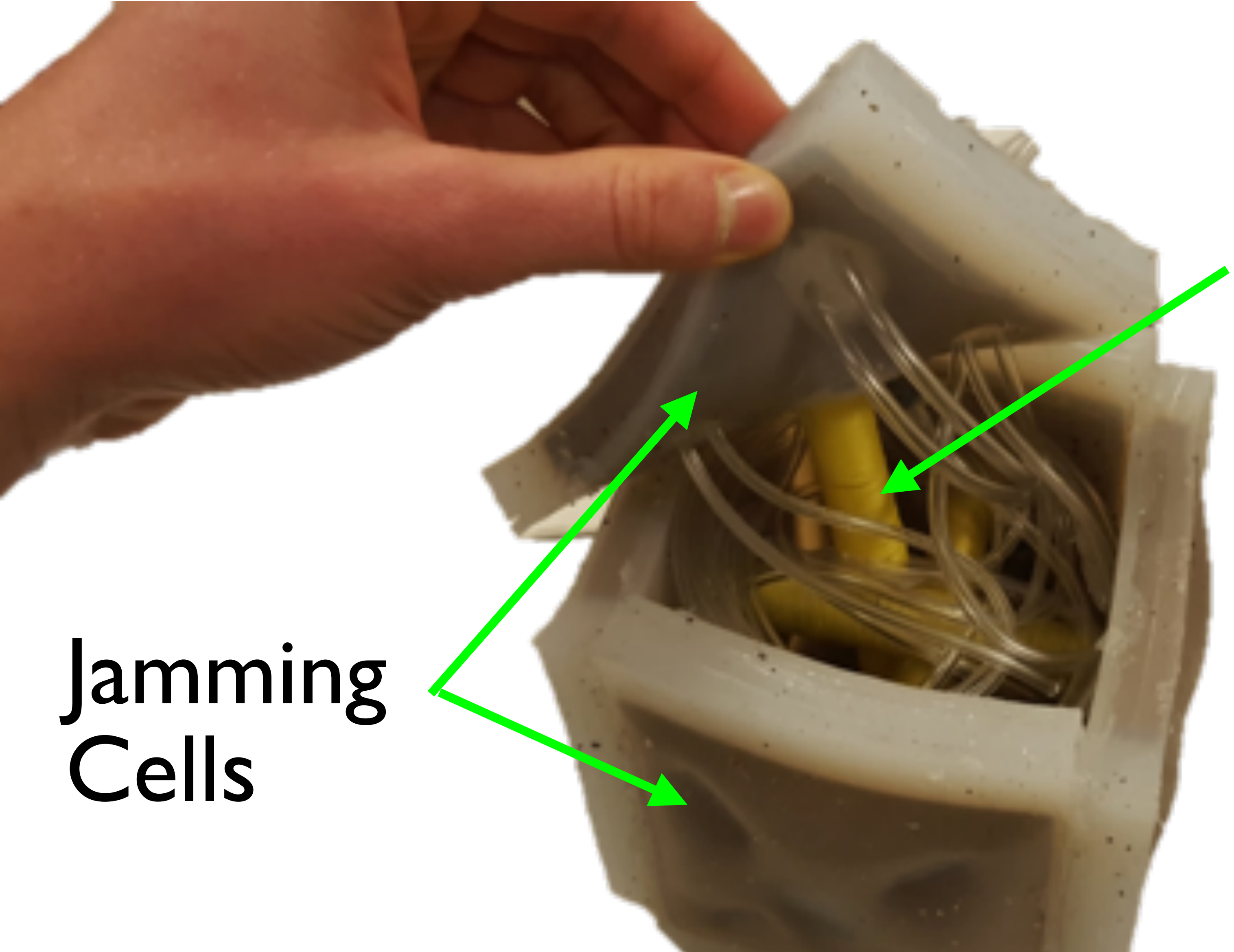
Simulated Output





Video is real time

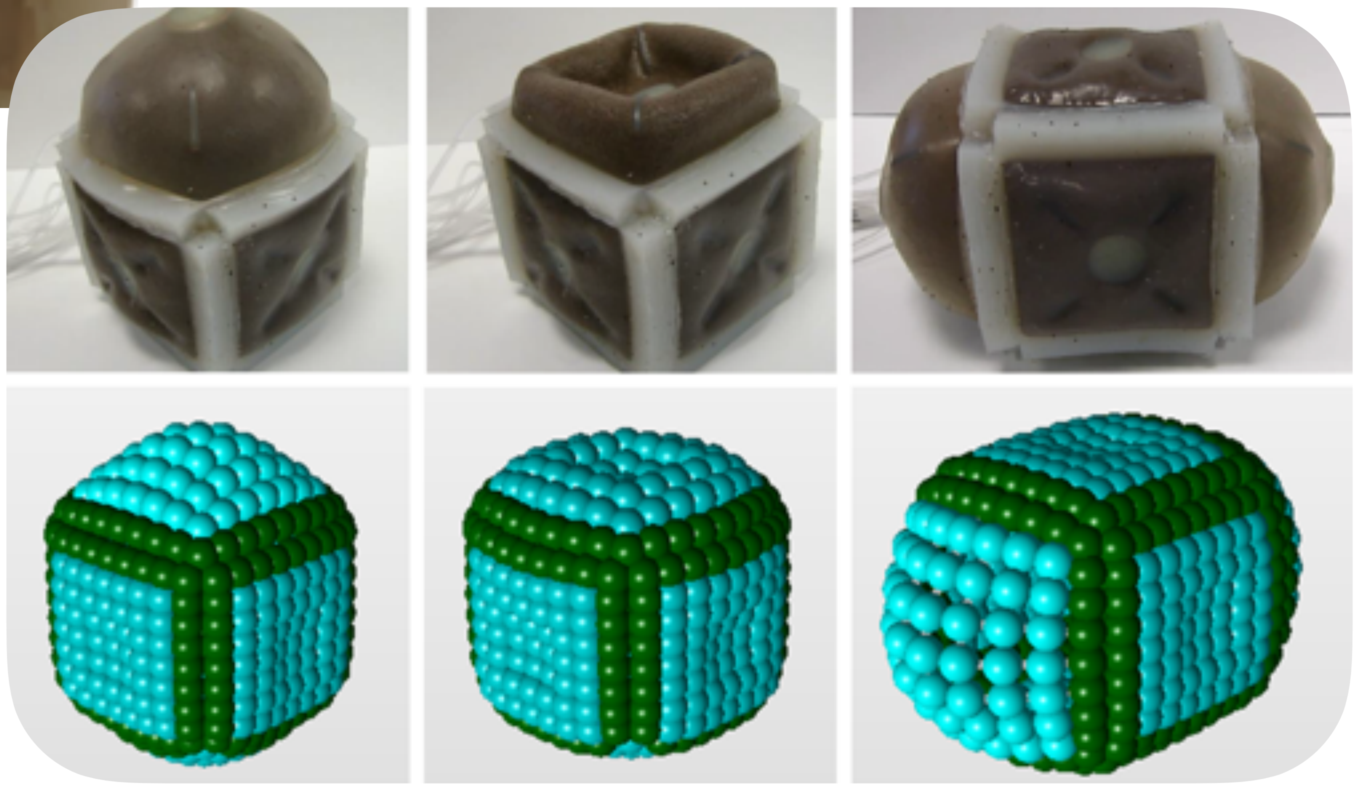
Stanley & Okamura in preparation



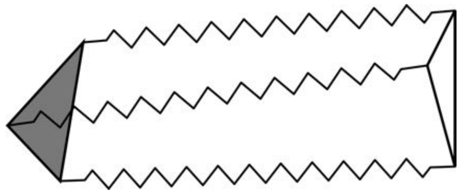
Jamming Cells

Inverse Pneumatic Artificial Muscles (IPAMs)

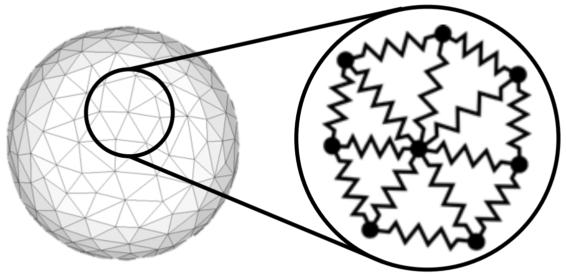
2.5D→3D



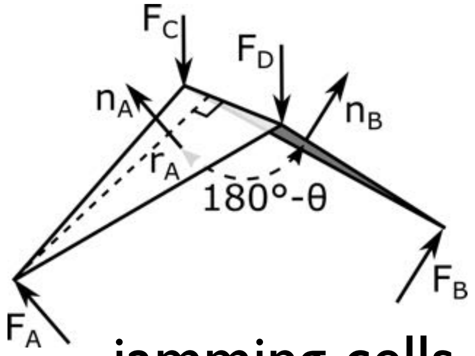
Automatic Design Algorithm



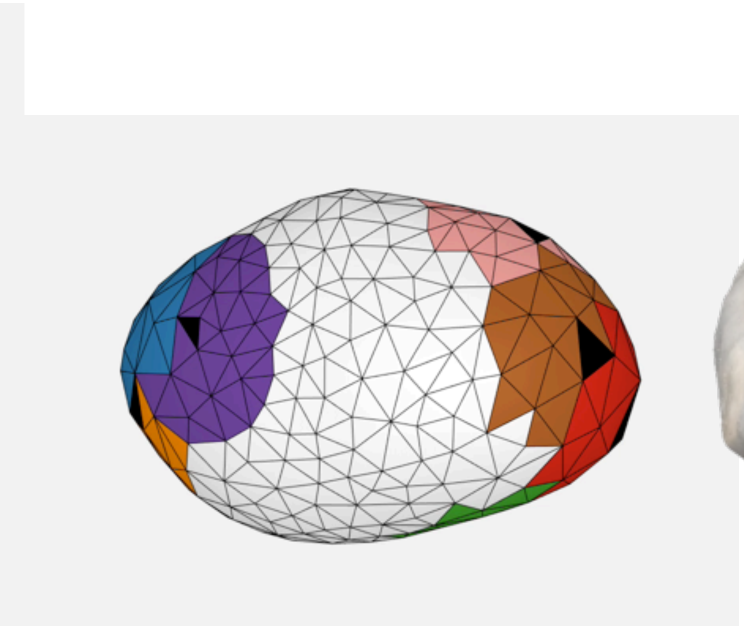
IPAM actuators



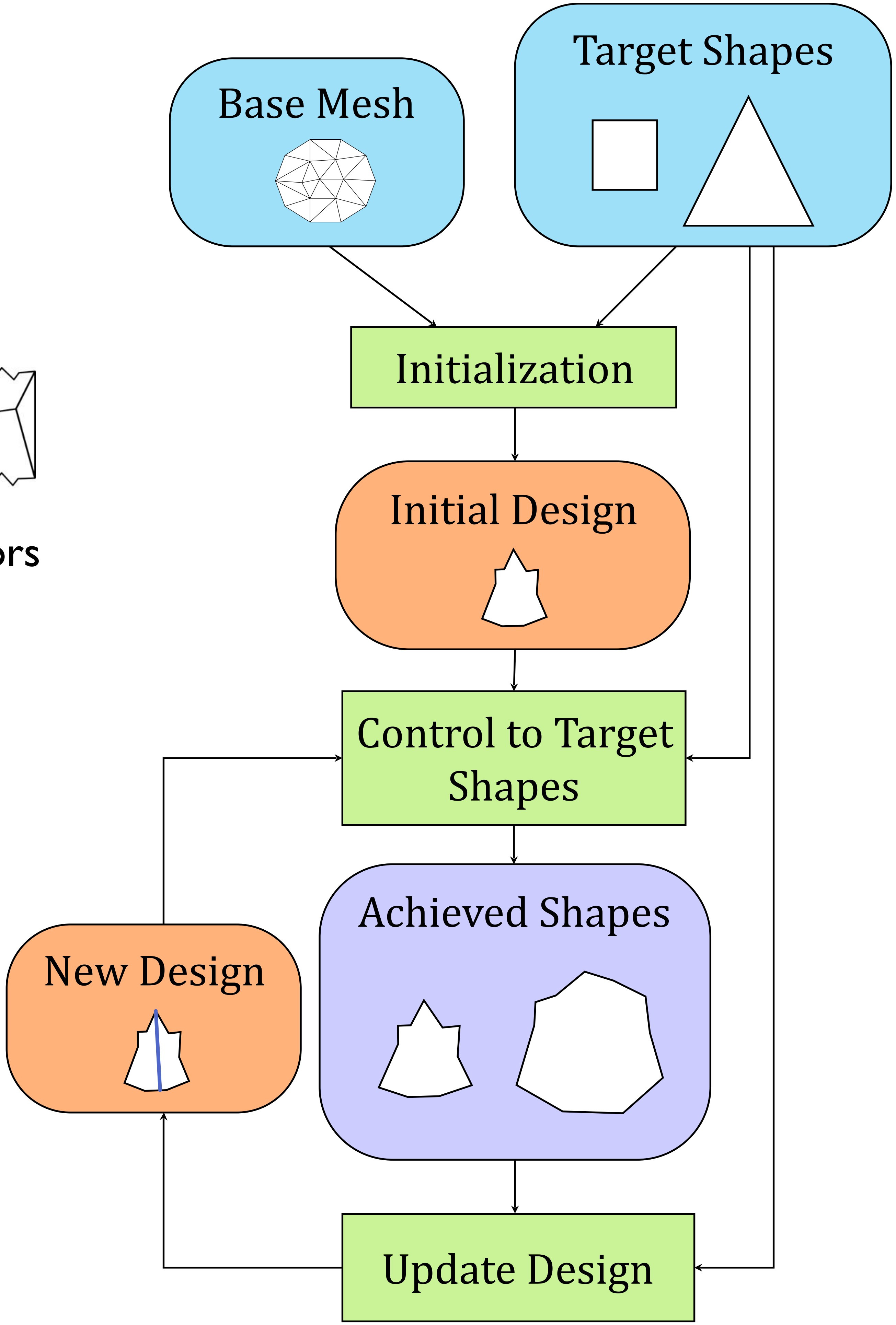
silicone membrane



jamming cells



Koehler et al. in review



Base Mesh

Target Shapes

Initialization

Initial Design

Control to Target Shapes

Achieved Shapes

Update Design

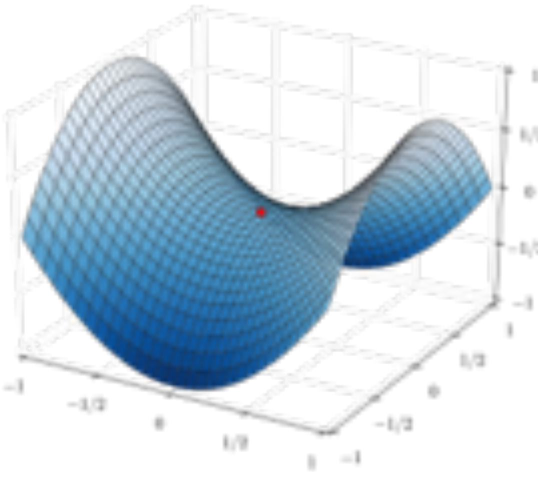
New Design

Other Applications

- Human-computer interaction scenarios
- Self-sensing of shape and contact with human
- “Fast refresh” 3D printing
- Changeable Product

consumer

assistive/rehab



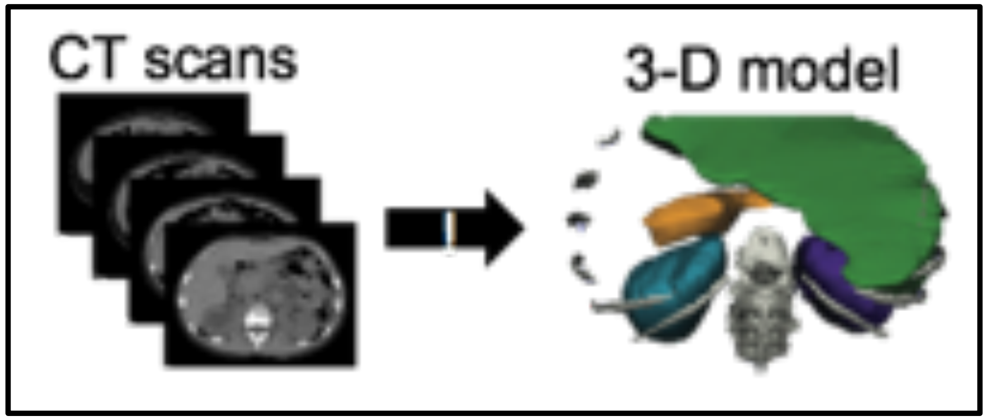
education

Flexible Patient-Specific Medical Robots

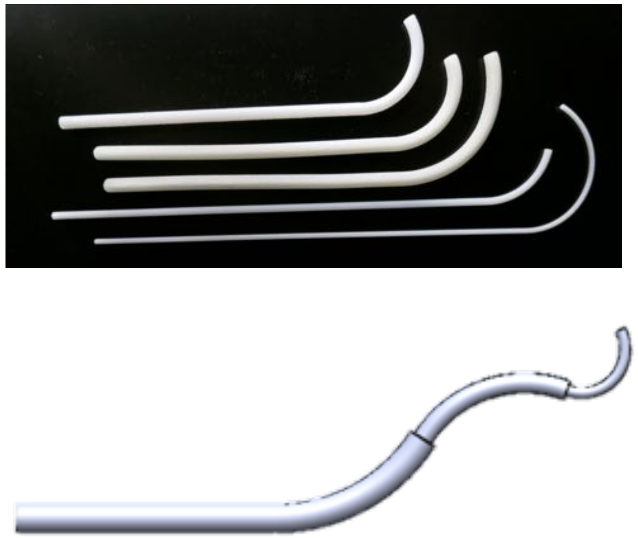
Template Robotic Surgical Systems

Marginalized Patient Populations

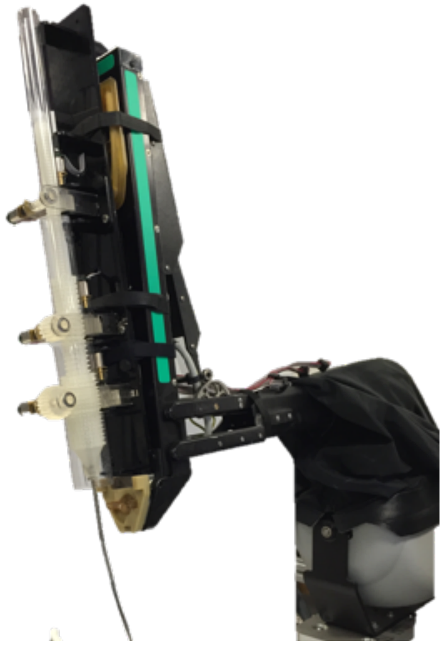
Patient-Specific Design Workflow



Design

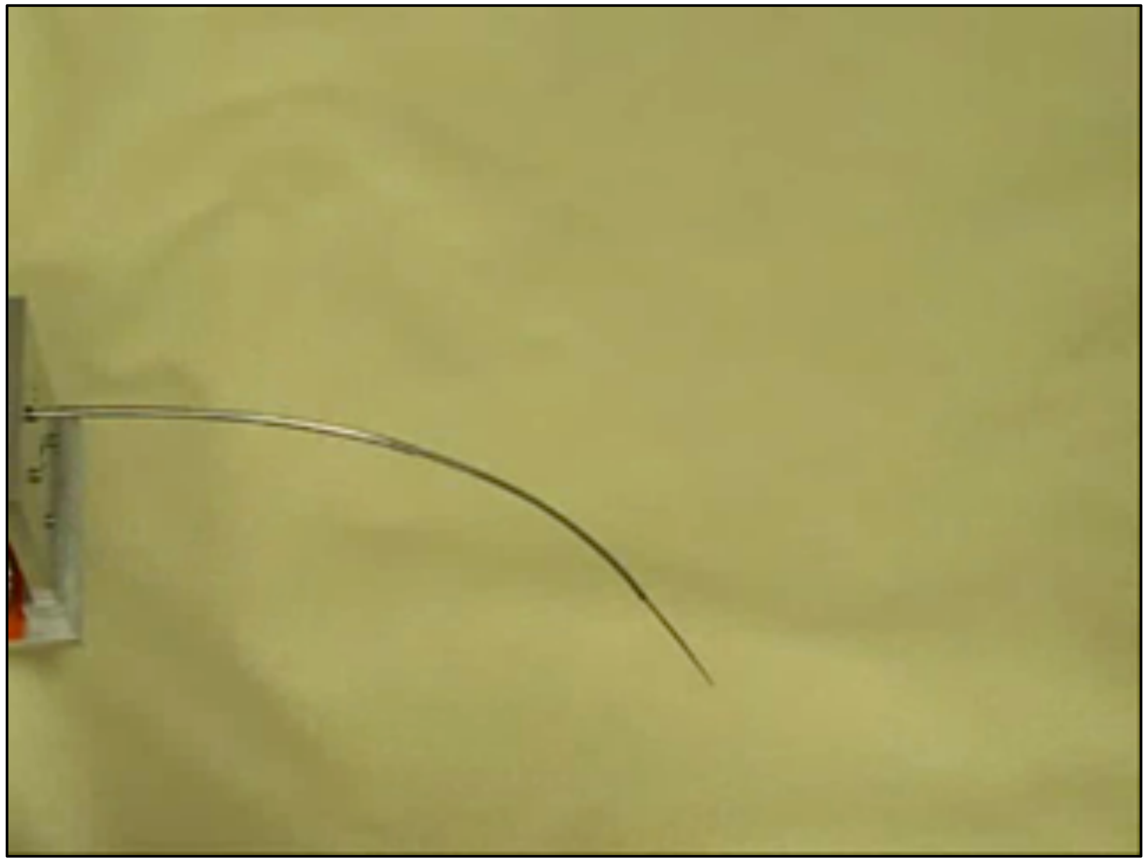


Fabricate



Drive

Concentric Tube Robots



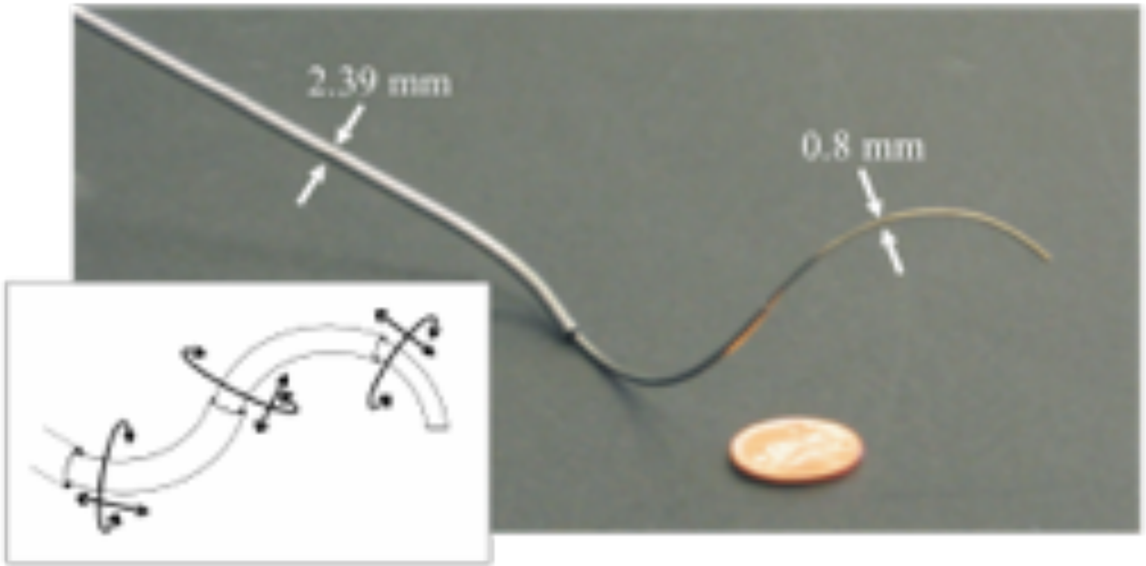
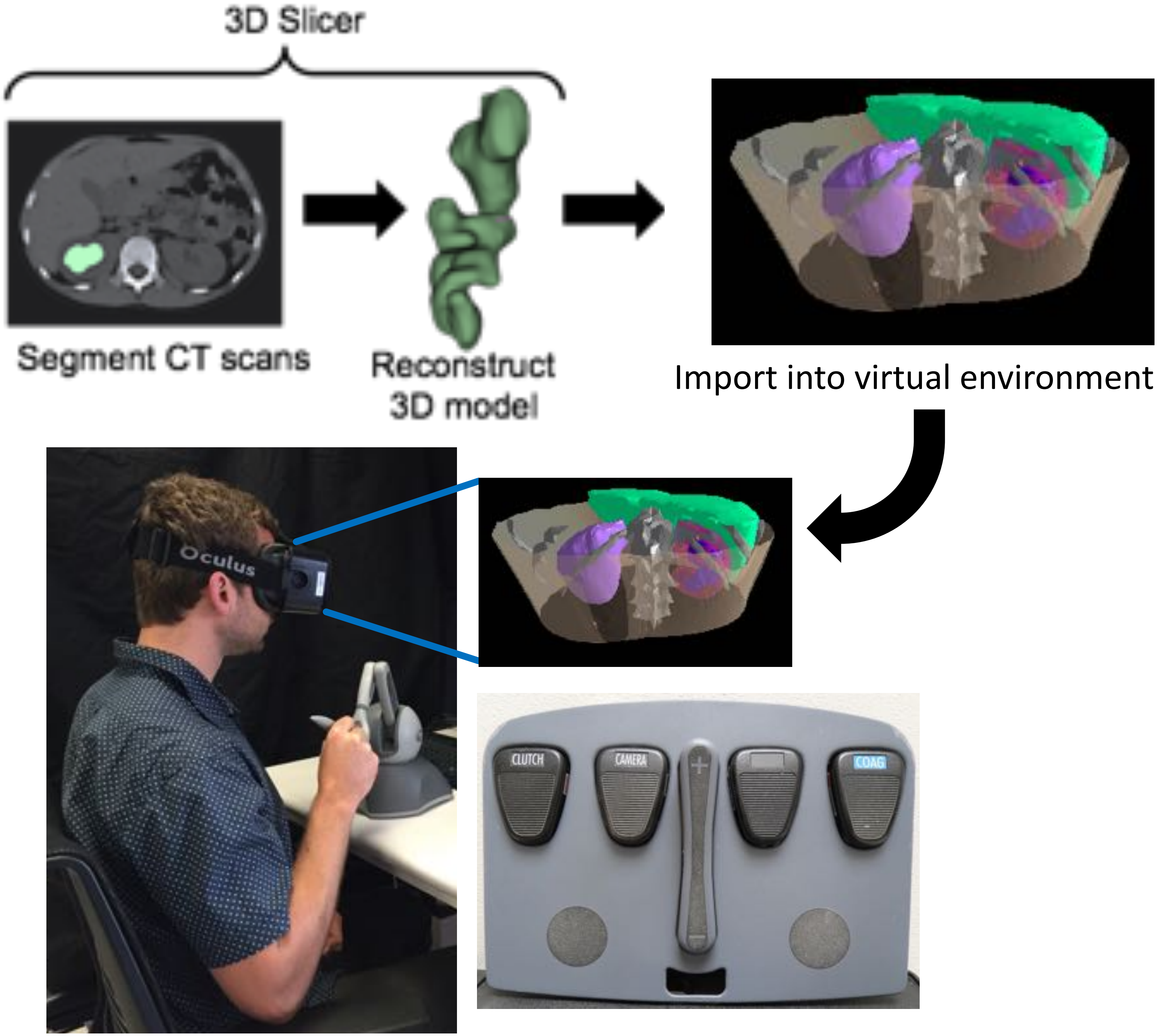


Image and video courtesy of Robert Webster III, Vanderbilt University

- Series of hollow, precurved tubes
- Fit concentrically one inside the next
- Relative insertion and rotation results in bending in free space

Webster et al. ICRA 2008
Webster et al. IROS 2006
Sears et al. IROS 2006
Dupont et al. TRO 2010
Bedell et al. ICRA 2011

Surgeon Design Interface

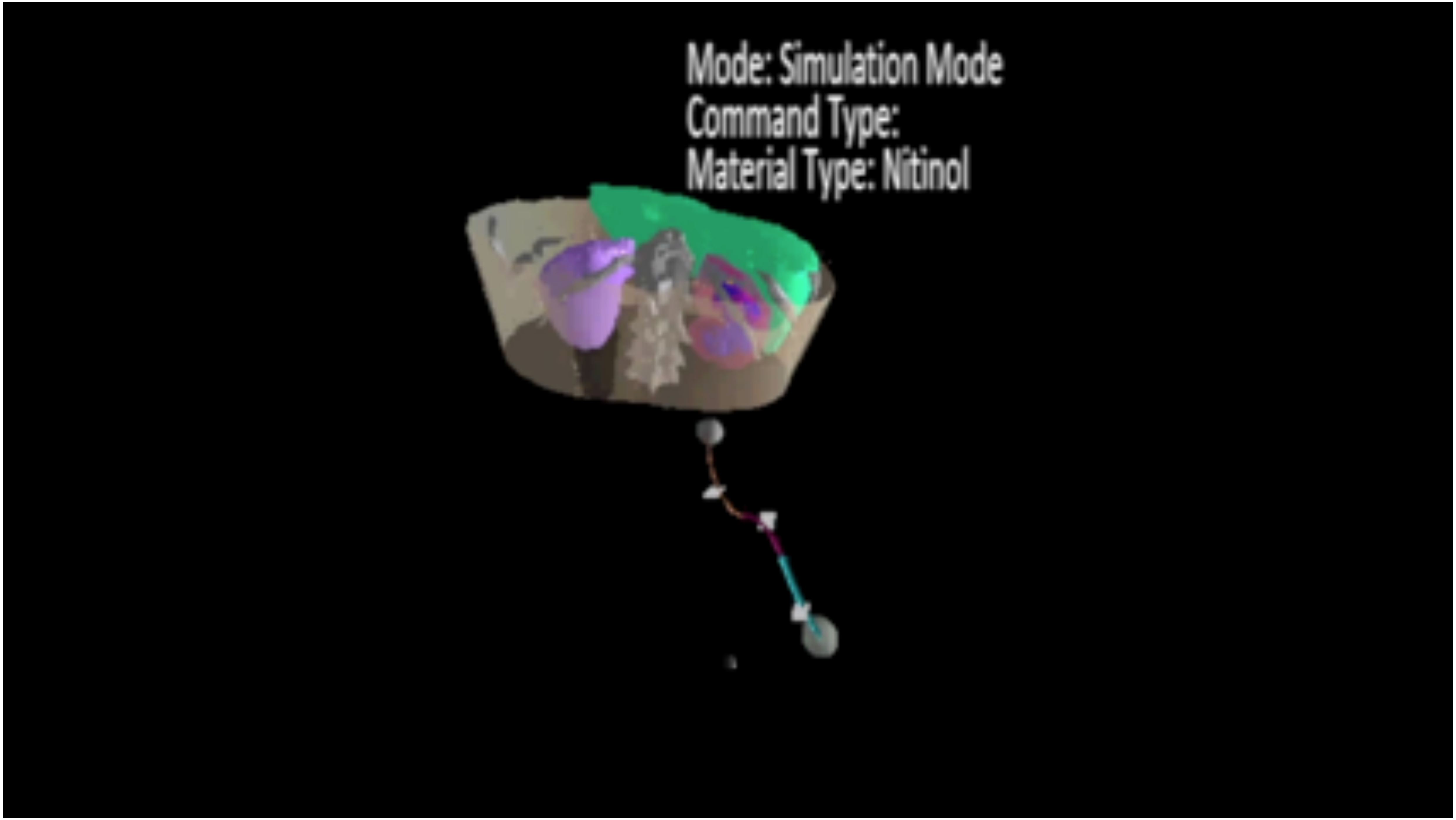


Import into virtual environment

Morimoto et al. BioRob 2016

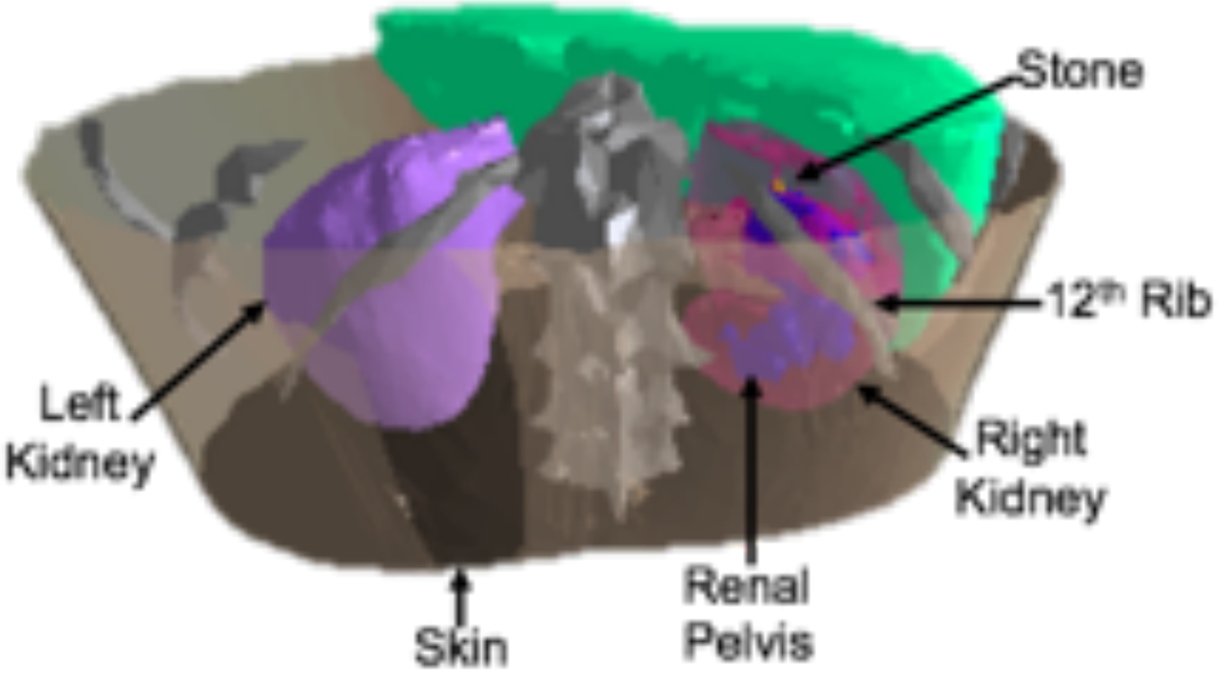
Initialize Concentric Tube Robot Design

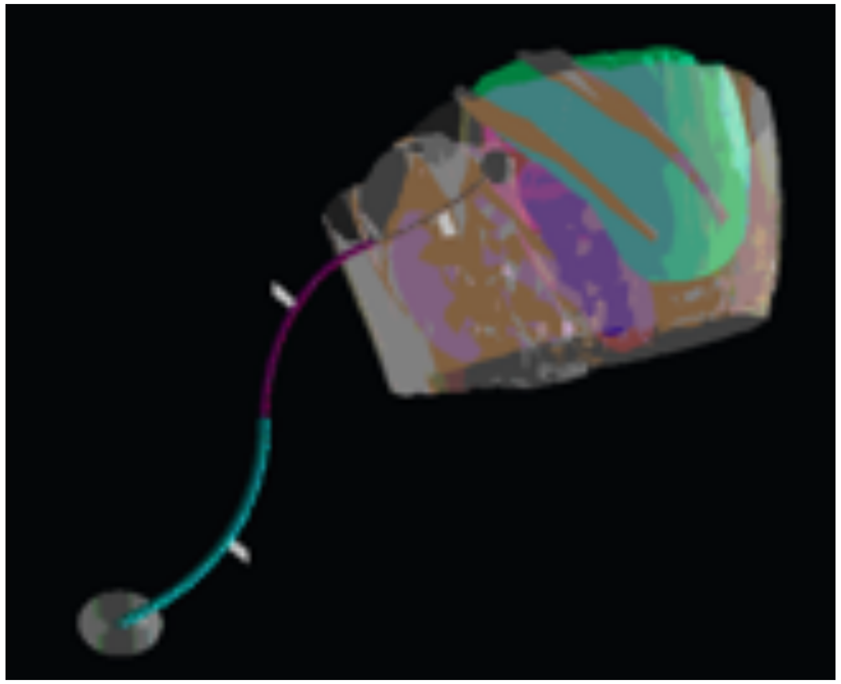
Simulate Concentric Tube Robot



Mode: Simulation Mode
Command Type:
Material Type: Nitinol

Demonstration

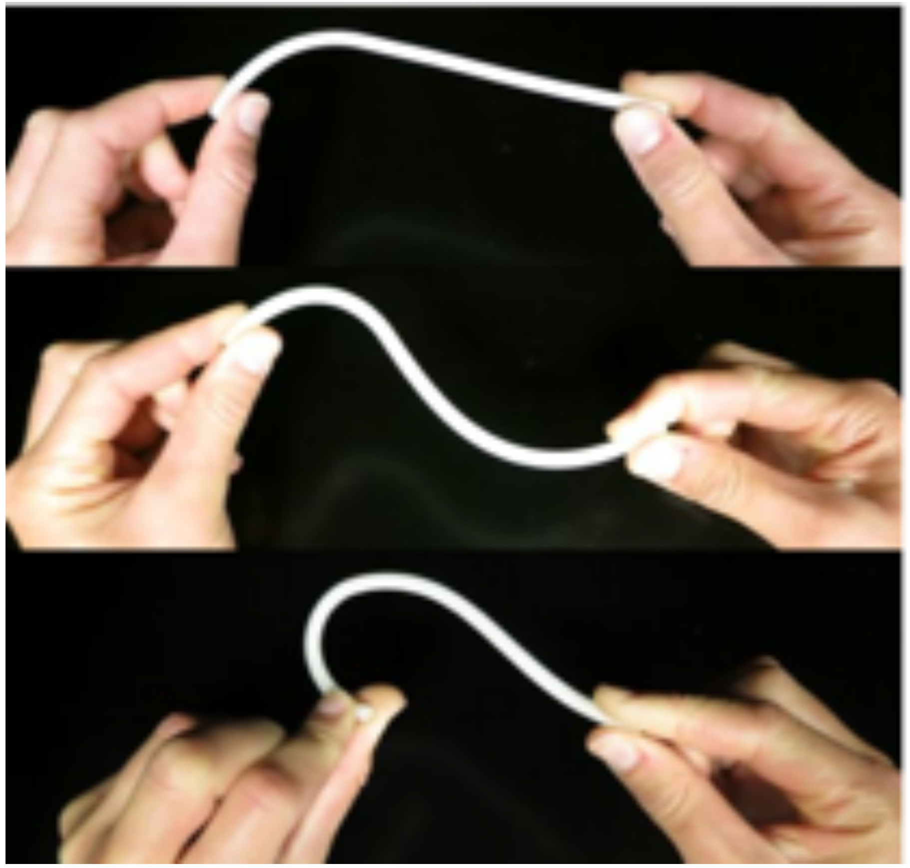


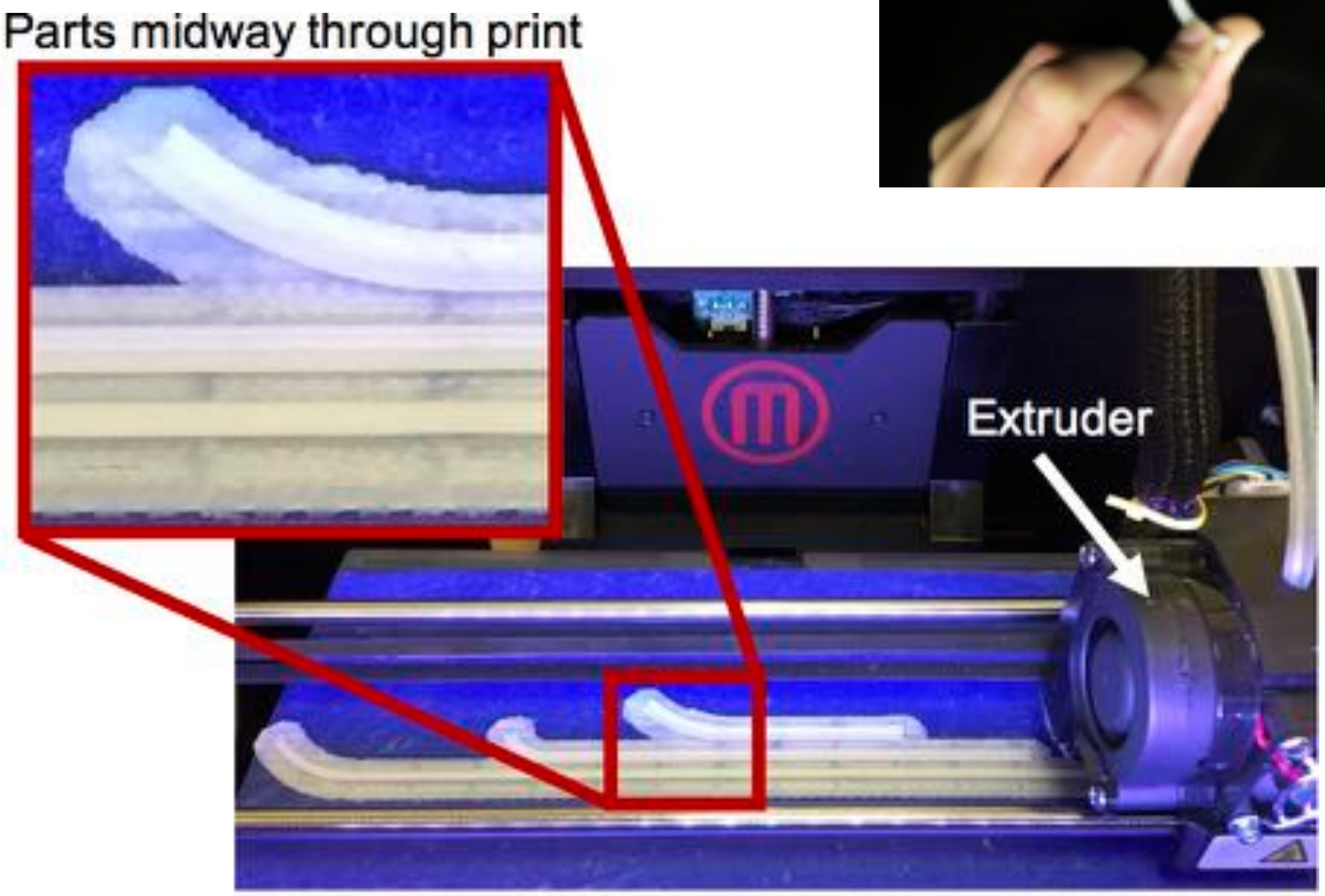


Michael Hsieh, MD, PhD
Childrens' National Medical Center

3D-Printed Polycaprolactone (PCL)

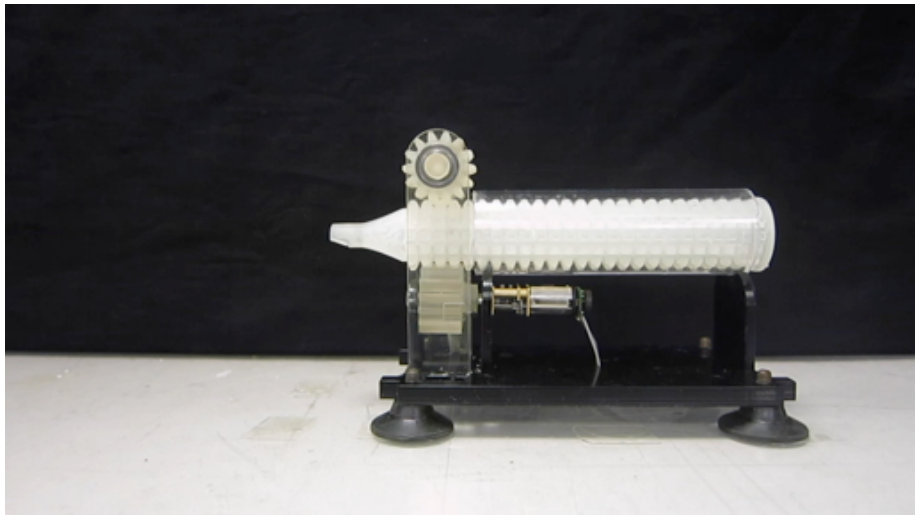
- Biodegradable polyester
- Often used for sutures and long-term implantable devices
- 3D print on Makerbot

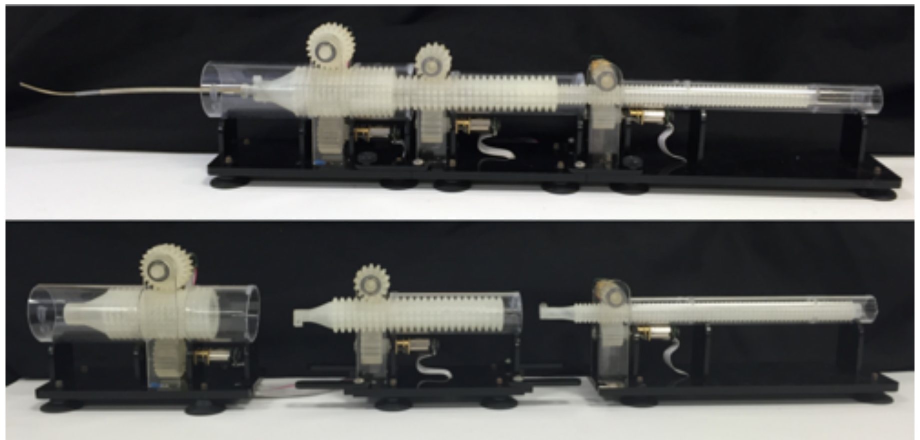


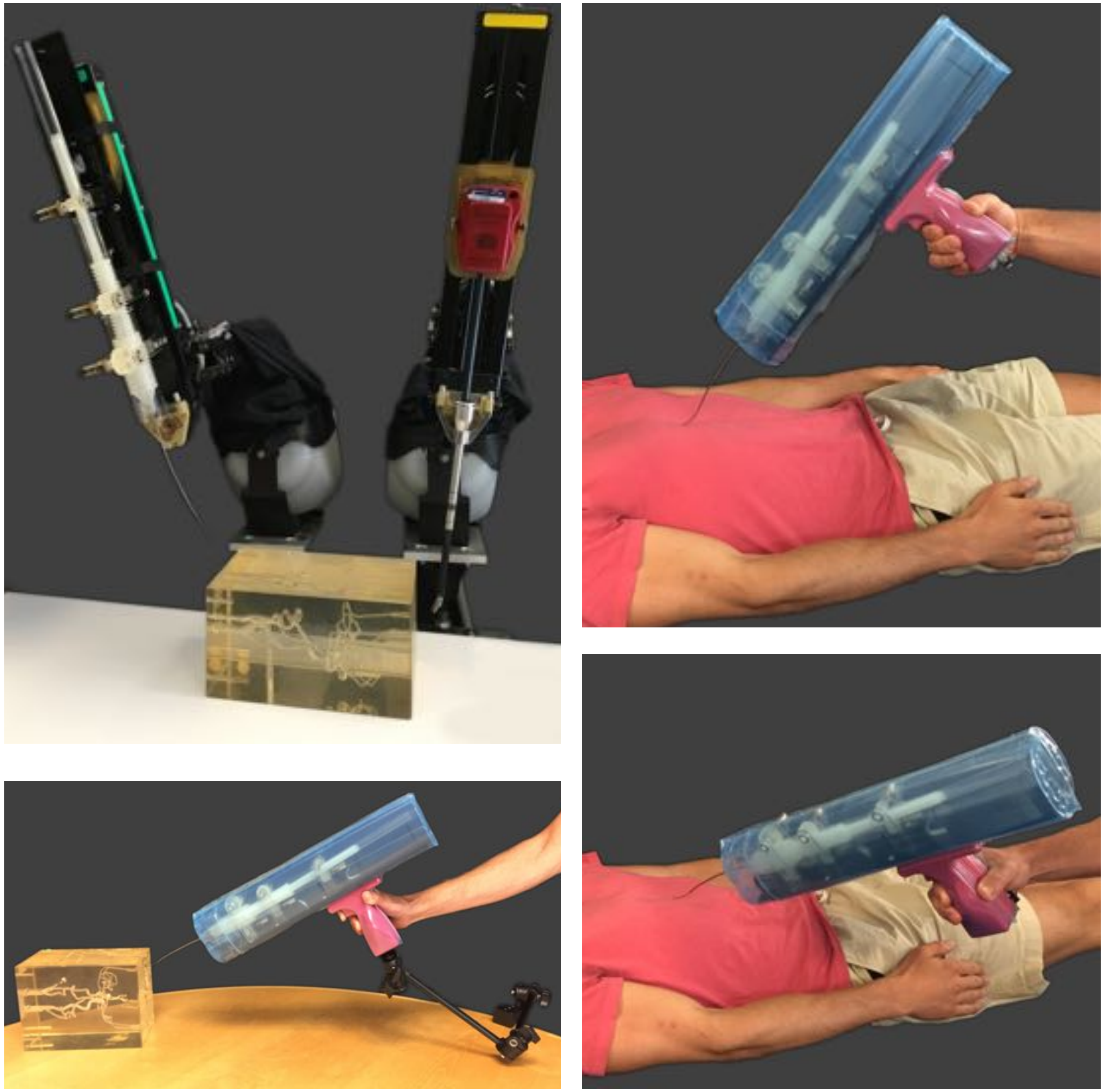


Morimoto et al. TRO 2016

Actuation System

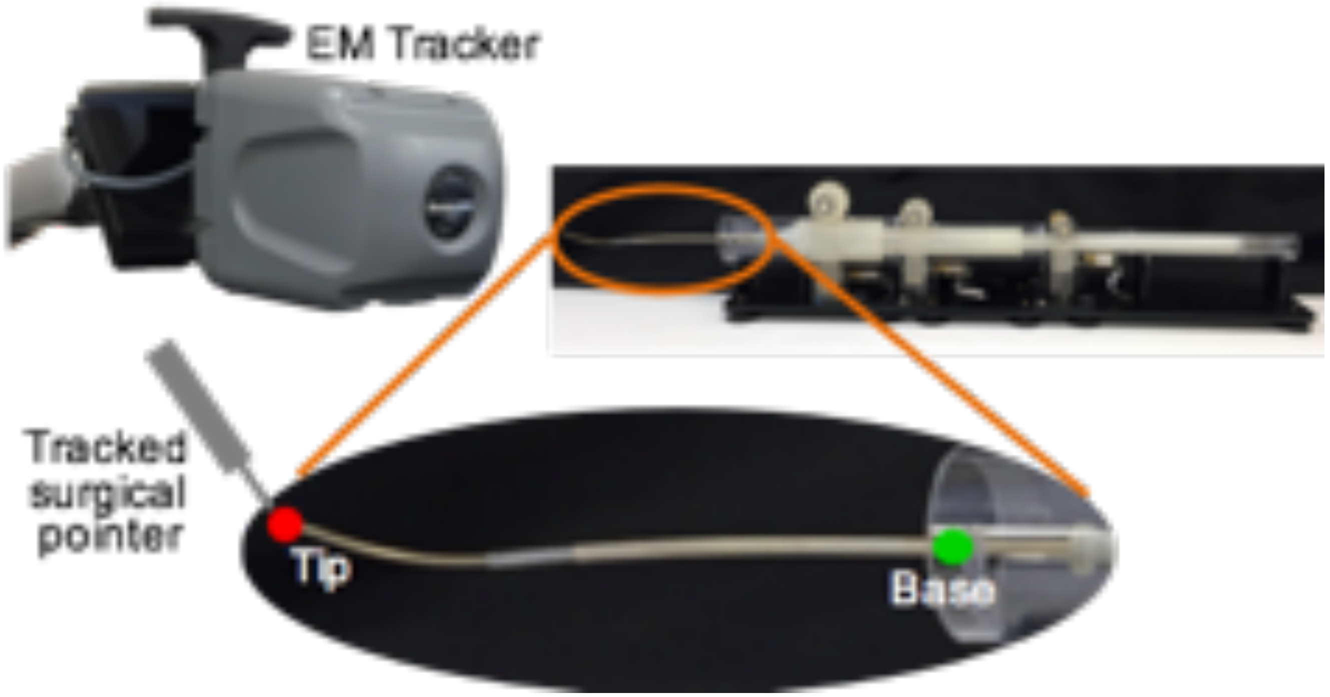


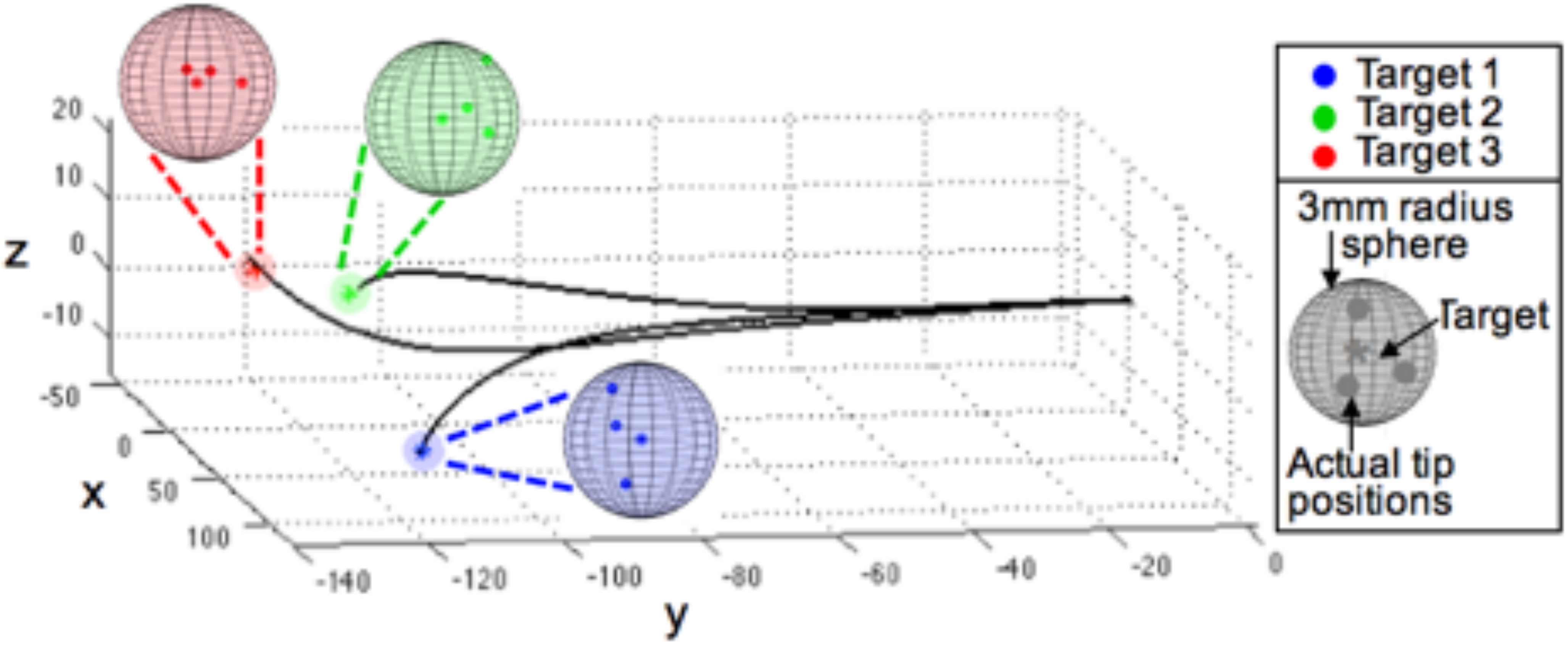




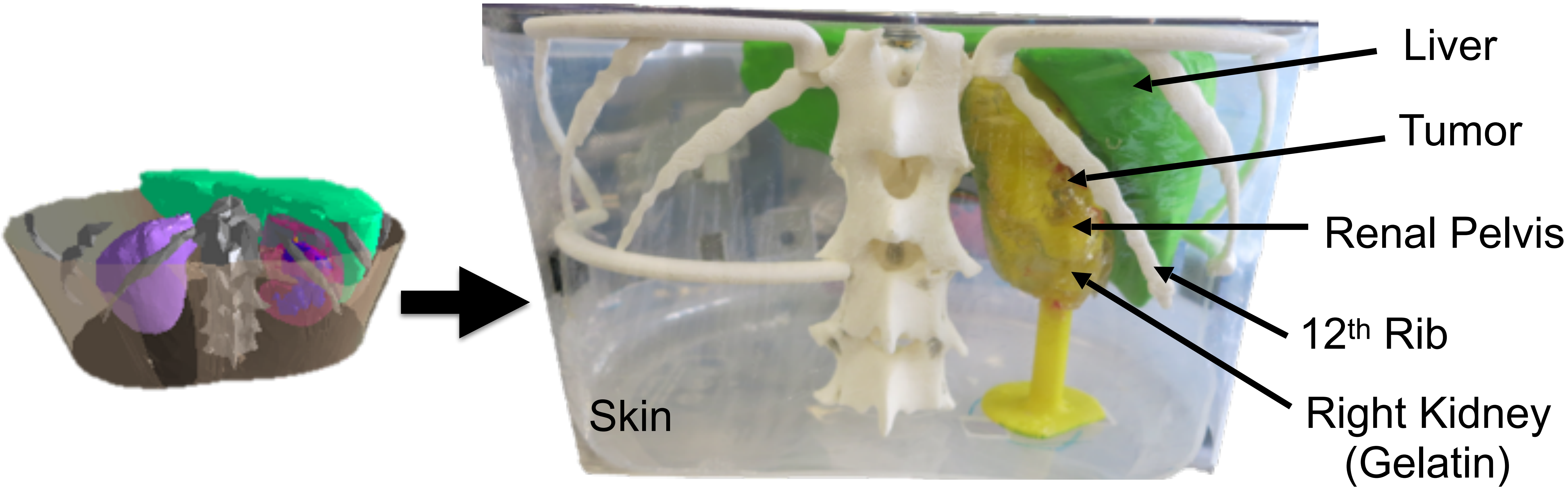
Morimoto et al. RA-L 2017

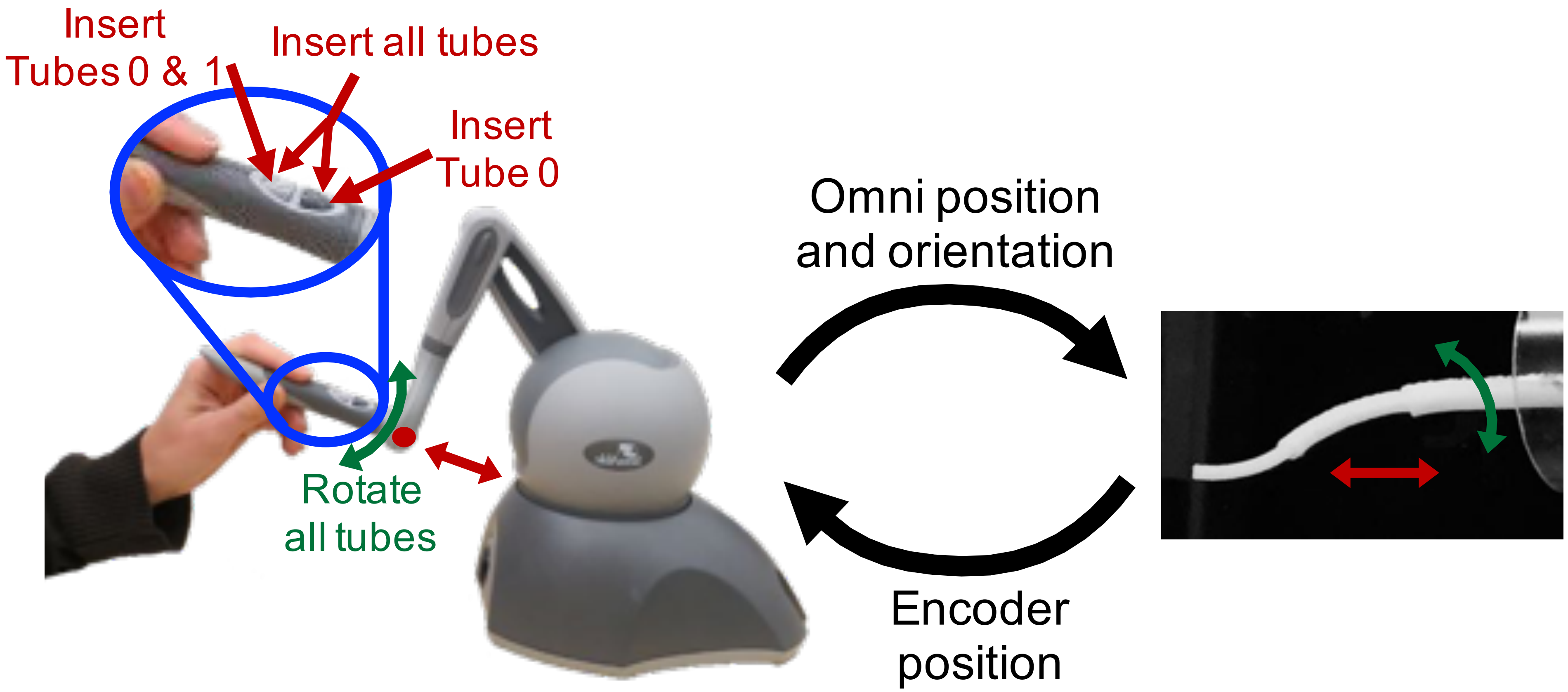
Targeting Experiments





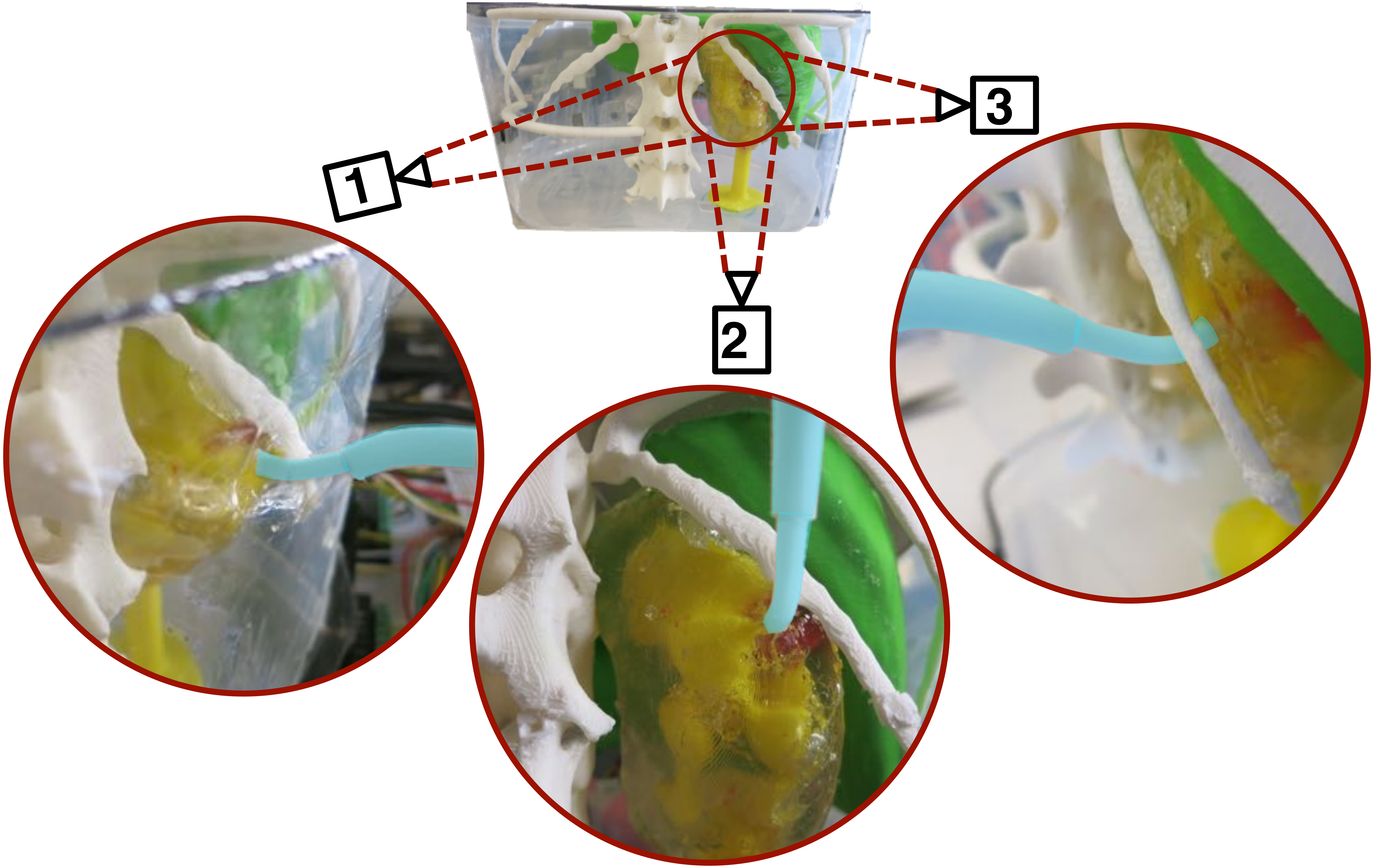
System Demonstration





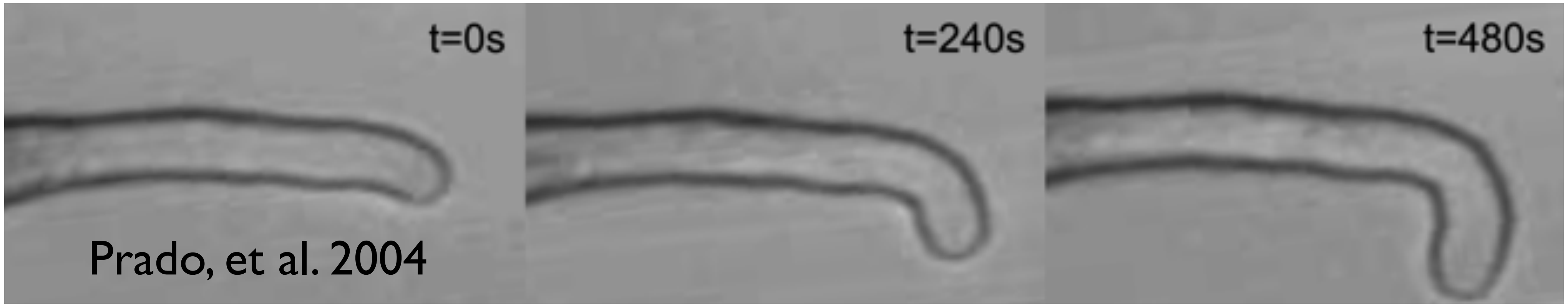
Morimoto et al. 2018

System Demonstration



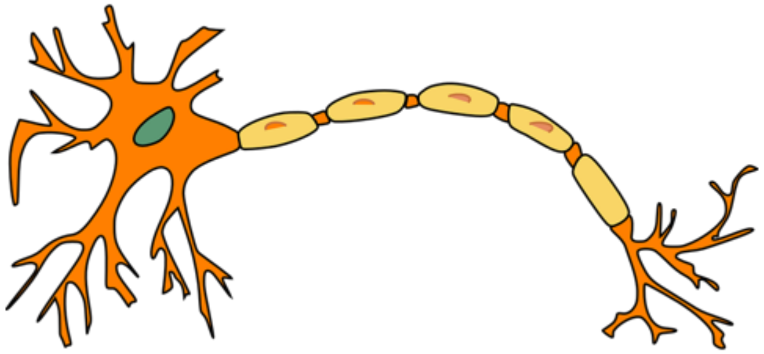
Biologically Inspired Robot Growth

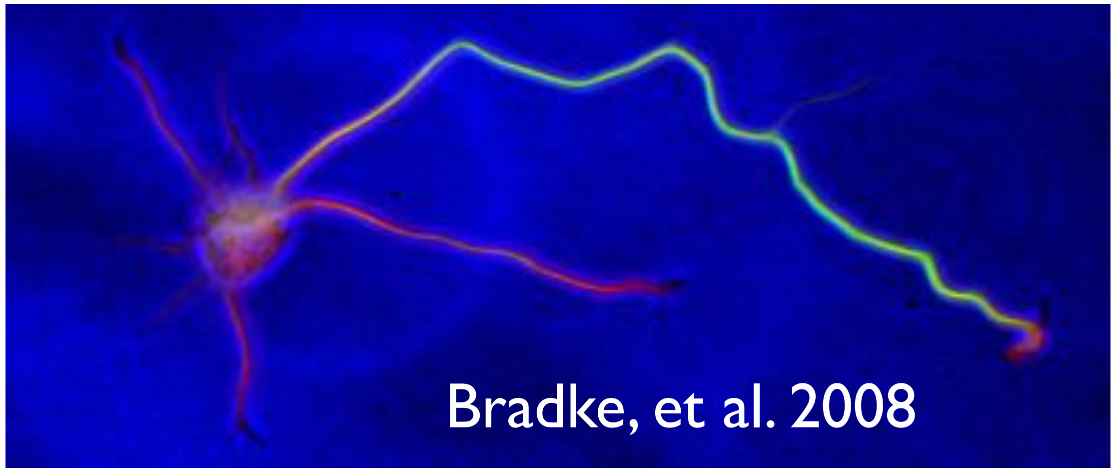
Pollen Tubes



Prado, et al. 2004

Nerve Cells





Bradke, et al. 2008

Vines

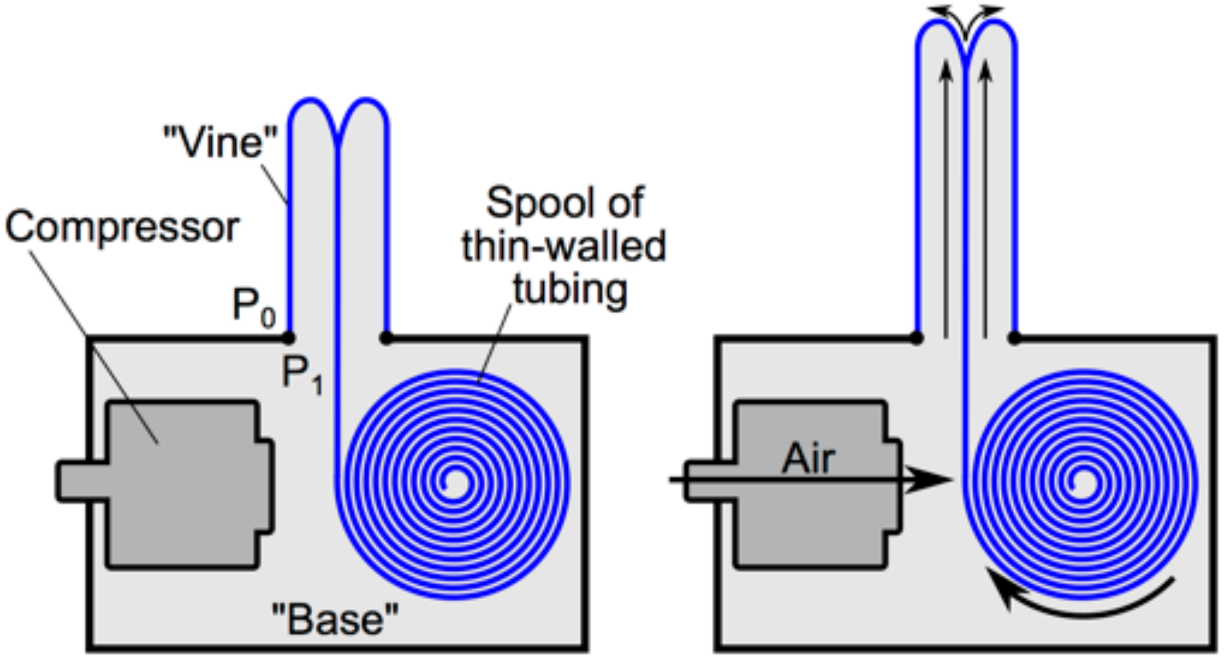
Sadeghi et al. 2013-17
Walker et al. 2015-16

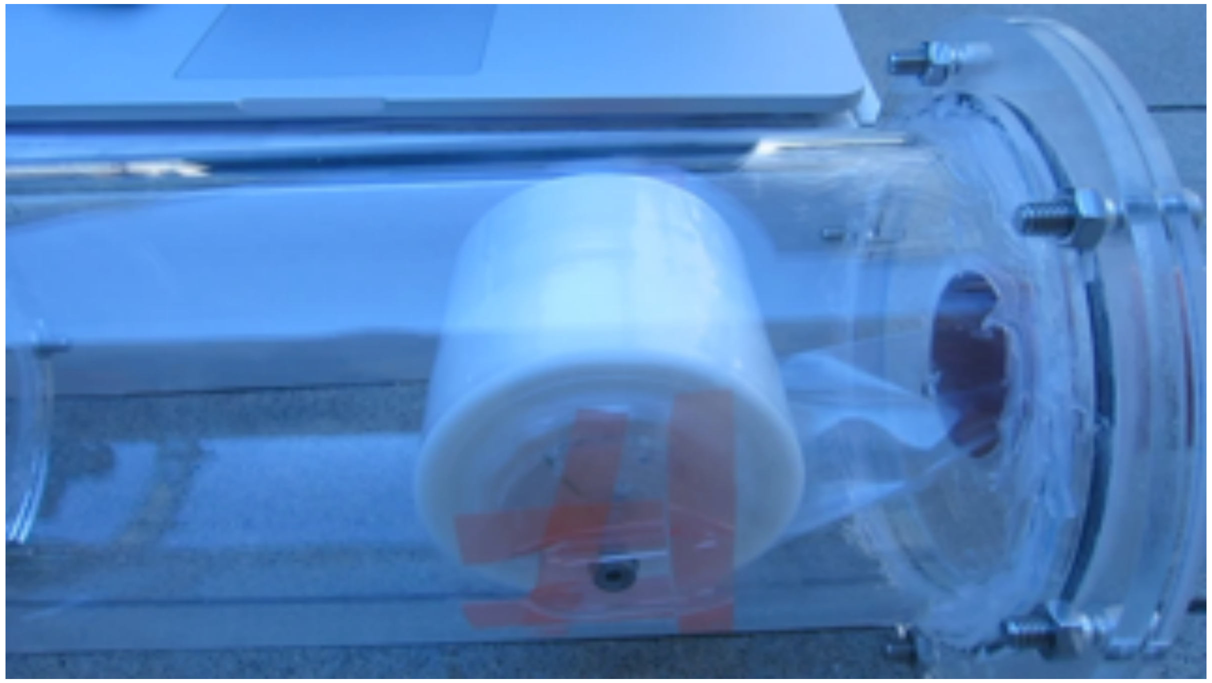

“water snake” toy

Passing flexible plastic material to the “growth” site is **reversible** and can be **very fast** (up to 10 m/s measured to date)

Hawkes et al. Science Robotics 2017 (prior: Orekhov et al. IROS 2010, Tsukagoshi et al. IJAT 2011, Mishima et al. FSR 2003)

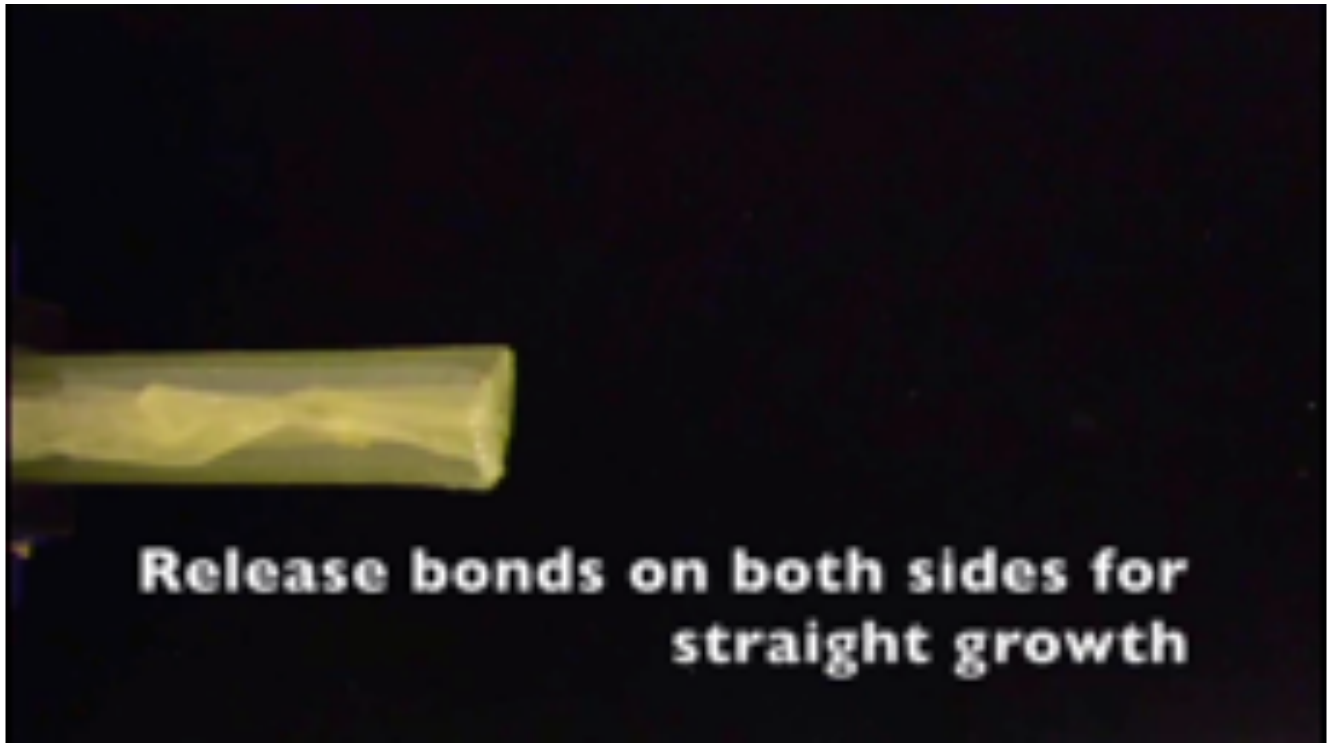
Extremely large change in length is achieved by using **air** for volume change and **thin polymer membranes** for surface area change





Blumenschein et al. Living Machines 2017

Control of growth direction can be achieved **permanently** (making/releasing bonds) or **reversibly** (pneumatic muscles)



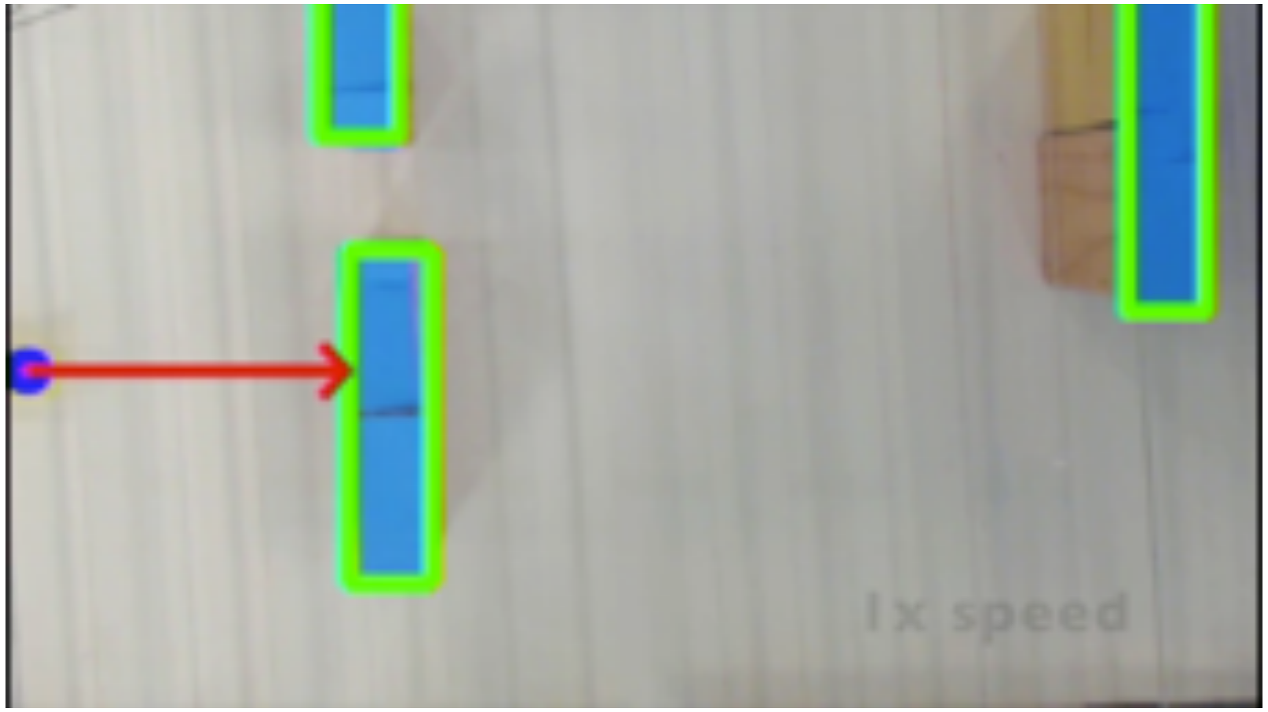
permanent direction change

reversible direction change

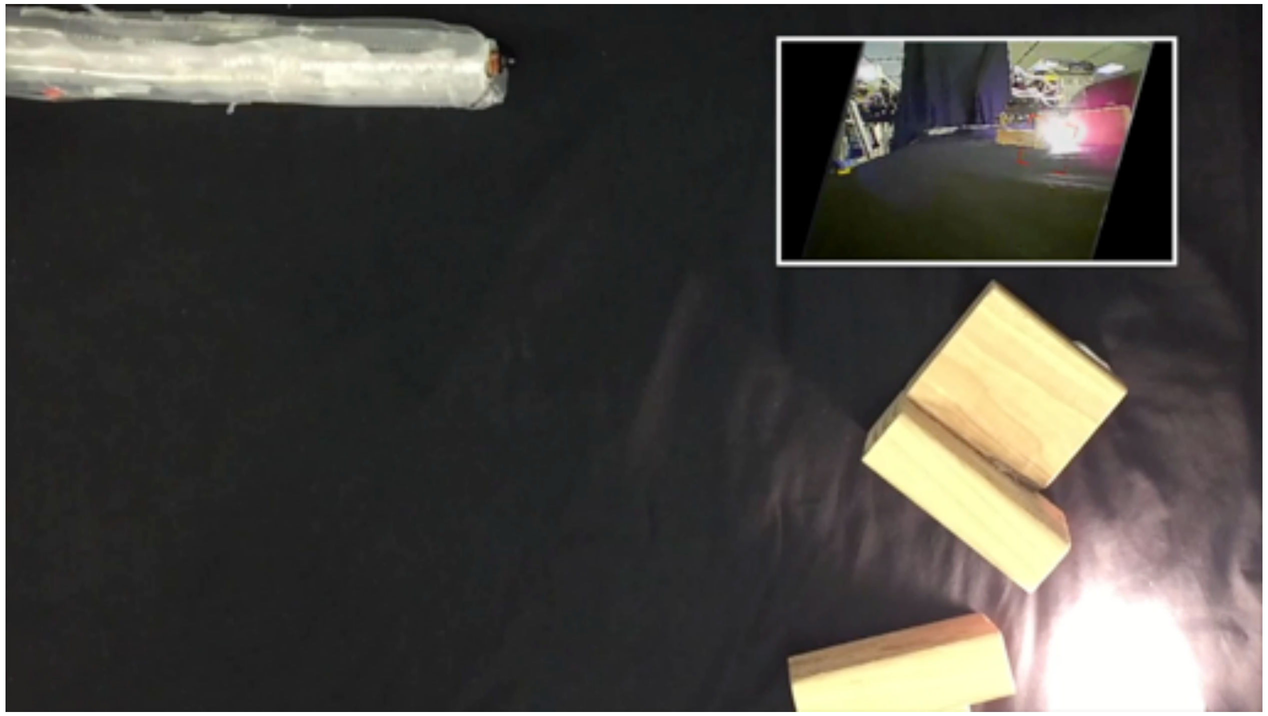
Greer et al. ICRA 2017

Control of growth direction can be achieved **actively** using sensor feedback

non-reversible methods:



active steering using overhead camera

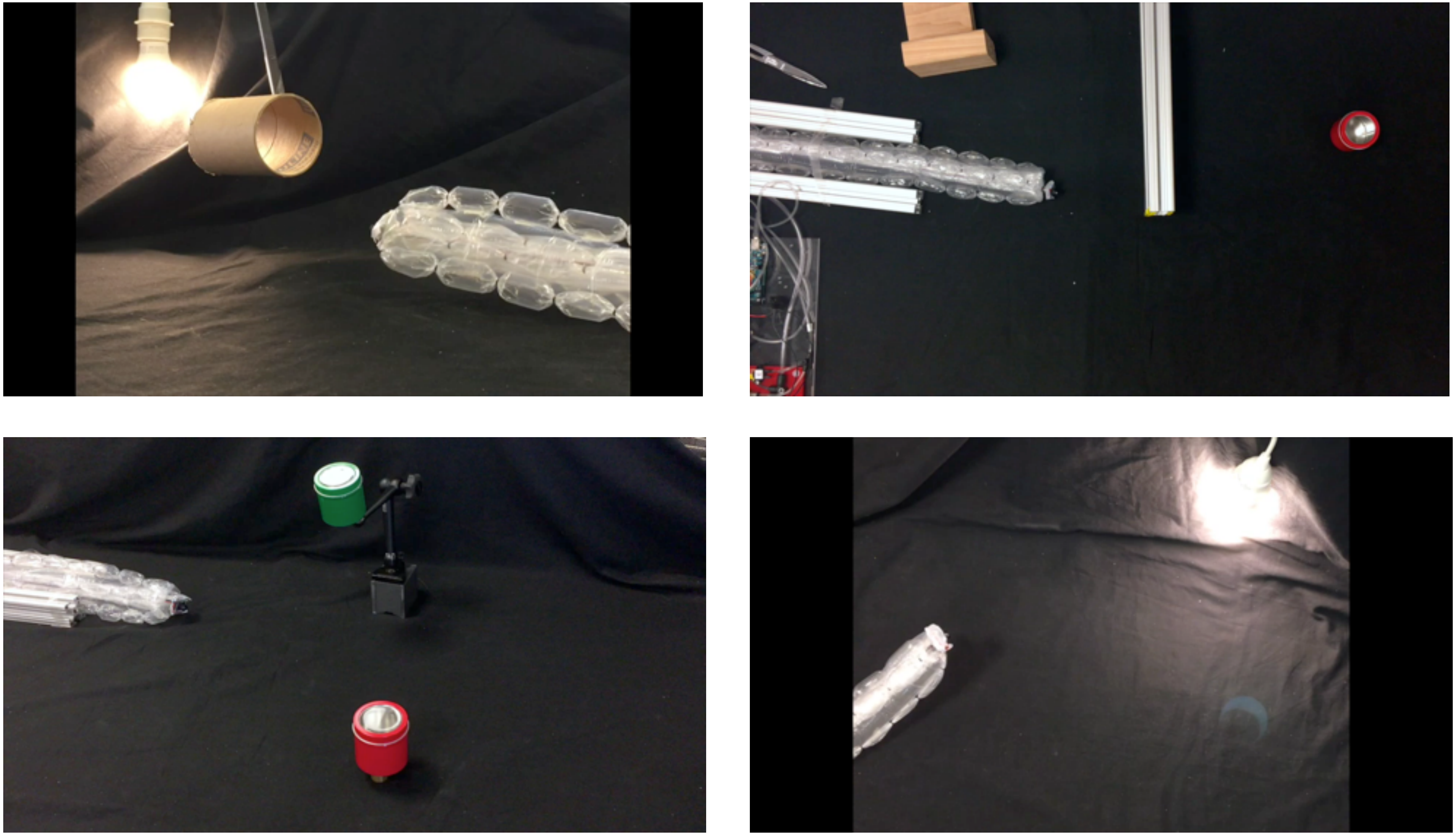


active steering using tip-mounted camera

Hawkes et al. Science Robotics 2017

Control of growth direction can be achieved **actively** using sensor feedback

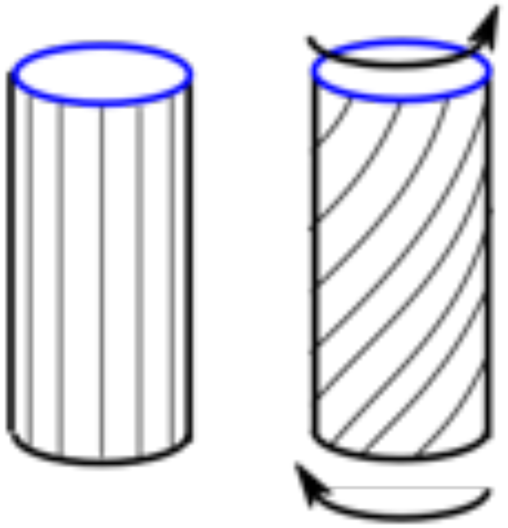
reversible methods:

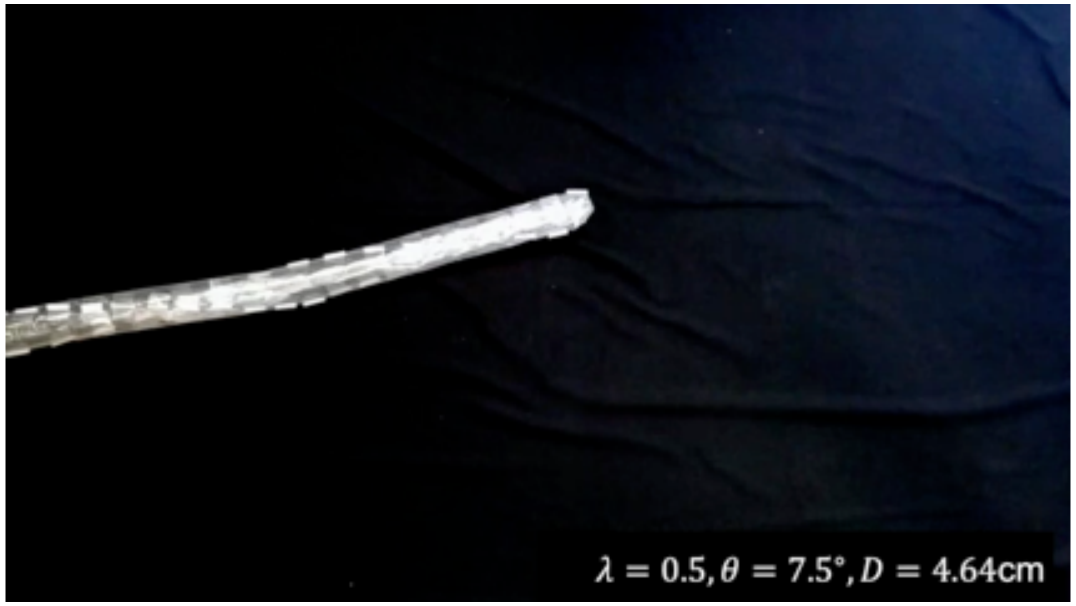


Greer et al. 2019

Control of growth direction can also be achieved through **tendon routing**

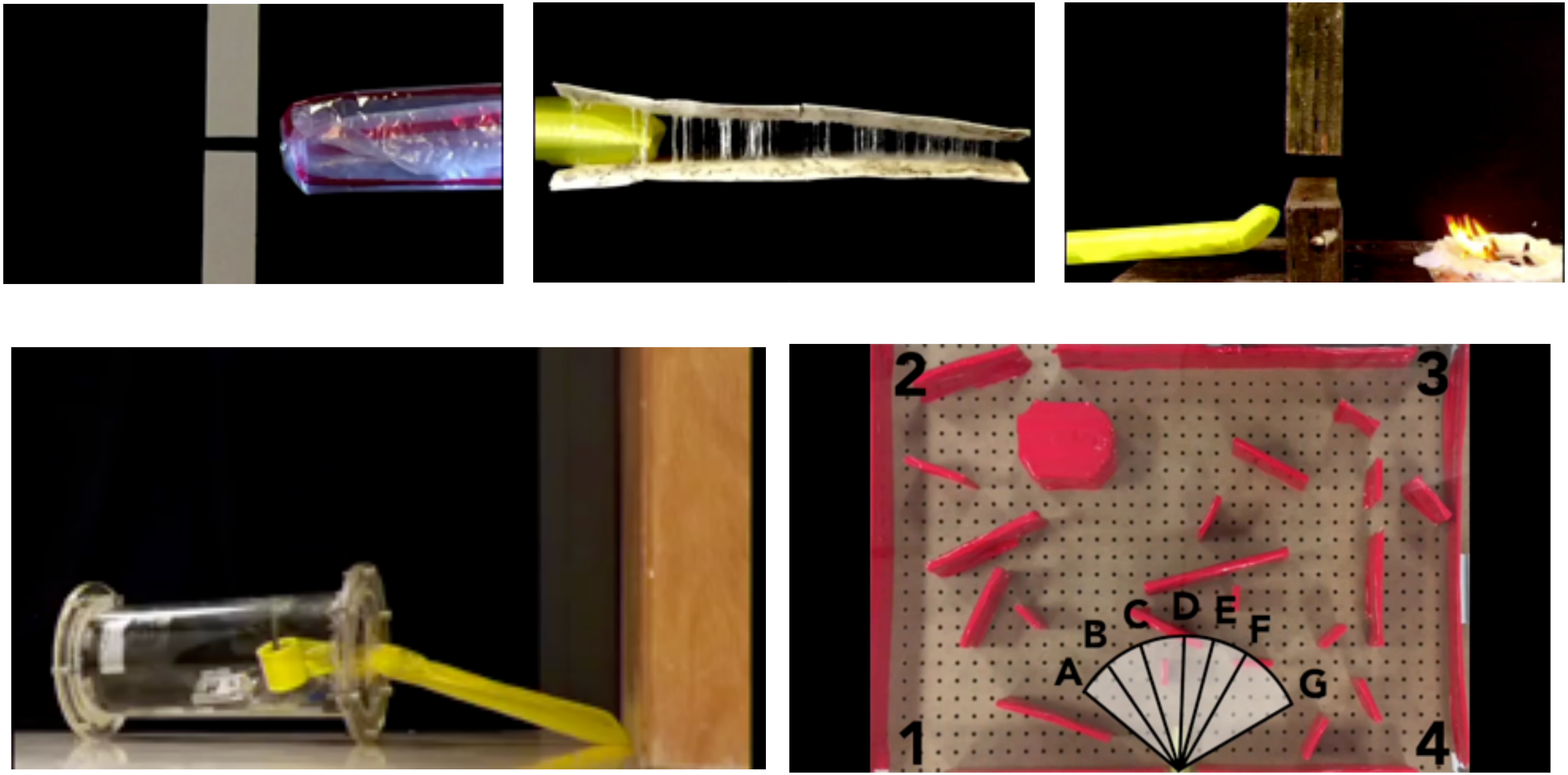
Circumferential Tendons





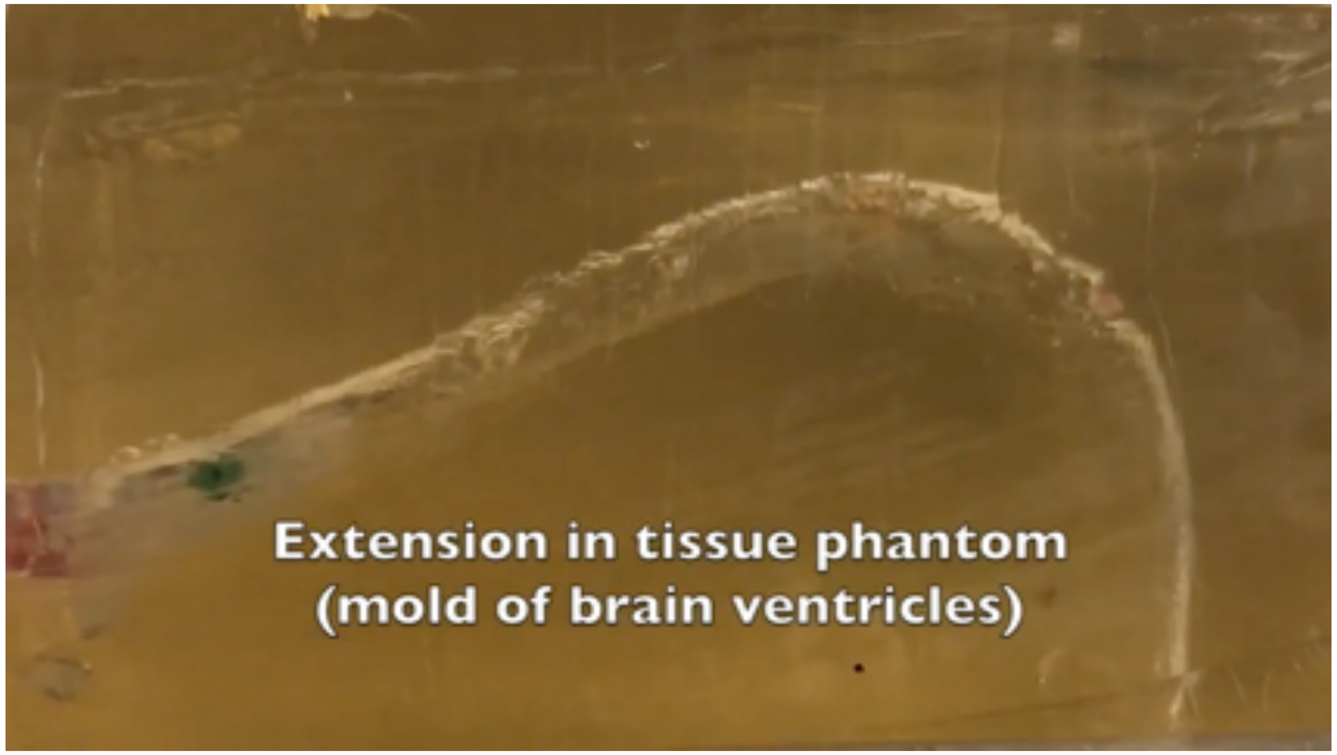
Blumenschein et al. 2018

Applications include scenarios that challenge our ability to safely access and create useful structures in locations remote in distance or scale



Hawkes et al. Science Robotics 2017, Greer et al. ICRA 2018

Catheters



Patrick Slade

Slade et al. IROS 2017

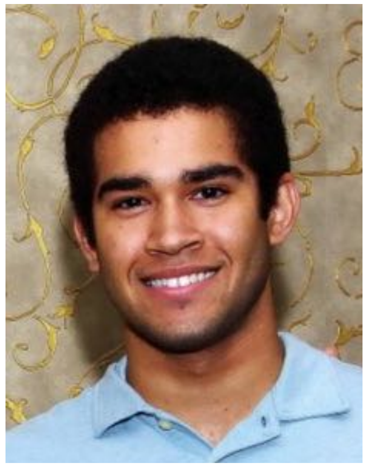
Tania Morimoto

Hawkes et al. in review 2019

HapWRAP

Wearable Restricted Actuator Pneumatics

Michael
Raitor

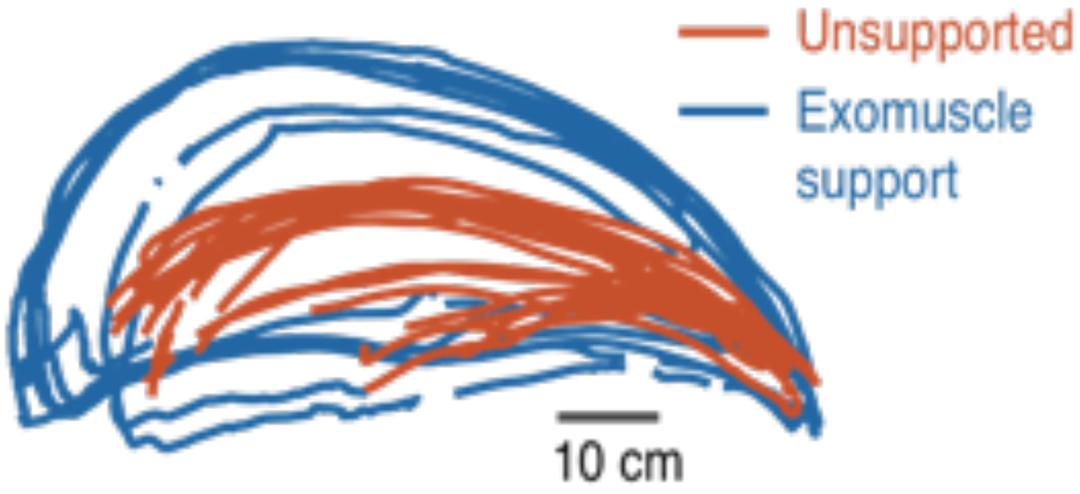


Nathaniel
Agharese

Agharese et al. in preparation 2017

Exomuscle

Cole Simpson



Simpson et al. 2017