Novel ***Sensing Mechanisms*** for Medical Robotics

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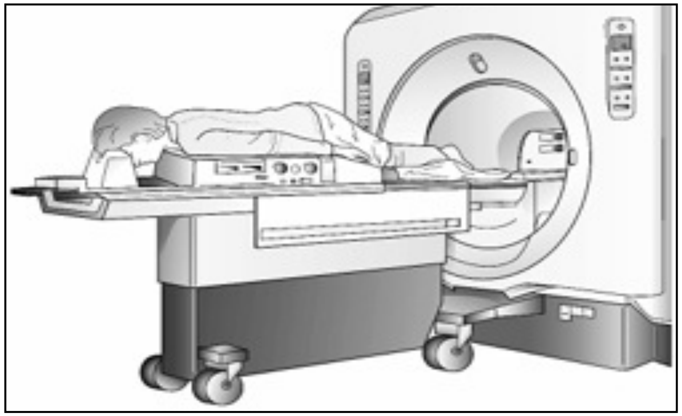
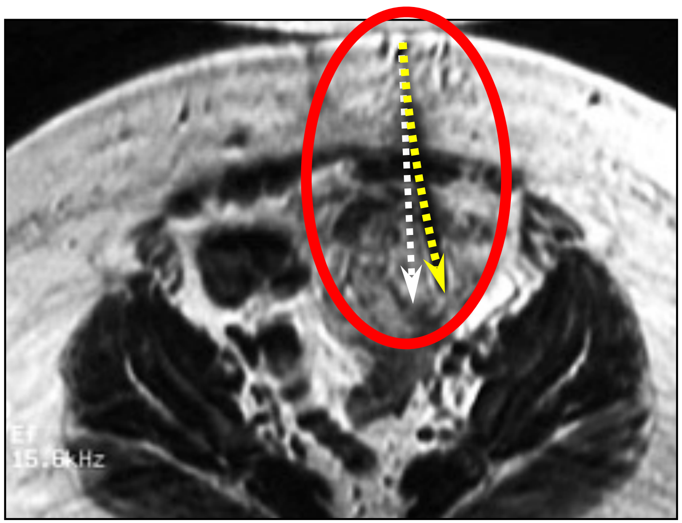
(*http://softrobotics.cs.cmu.edu*)

- **MRI-Compatible Shape Sensing Interventional Tools**
- MRI-Compatible Robotic End-Effector
- Soft Sensors
- Soft Actuators

Background



MRI Core Breast Biopsy (*Image from http://www.uwhealth.org*)



MRI of needle puncturing an abscess in the pelvis.

- MRI-Guided Interventional Procedures
  - MR Guided Biopsy
  - Lesion Localization
  - Tumor Ablation
  - Therapeutic Injection
- **Problems:**
  - Needle Deflection
  - Lack of sensing capability

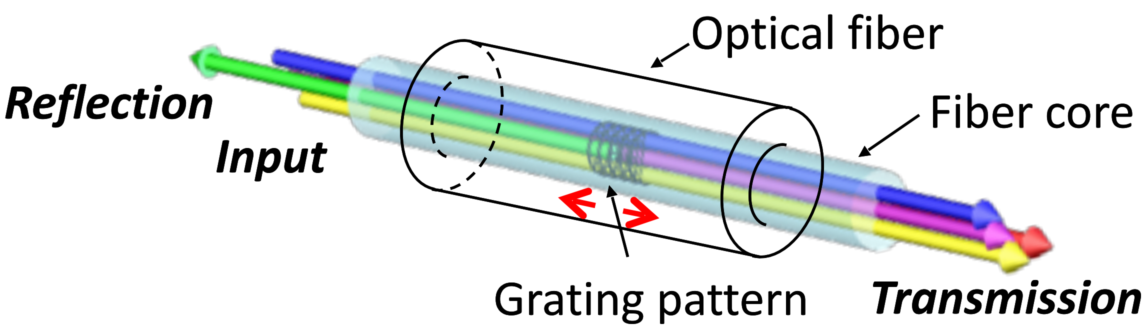
Goal: Detection of Needle Deflection

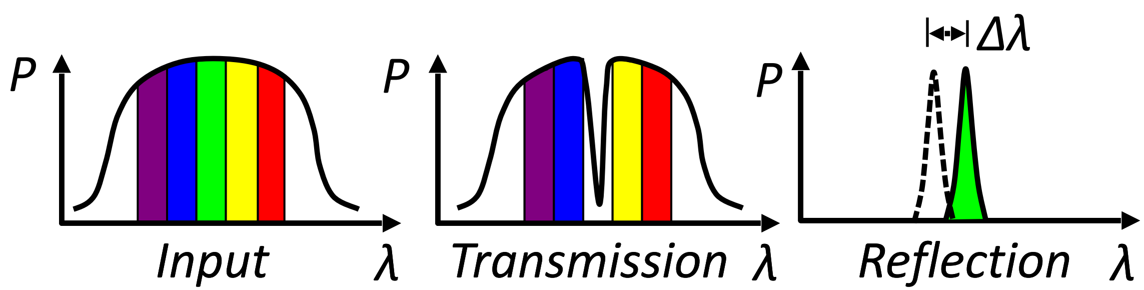
- Existing Technologies
  - MR Tracking
  - Rapid MRI
  - Gradient-based Tracking
- Objective: MR-Haptics
  - Real-time sensing of needle deflection and bend-shape
  - Strain sensing approach

Fiber Bragg Grating (FBG) Sensors (1)

Fiber Bragg Grating Sensor

- optic strain sensor





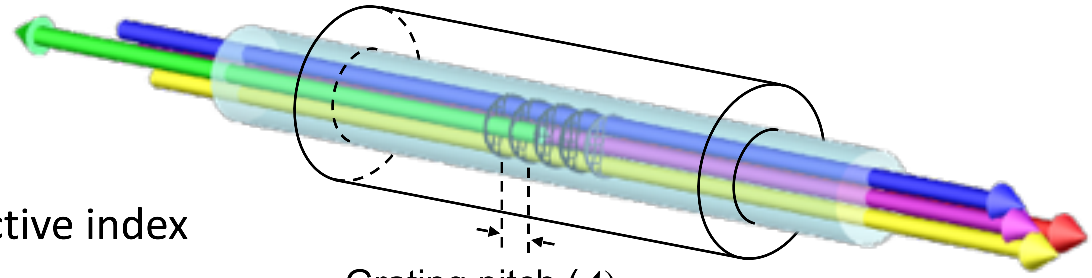
- Light, small, and flexible
- Electrically passive
- Multiplex / de-multiplex
- High resolution (0.1 $\mu\varepsilon$)
- High accuracy (1 $\mu\varepsilon$)

K. O. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," *J. Lightwave. Technol.*, 15(8): 1263–1276, 1997.

Fiber Bragg Grating (FBG) Sensors (2)

- Bragg wavelength:

$$\lambda_B = 2n_{eff}\Lambda$$



n_{eff}: effective refractive index

Λ : spatial period of grating

- ***Strain*** and ***temperature*** dependent: 1.2 pm/$\mu\varepsilon$, 10 pm/ºC

$$\Delta\lambda_B/\lambda_B = (1 - p_\varepsilon)\varepsilon + (\alpha_\Lambda - \alpha_N)\Delta T$$

ε : strain

ΔT : temperature change

p_ε : strain optic coefficient

α_Λ : thermal expansion coefficient of fiber

α_N : thermal optic coefficient

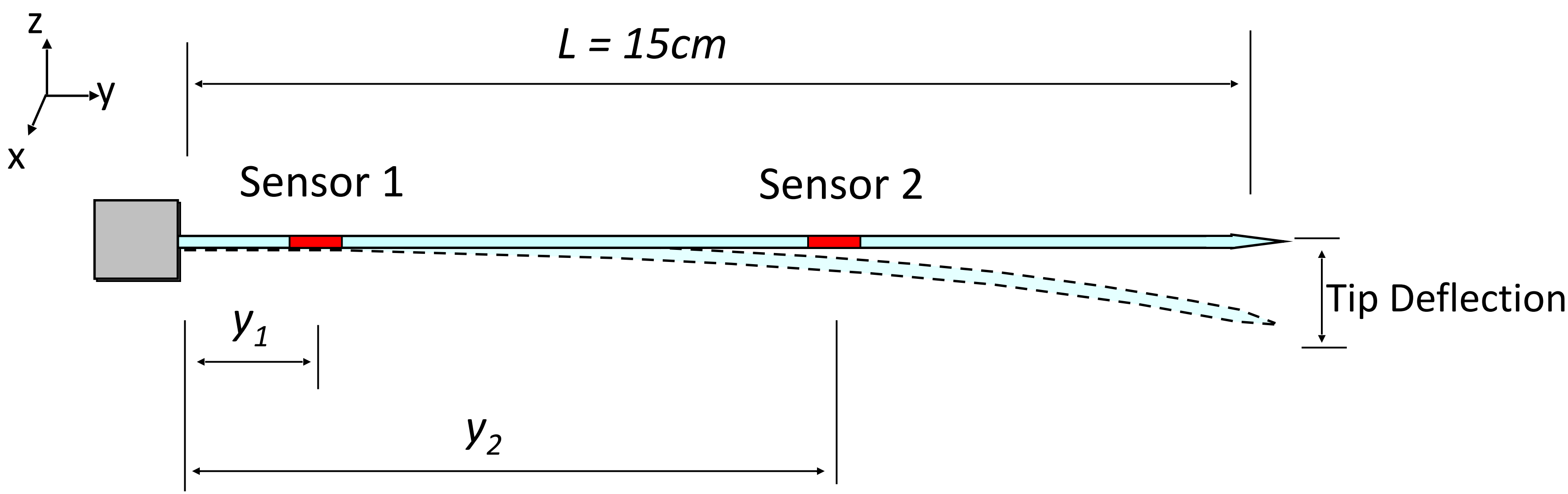
Model Construction

- MRI-compatible biopsy needle

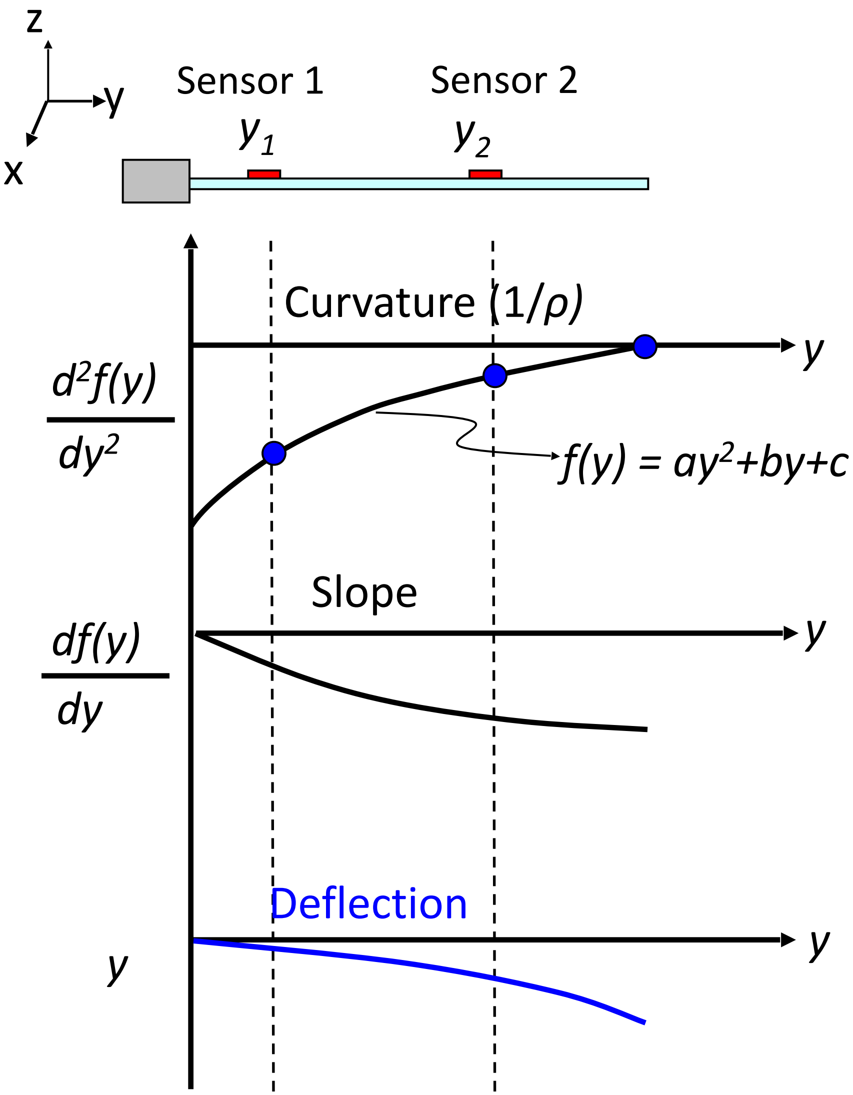
  (MR1815, E-Z-EM Inc, Westbury, NY)

  – 18 ga x 15 cm

  – Material: Inconel 625 alloy



Deflection Estimation using Beam Theory



ε_n: strain measured by FBG sensor

ρ: radius of curvature

d: distance from neutral axis

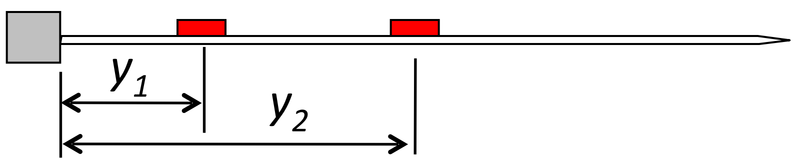
$$\text{Curvature} = \frac{1}{\rho} = \frac{\varepsilon_n}{d}$$

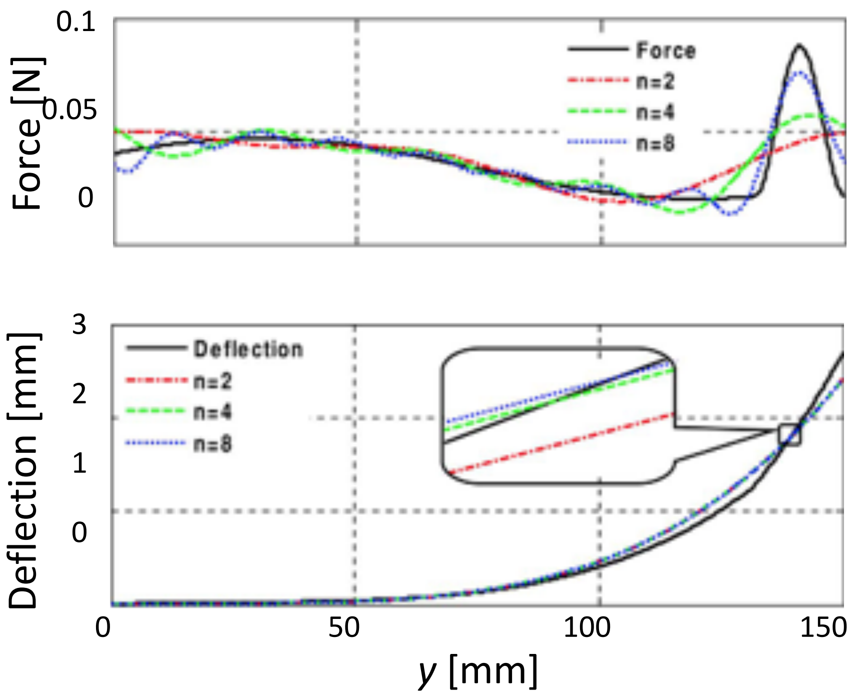
$$\text{Slope} = \int f(y)\,dx$$

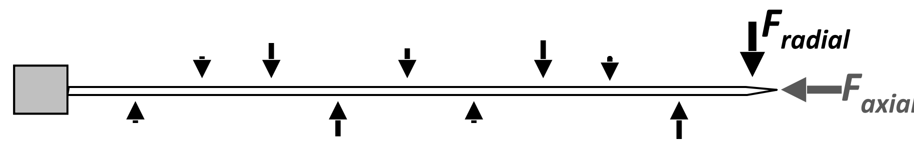
$$\text{Deflection} = \iint f(y)\,dx$$

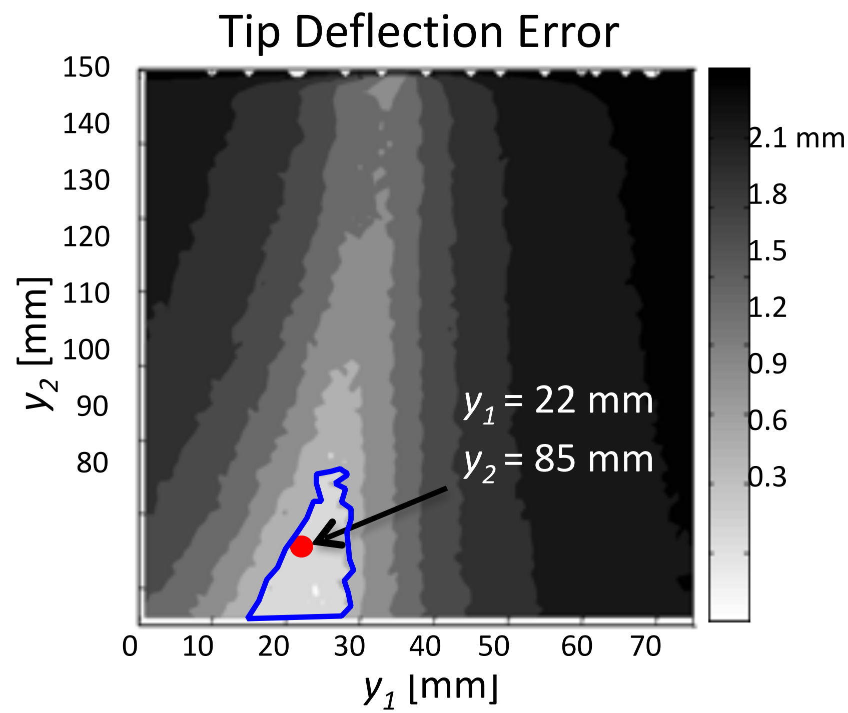
Sensor Placement

L=150 mm, Φ=1 mm



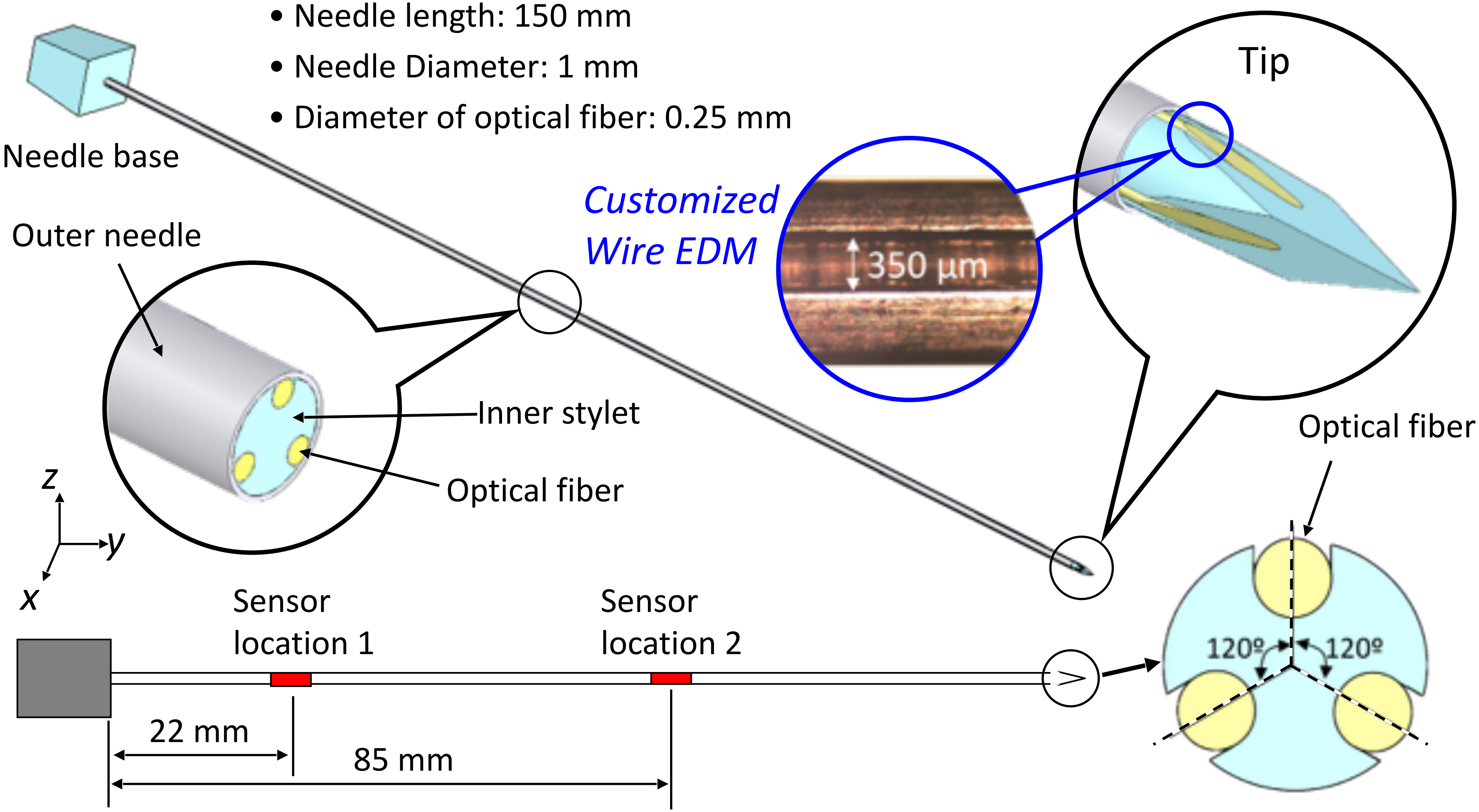






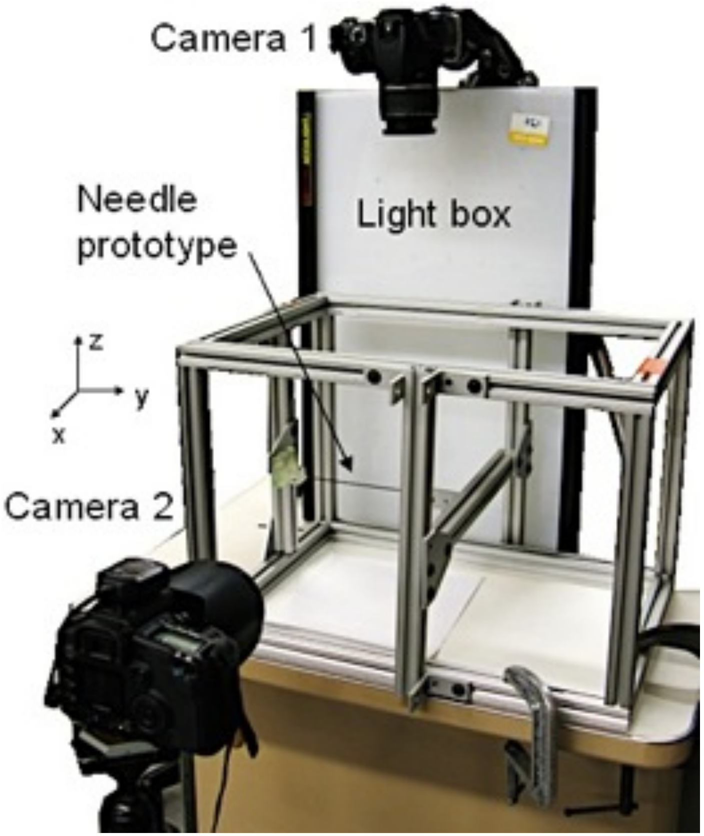
Prototype Design

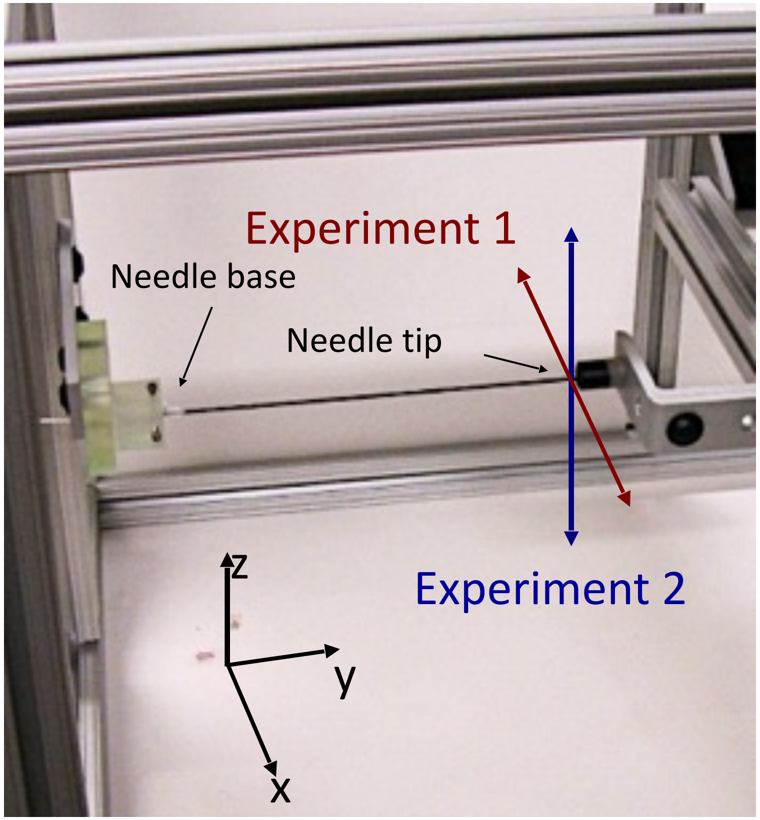
- Needle length: 150 mm
- Needle Diameter: 1 mm
- Diameter of optical fiber: 0.25 mm



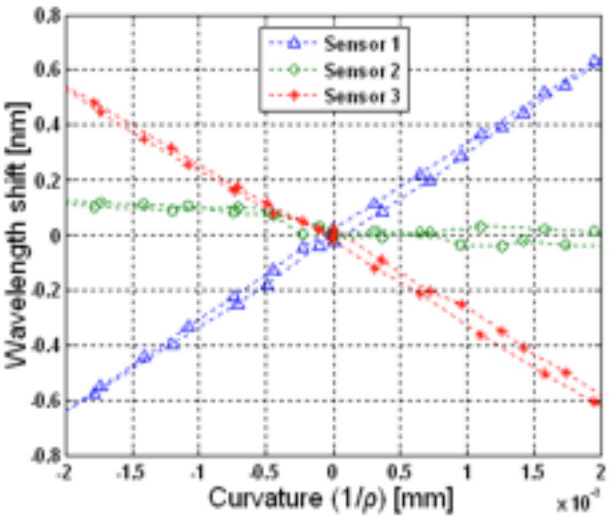
Y-L Park, S Elayaperumal,MR Cutkosky et al., ***IEEE/ASME Transactions on Mechatronics (TMech)***, Vol. 15, No. 6, 2010.
S Elayaperumal, J. Plata, **Y-L Park** et al., ***IEEE Transactions on Medical Imaging (TMI)***, 2014.

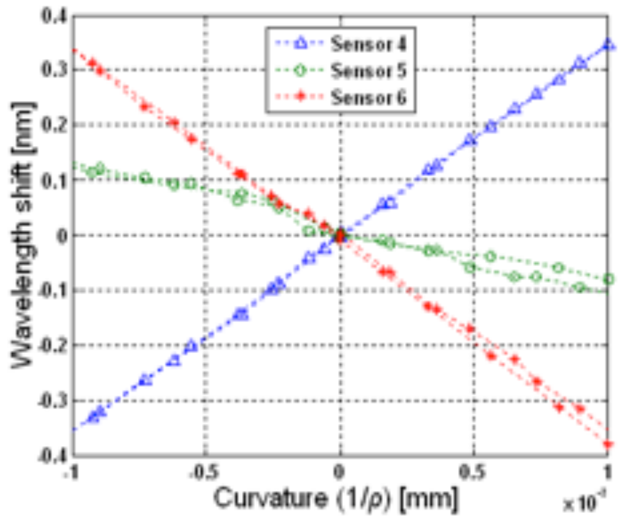
Sensor Calibration

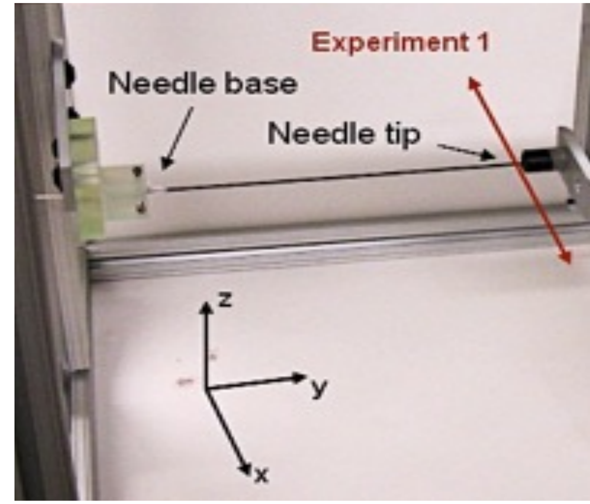


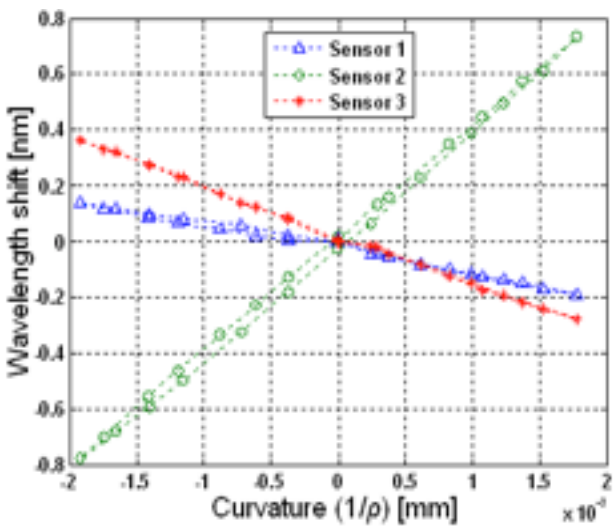


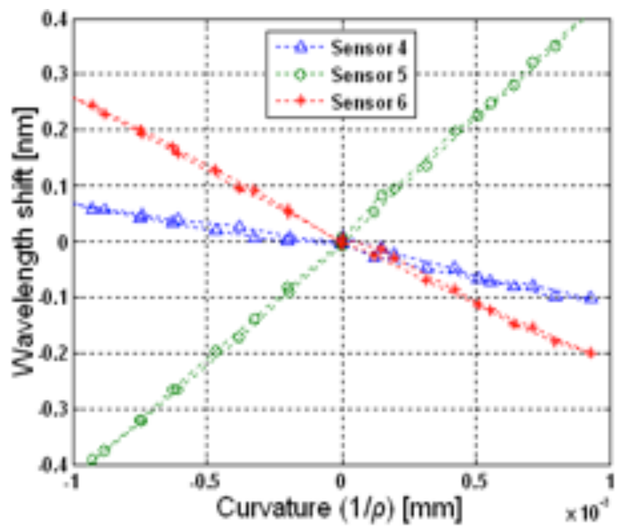
Calibration: $\Delta\lambda$ vs. Curvature

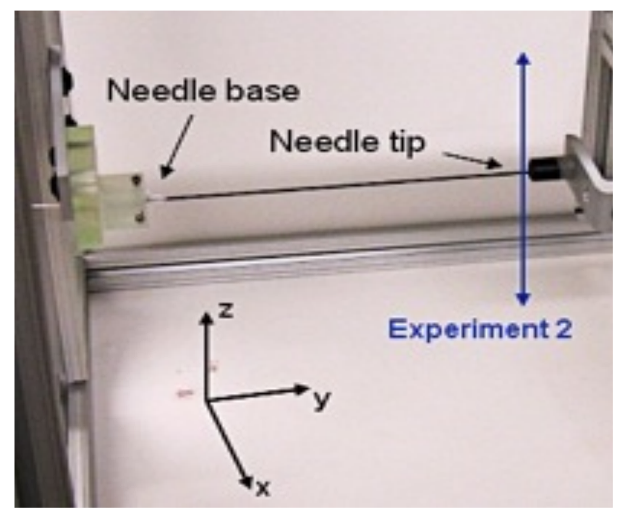












Calibration: $\Delta\lambda$ vs. Curvature

$$\delta y_n = \delta s_n \cdot C_n$$

$$\delta y_n = [k_{xy} \quad k_{yz} \quad \Delta t\,]$$
$$\delta s_n = [\Delta\lambda_1 \;\; \Delta\lambda_2 \;\; \Delta\lambda_3]$$

Moore-Penrose pseudo inverse
with a weight matrix

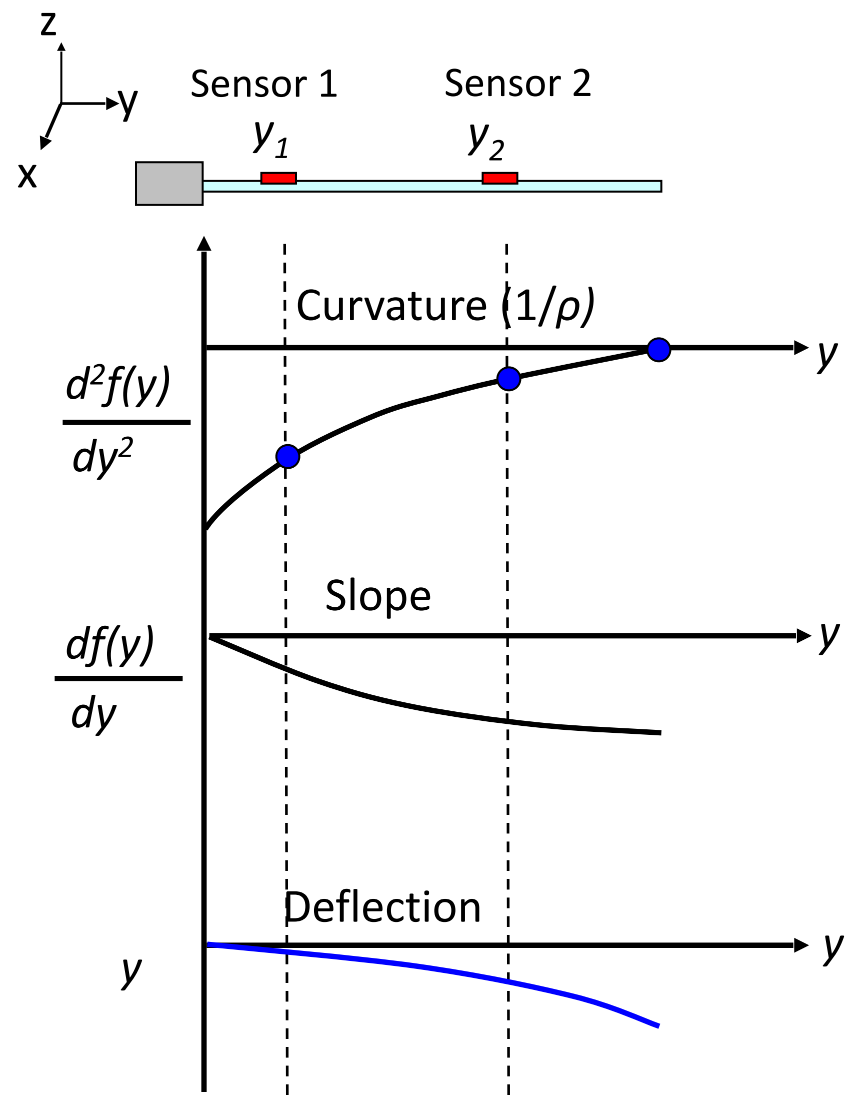
$$C_n = [\delta s^T W \delta s]^{-1} \delta s^T W \cdot \delta y_n$$

C_n: Calibration matrix at sensor location n

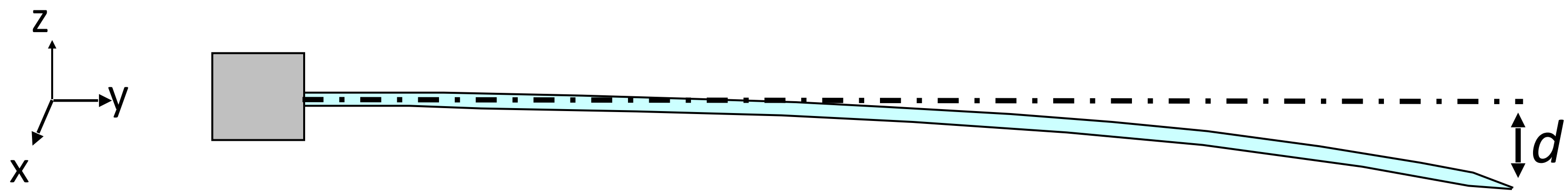
$k_{xy\ (or\ yz)}$: Local curvature in xy- (or yz-) plane

Δt: Temperature change

$\Delta\lambda_i$: Wavelength shift of sensor i



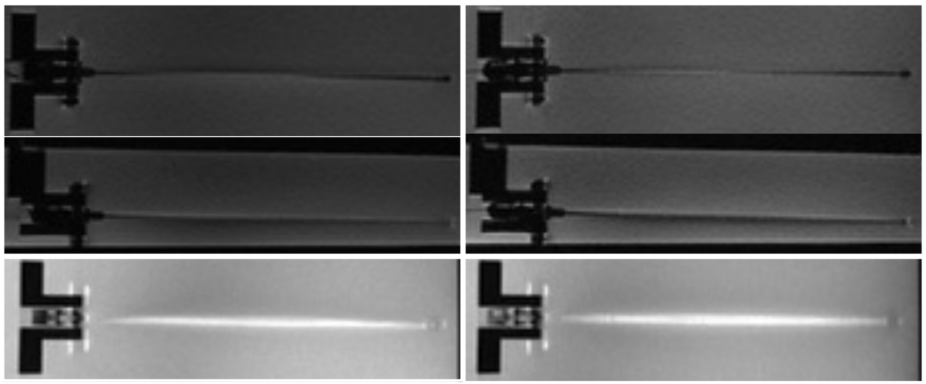
Results: $\Delta\lambda$ vs. Curvature

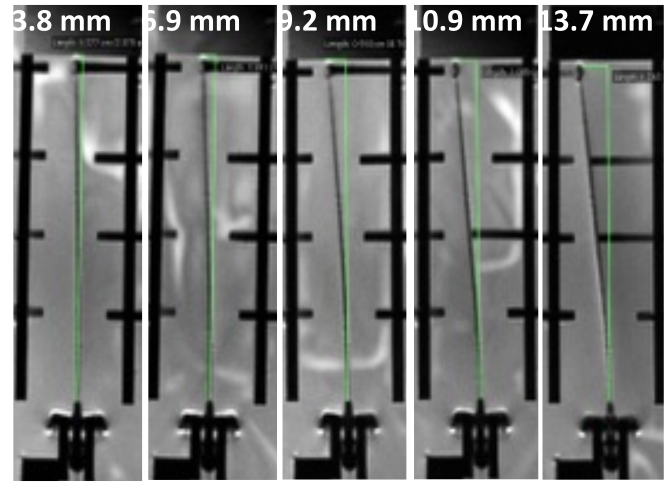


Deflection Range (mm)	$-7 \leq d \leq 7$	$-10 \leq d \leq 10$	$-15 \leq d \leq 15$
Error RMS (*xy*)	0.35	0.38	0.38
Error RMS (*yz*)	0.26	0.26	0.28

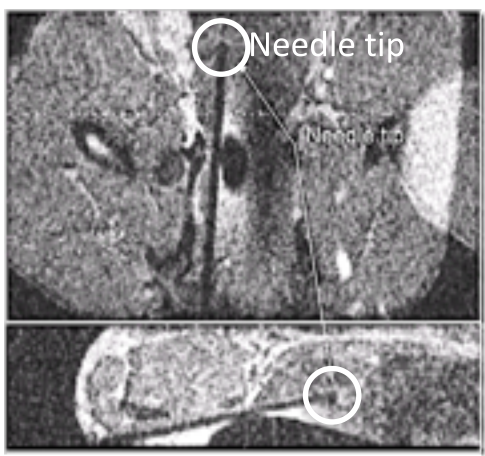
MRI Scanner Tests

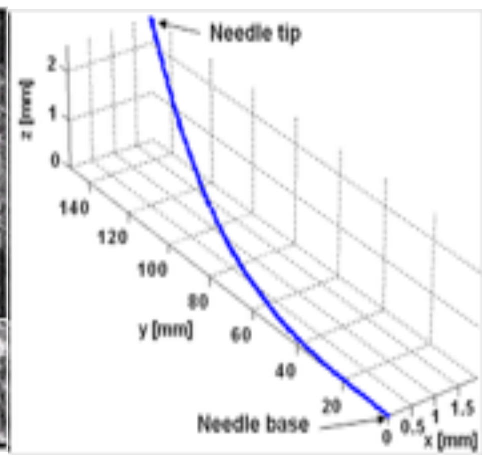
Without Sensor With Sensor

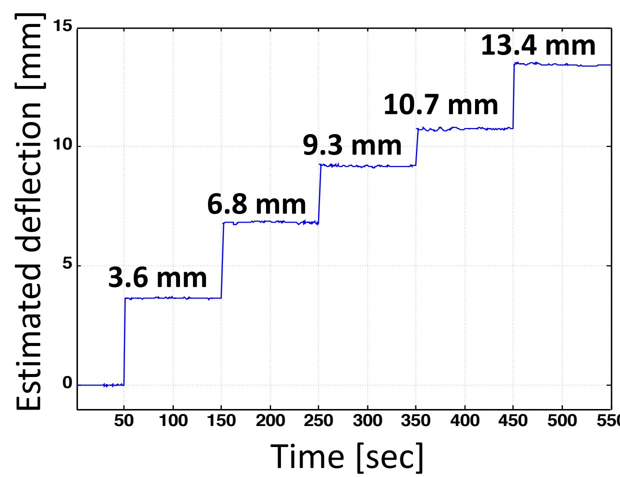




In-Vivo Animal Test





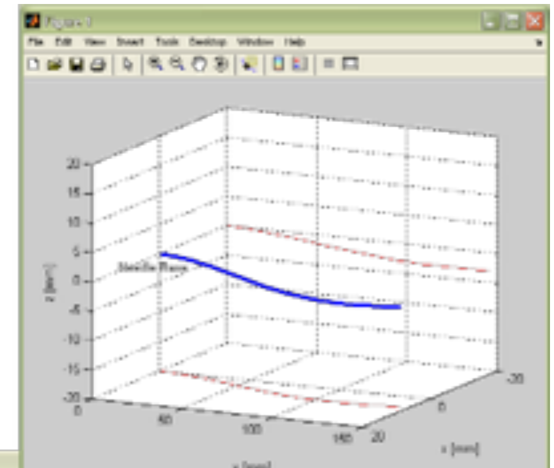


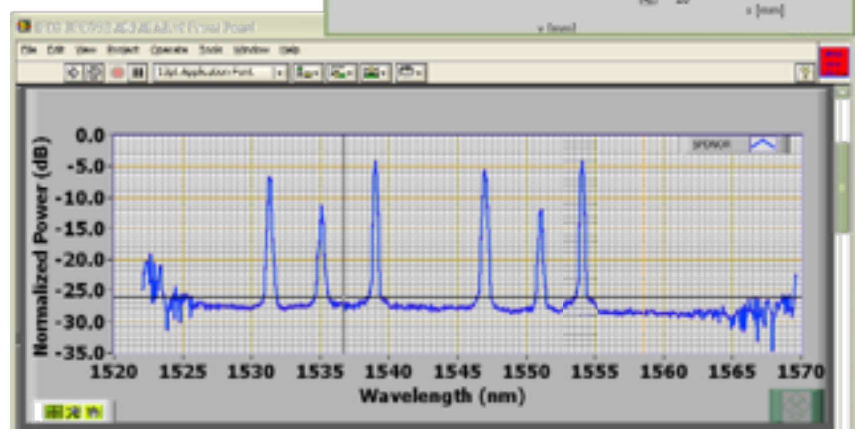
<u>Clinical Collaboration</u>:
Bruce Daniel, MD, Radiology, Stanford Medical Center

Real-Time Monitoring System

Video Link:
http://www.youtube.com/watch?v=m1MR9QtOU4o

MATLAB window for showing
3D **Needle Shape** in real-time





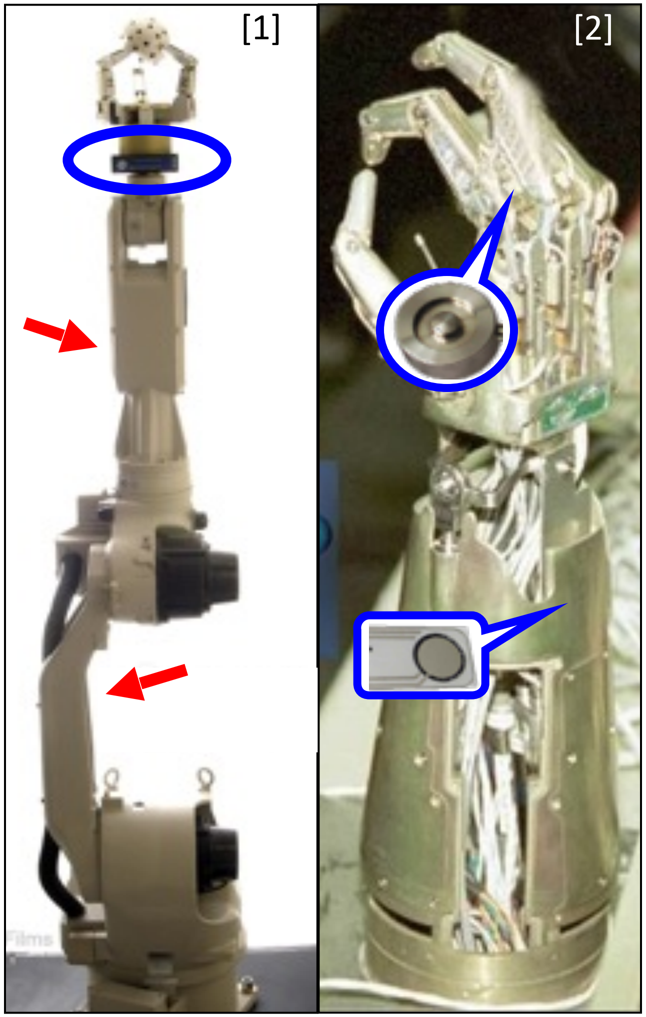
LabView window showing **Wavelength Shifts**

Summary

- MRI-Compatible Shape Sensing Biopsy Needle
- Objective:
  - Instrumentation of MRI-compatible biopsy tools.
- Solution:
  - Embedded fiber optic sensors with customized EDM.
- Results:
  - Tip position error: ≈ 0.3 mm
  - Completely MRI-safe
- Publications:
  - **YL Park**, S Elayaperumal, B. Daniel et al., "Real-Time Estimation of 3-D Needle Shape and Deflection for MRI-Guided Interventions," ***IEEE/ASME Transactions on Mechatronics***, Vol 15, No 6, 2010.
  - S Elayaperumal, J Plata, A Holbrook, **YL Park**, MR Cutkosky et al. , "Autonomous real-time interventional scan plane control with a 3-D shape-sensing needle." ***IEEE Transactions on Medical Imaging***, 2014.
  - **YL Park**, S Elayaperumal, MR Cutkosky et al., "MRI-compatible Haptics: Strain sensing for real-time estimation of three dimensional needle deflection in MRI environments," *ISMRM 2009* (oral presentation), April 2009.
  - **YL Park**, S Elayaperumal, MR Cutkosky et al., "MRI-compatible Haptics: Feasibility of using optical fiber Bragg grating strain-sensors to detect deflection of needles in an MRI environment," *ISMRM 2008* (oral presentation), May 2008.

- MRI-Compatible Shape Sensing Interventional Tools
- **MRI-Compatible Robotic End-Effectors**
- Soft Sensors
- Soft Actuators

Force Sensing for Dexterous Manipulation



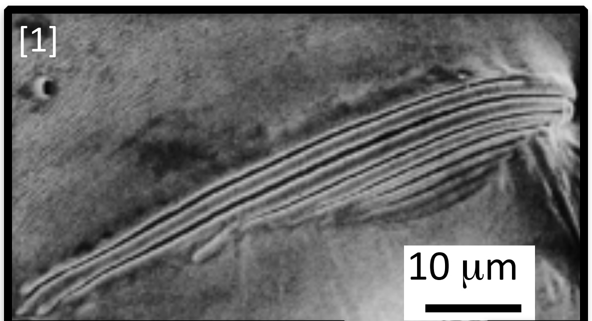
- Industrial Robot
  - 3 or 6 axis force-torque sensors
  - Sufficient for routine and expected tasks
  - No unexpected events allowed
- ROBONAUT (NASA)
  - Load cells and force sensitive resistors
- Limitations:
  - Electromagnetic interference
  - Complicated circuits and wiring
  - Limited area sensing
- Need a ***new approach to force sensing***

[1] *http://www.gdl.cinvestav.mx/~edb/images/Barret-arm.jpg* [2] Robonaut <*http://robonaut.jsc.nasa.gov/robonaut.html*>

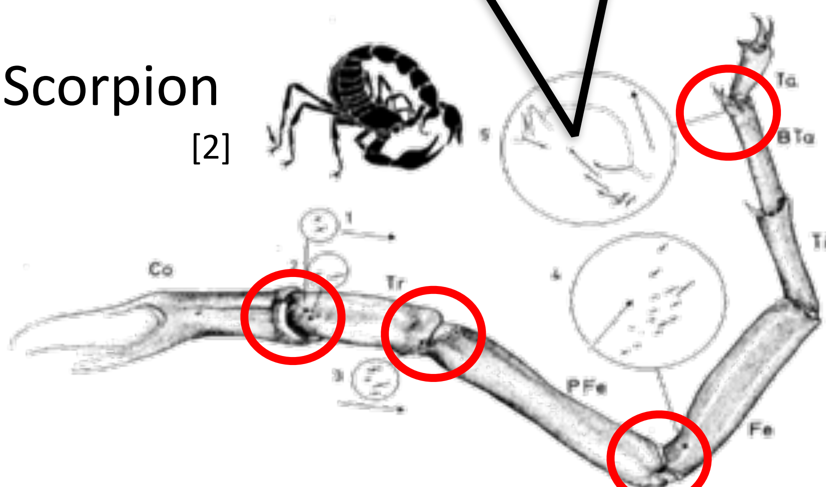
Biological Strain Sensors

Bio-Inspiration

Slit Sensilla*: biological strain sensors*
in exoskeletons (e.g. spiders, lobsters etc.)

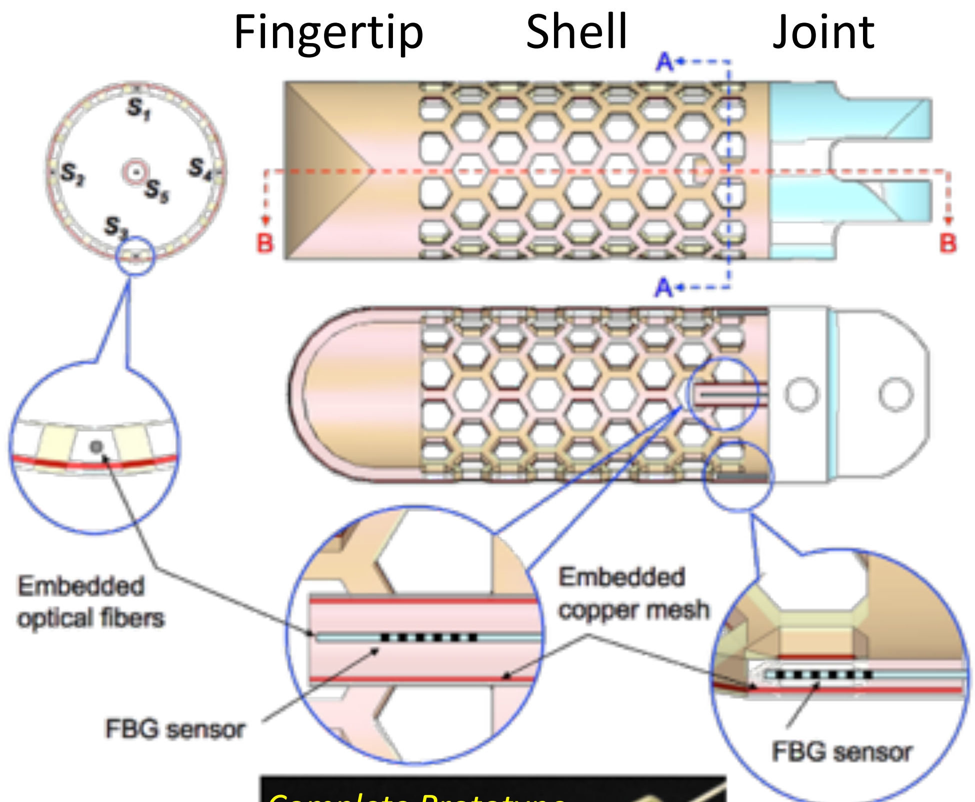


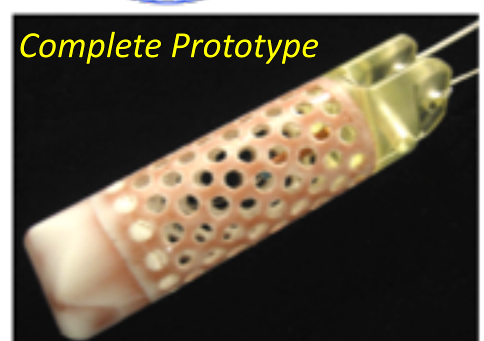
Scorpion
[2]



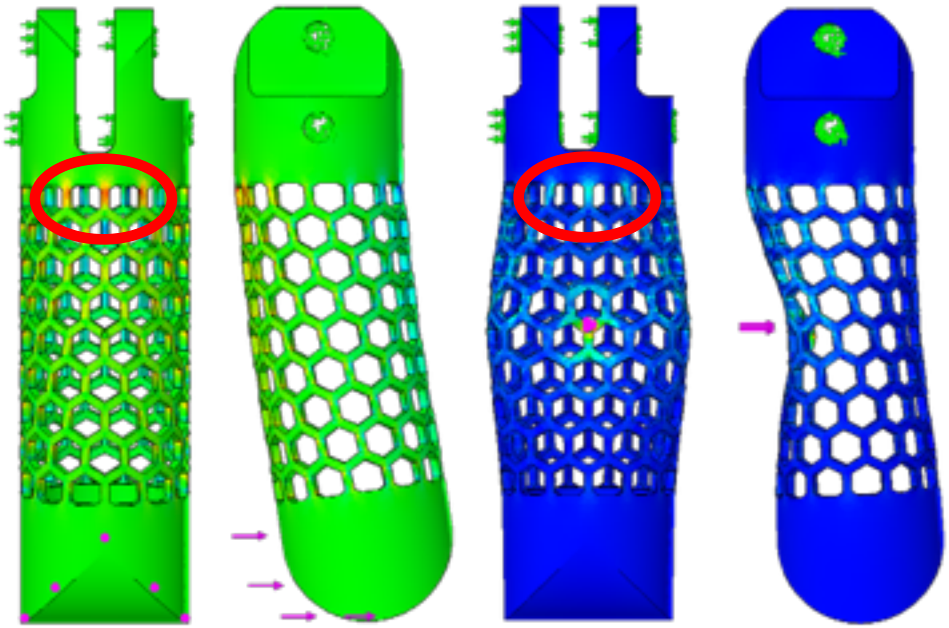
[1] FG Barth and M Wadepuhl. *J. Morphol.,* 145(2): 209-227, 1975.
[2] FG Barth, *Zoomorphologie,* 86:1-23, 1976

Design: sensor embedded exoskeleton

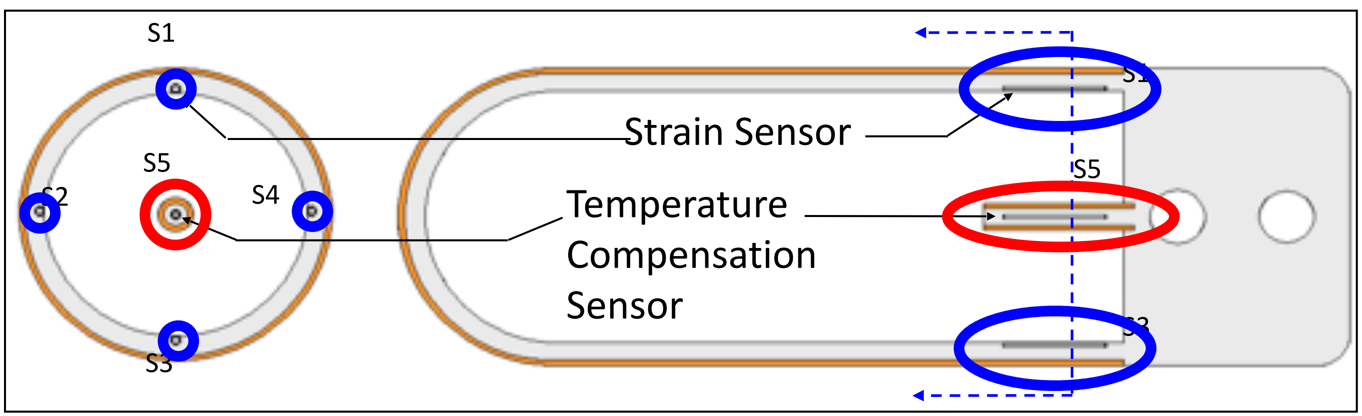


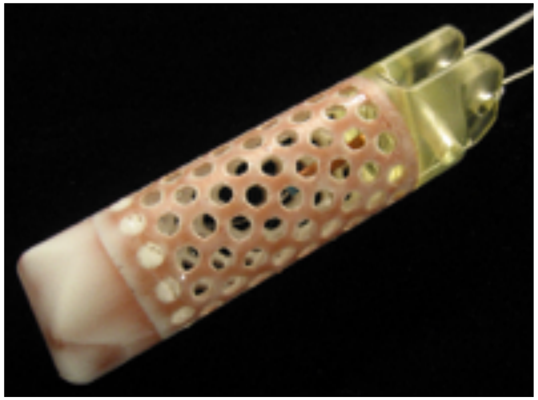


Sensor Configuration

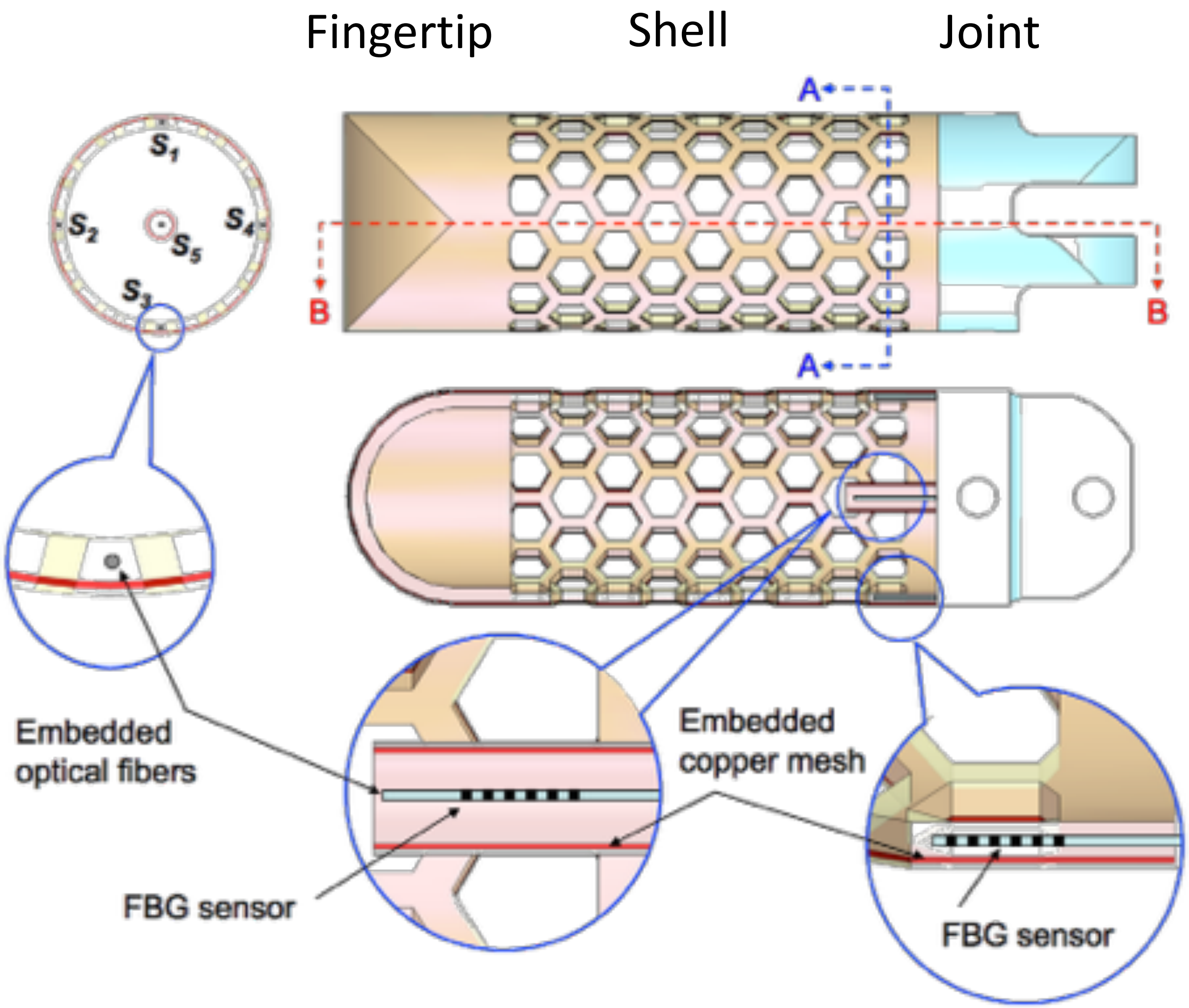


- Strains are mostly concentrated on the top of the shell
- **Four strain sensors** at 90° interval (first rib of the shell)
- One temperature compensation sensor in the middle



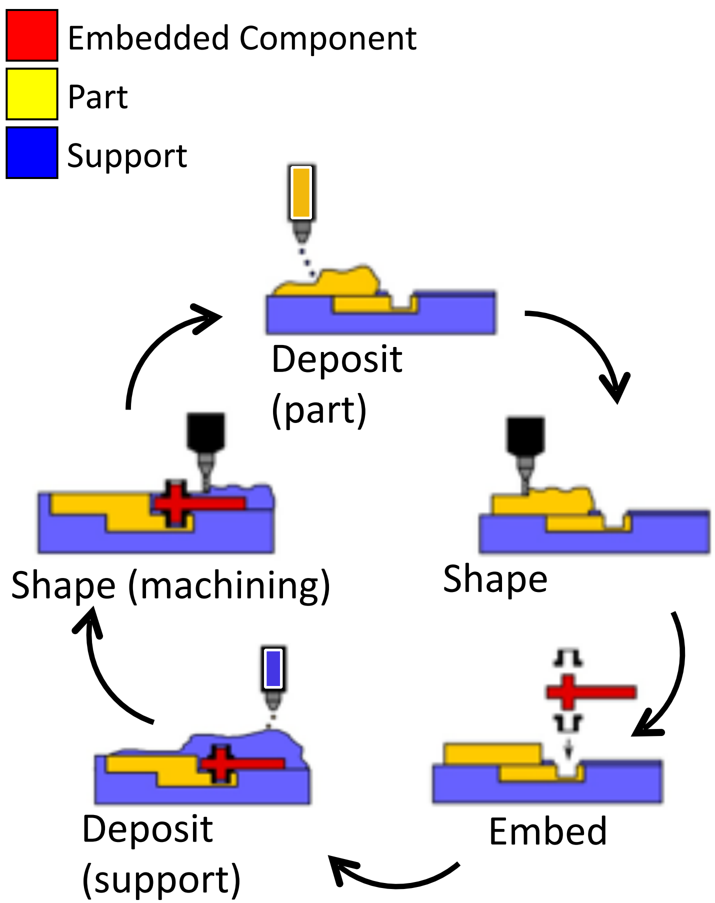


Fabrication Challenge



- Hollow structure
- Hexagonal shell patterns
- Embedded copper mesh
- Embedded optical fibers

Shape Deposition Manufacturing (SDM)



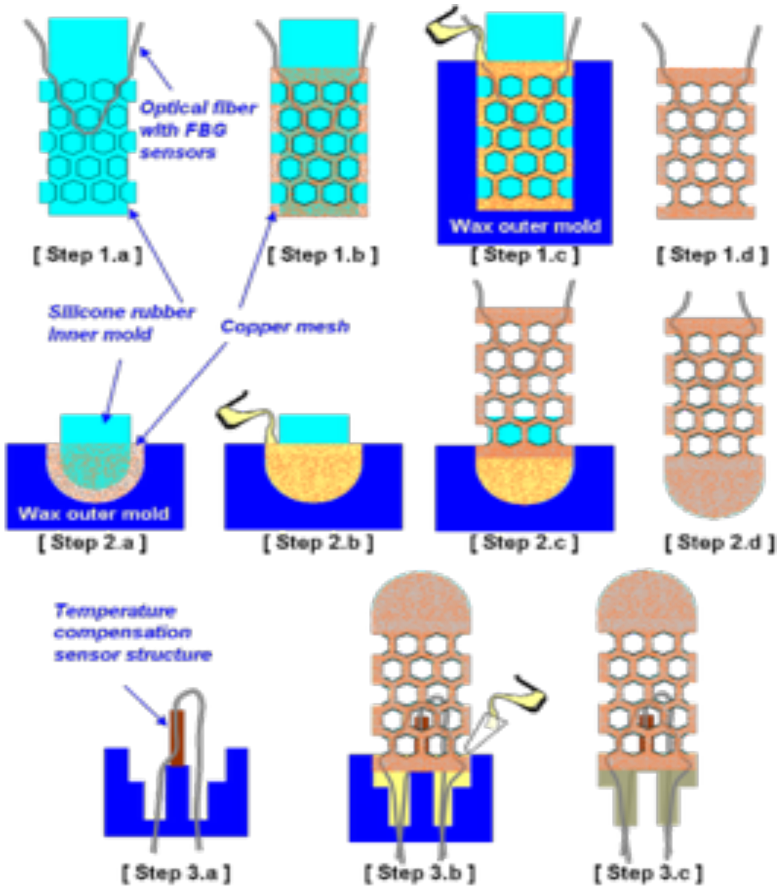
- Easy to build multi-material structure
- Easy to build multiple parts with different shapes at the same time
- Easy to embed different parts during the fabrication

- ***Limitations:***
  - Hard to make a hollow structure
  - Hard to make a fully 3D part

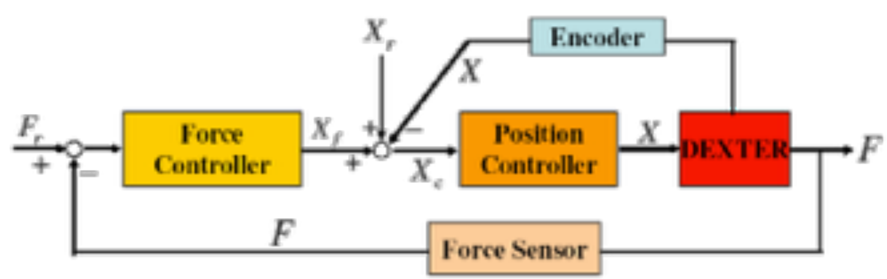
LE Weiss, R Merz FB Prinz et al., "Shape deposition manufacturing of heterogeneous structures," J. Manuf. Syst., 16(4): 239-248, 1997.
SA Bailey, JG Cham, MR Cutkosky, et al., "Biomimetic Robotic Mechanisms via Shape Deposition Manufacturing," *9th Int. Symp. Rob. Res.*, 1999.

New Manufacturing Method – Modified SDM

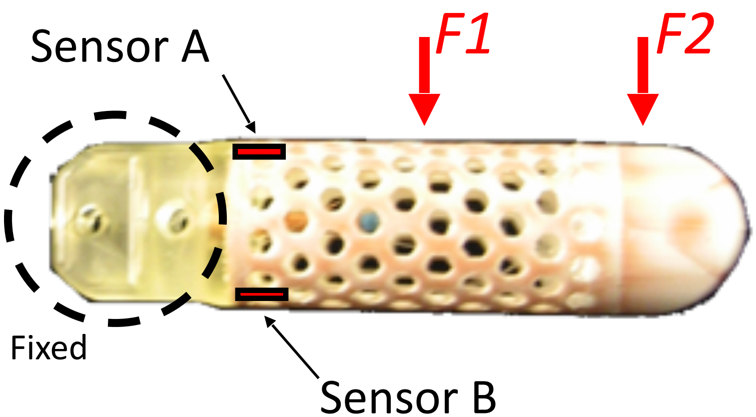
Manufacturing: Low cost, fast turn-around polymer manufacturing with embedded sensors



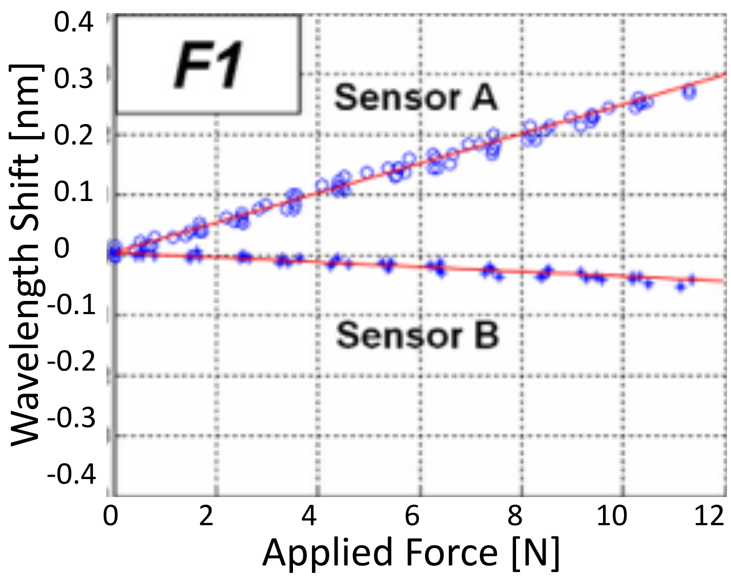
Sensor-Integrated Control: Nonlinear feedback force/position control

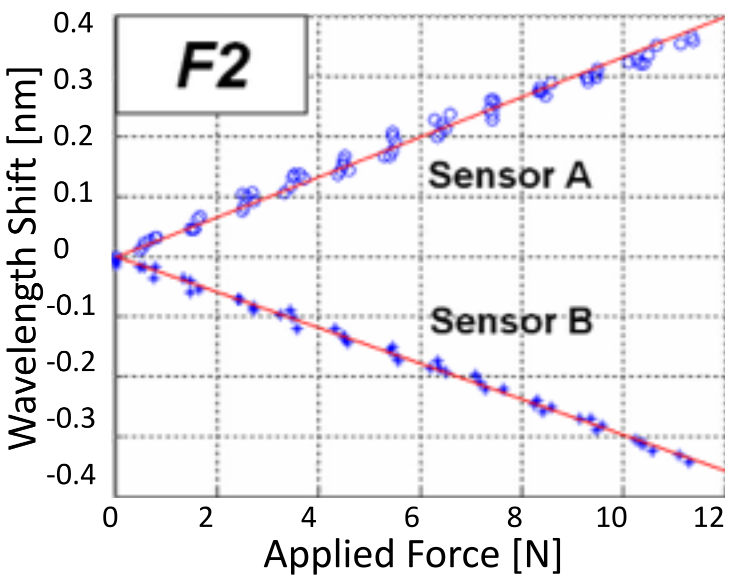


Force Calibration

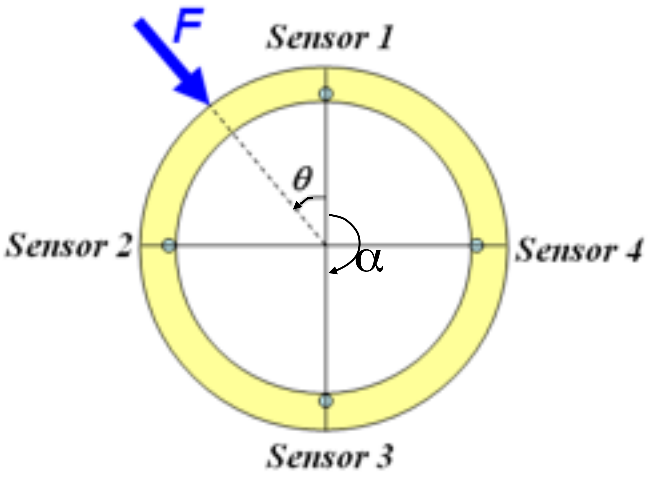


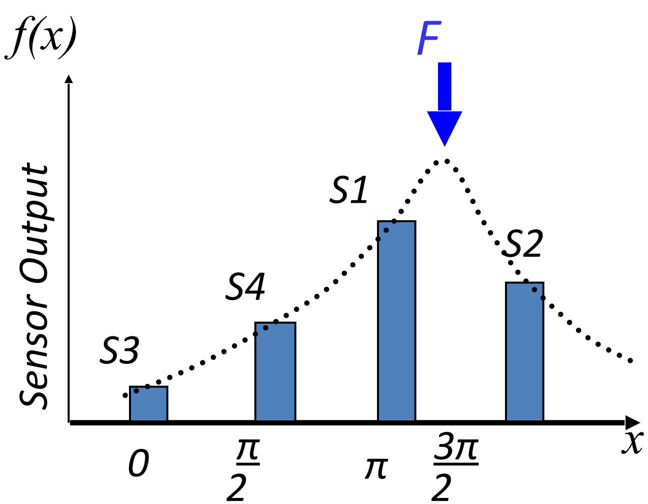
- *Shell (F1)*
  - Sensitivity: 0.024 nm/N
  - Detectable force change: < 0.03 N
  - Practical resolution: 0.1 N
- *Fingertip (F2)*
  - Sensitivity: 0.032 nm/N
  - Detectable force change: < 0.02 N
  - Practical resolution: 0.15 N





Latitudinal Location





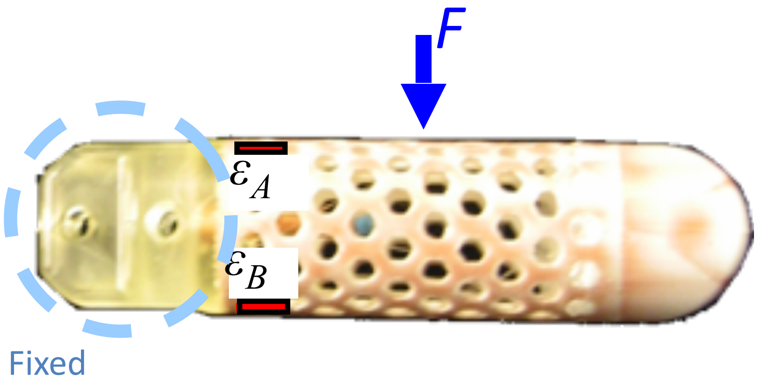
- Use centroid method to find the latitudinal location

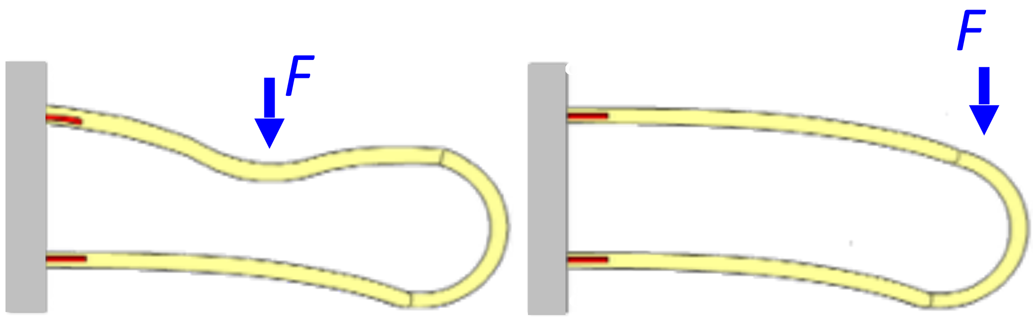
$$\theta = \frac{\sum x \cdot f(x)}{\sum f(x)} - \alpha$$

$$= \frac{0\cdot(S3) + \pi\cdot(S4) + 3\pi/2\cdot(S1) + 2\pi\cdot(S2)}{S3 + S4 + S1 + S2} - \alpha$$

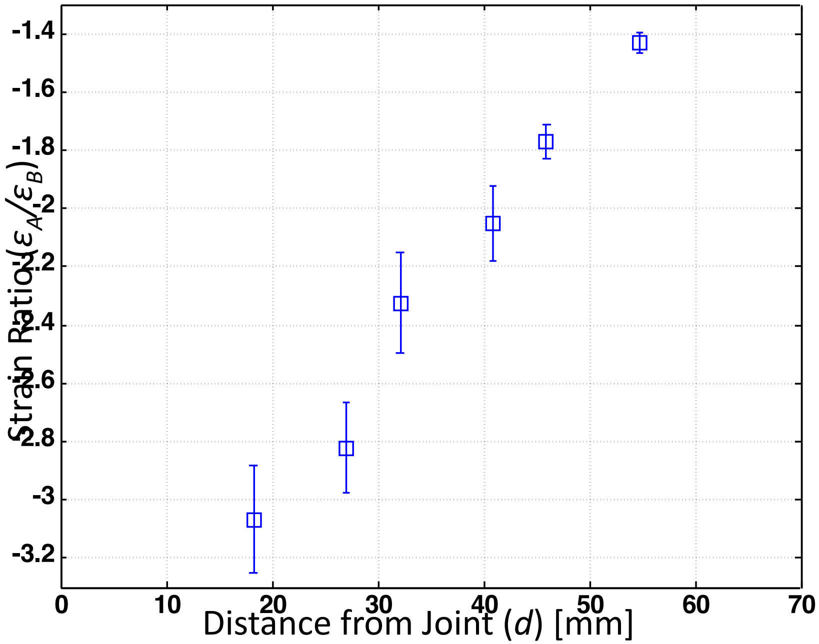
- FEM Simulation:
  - Offset: 1.5 °
  - Error: 2 ° (< 0.5 mm on the perimeter)
- Experiment:
  - Offset: 5 °
  - Error: 2 °

Longitudinal Location





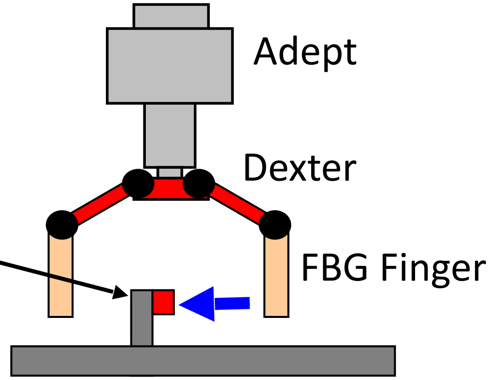
$|\varepsilon_A| > |\varepsilon_B|$ $|\varepsilon_A| = |\varepsilon_B|$

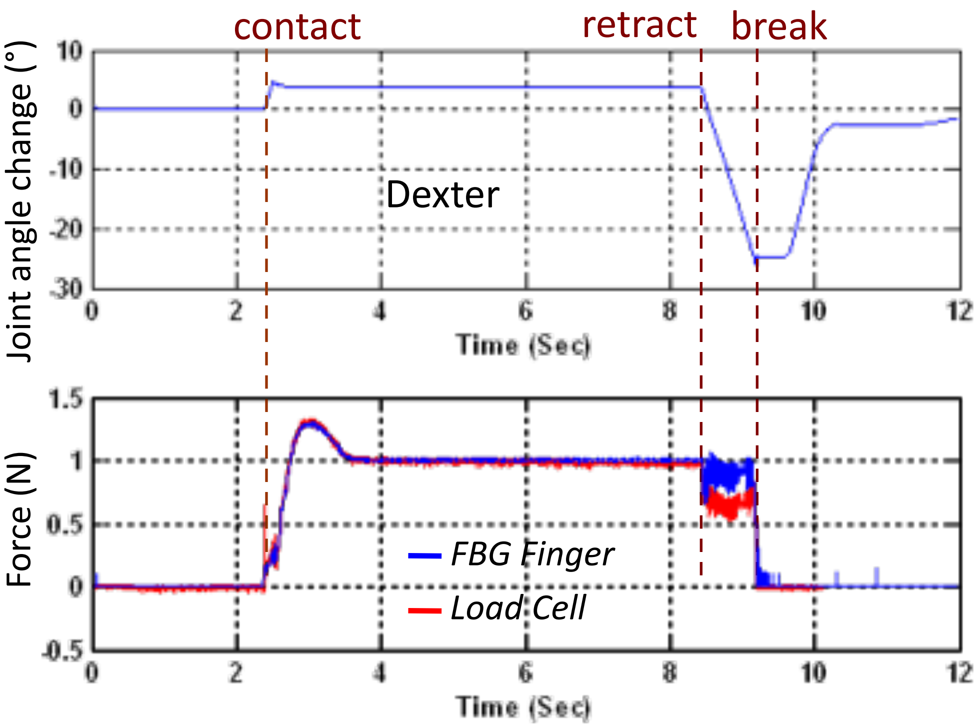


- d_0: distance with minimum $\varepsilon_A/\varepsilon_B$
- We can localize the contact force as long as $d > d_0$
- Advantage of hollow mesh structure
  $\Rightarrow$ Local variation in strain

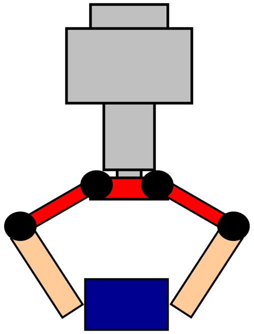
Force Control Experiments

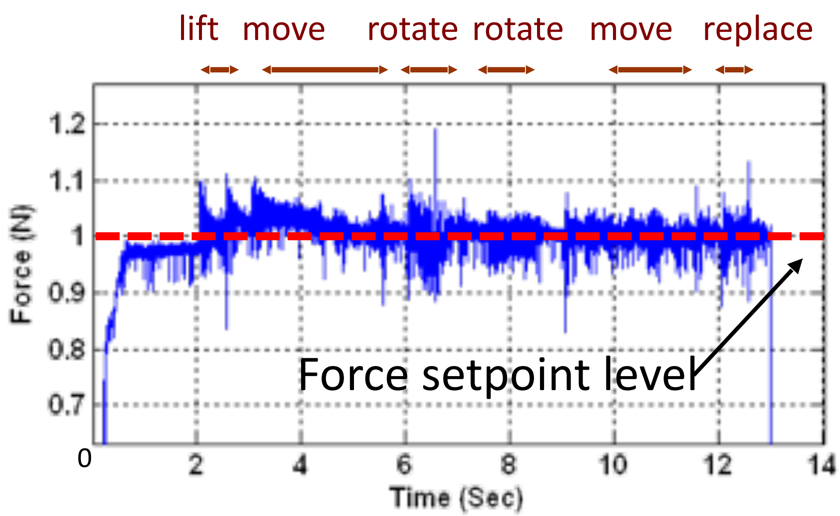
- Setpoint Tracking





- Manipulation

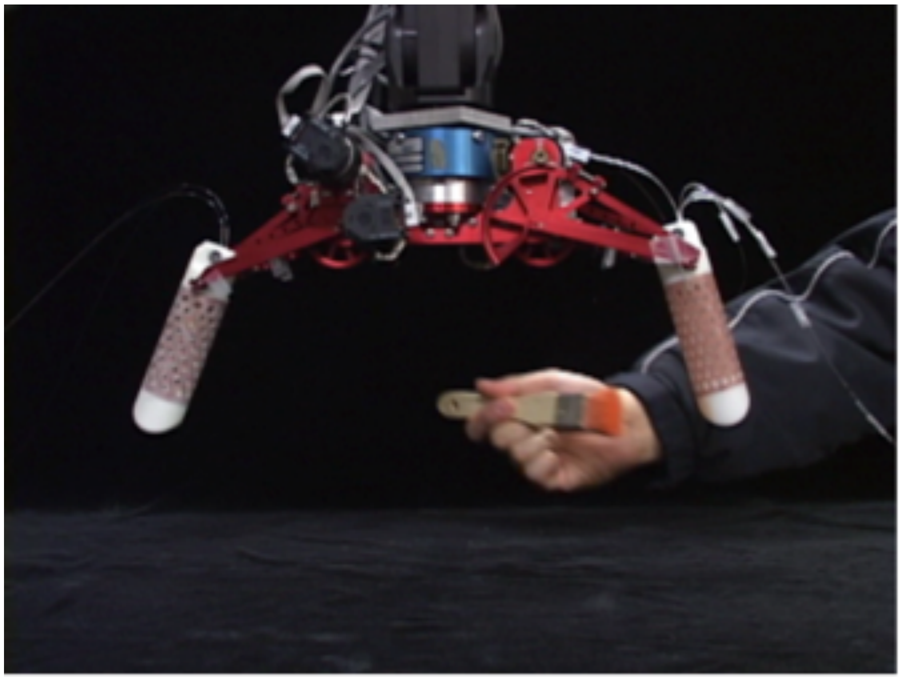




- RMS of force error: < 0.03 N
- Force recovery: < 0.01 sec

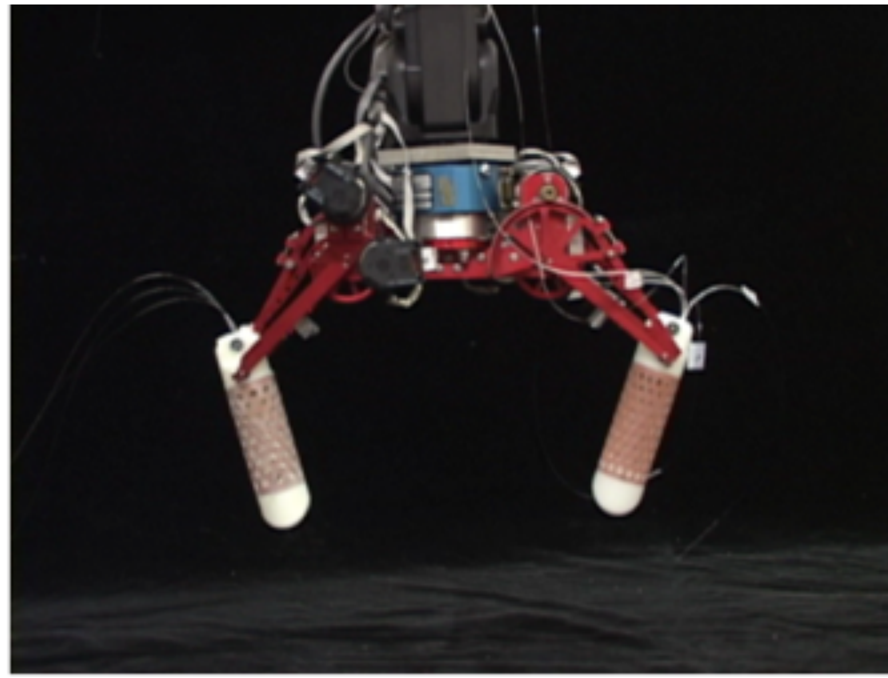
Working Prototype

Smart force/position control



Video Link:
http://www.youtube.com/watch?v=gO-6H1bi9PA

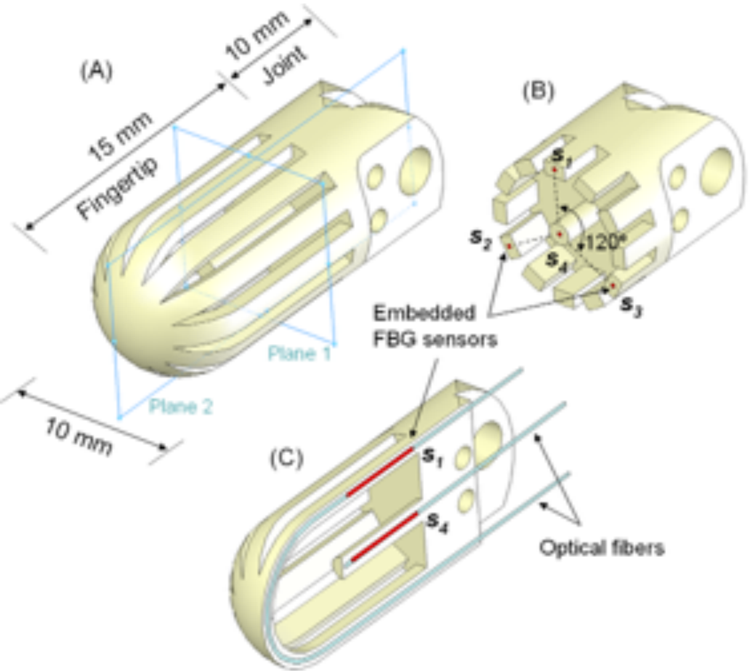
Avoidance of unexpected contacts

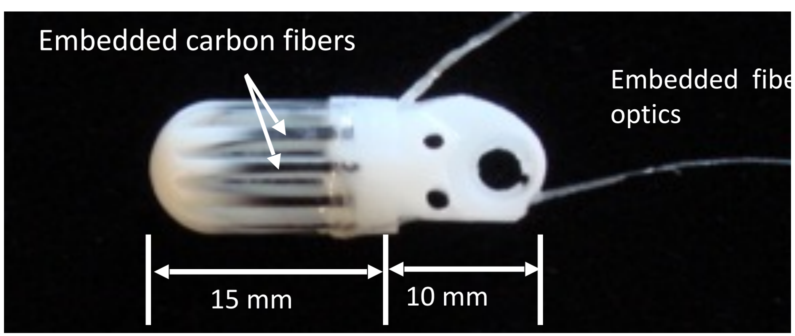


Video Link:
http://www.youtube.com/watch?v=tyjpP3wYKmE

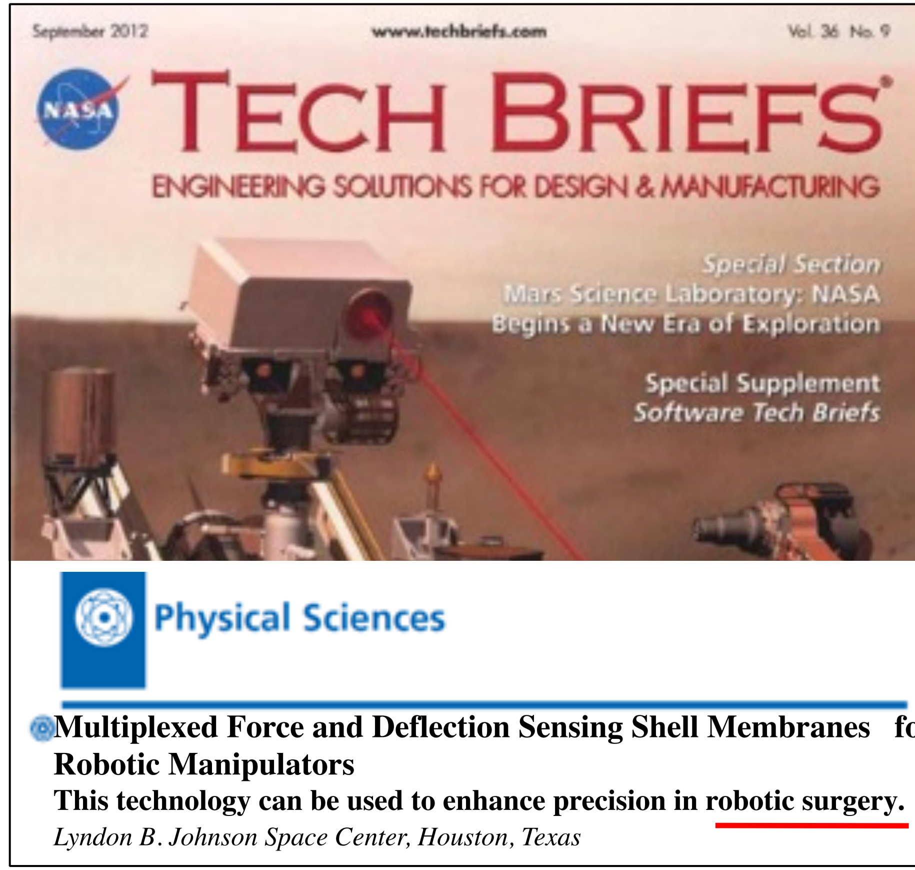
Y-L Park, SC Ryu, MR Cutkosky et al., ***IEEE Transactions on Robotics (T-RO)***, Vol. 25, No. 6, pp. 1319-1331, 2009.
Y-L Park, SC Ryu, MR Cutkosky et al., ***Proc. IEEE ICRA'08***, pp. 3431-3136, 2008.
Y-L Park, K Chau, MR Cutkosky et al., ***Proc. IEEE ICRA'07***, pp. 1510-1516, 2007 – **Best Manipulation Paper Award finalist**.

Miniaturization





NASA Tech Brief Award (2012)


September 2012 www.techbriefs.com Vol. 36 No. 9

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Physical Sciences

Multiplexed Force and Deflection Sensing Shell Membranes for Robotic Manipulators

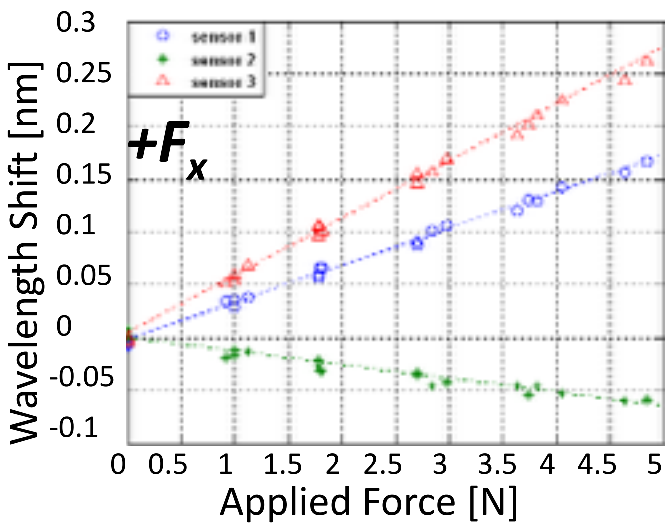
This technology can be used to enhance precision in robotic surgery.

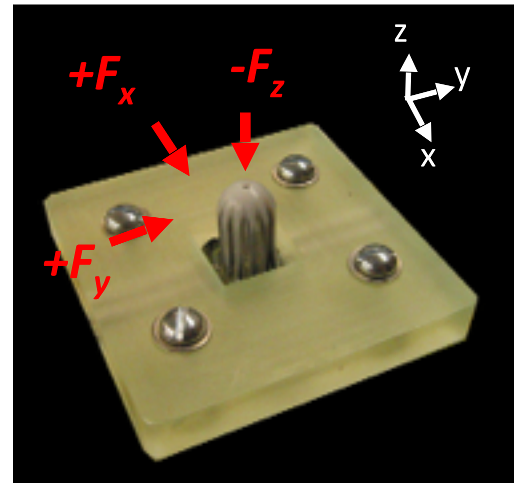
Lyndon B. Johnson Space Center, Houston, Texas

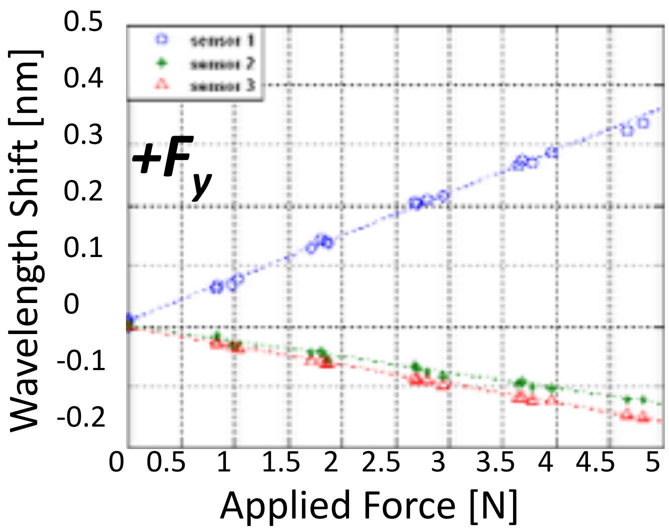
Y-L Park, MR Cutkosky et al., ***US Patent 7,903,907*** (2011).
Y-L Park, MR Cutkosky et al., ***US Patent 8,257,991*** (2012).

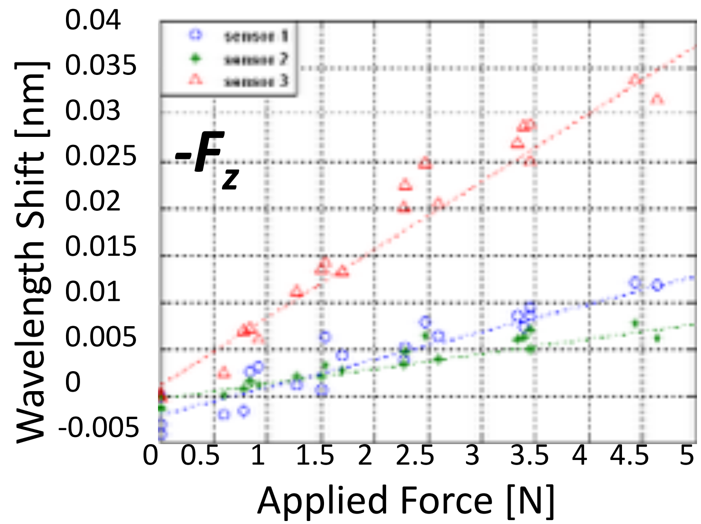
Video Link: http://www.youtube.com/watch?v=QflufC-j7xI

Force Calibration









Summary

- Force Sensing Robot Fingers
- Objective:
  - Make light and strong robot structures that sense forces.
- Solution:
  - Biologically inspired, multi-material hollow structures with embedded fiber optic sensors and modified SDM.
- Results:
  - Force control RMS error: < 0.03 N
  - Force recovery time: 0.01 sec.
- Publications:
  - **YL Park**, SC Ryu, MR Cutkosky et al., "Design, Fabrication, and Control of Force Sensing Smart Robot Structures with Embedded Optical Fiber Grating Sensors," *IEEE Transactions on Robotics*, Vol. 25, No. 6, 2009.
  - **YL Park**, SC Ryu, MR Cutkosky et al., "Fingertip Force Control with Embedded Fiber Bragg Grating Sensors," I*CRA 2008*.
  - **YL Park**, K Chau, RJ Black, and MR Cutkosky, "Force Sensing Robot Fingers using Embedded Fiber Grating Sensors and Shape Deposition Manufacturing," *ICRA 2007* **– Finalist for Best Manipulation Paper Award.**

- MRI-Compatible Shape Sensing Interventional Tools
- MRI-Compatible Robotic End-Effector
- **Soft Sensors**
- Soft Actuators

Background: Soft Sensing

Body Motion Sensing

- Soft sensors for detecting 3-D body motions in real-time
- Requirements
  - Low-cost and low-power
  - Easily wearable
  - Conformable to body shape
- 3D Motion Capture Systems

Optical System (*Vicon*)

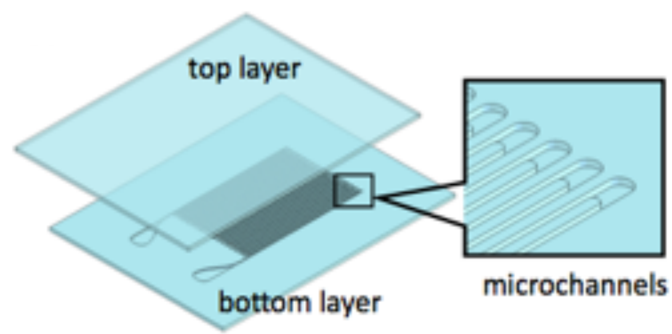
Inertial System (*Xsens*)

1. http://www.youtube.com/watch?v=lihzWT6QRiU
2. http://www.youtube.com/watch?v=rKPrYftacFg

- Eutectic Gallium-Indium (EGaIn)
  - Liquid metal at room temperature

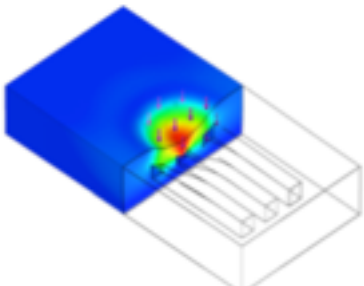
Chiechi et al., *Angew. Chem. Int. Ed.* 2008, *47*, 142.

- Elastomer with embedded micochannels

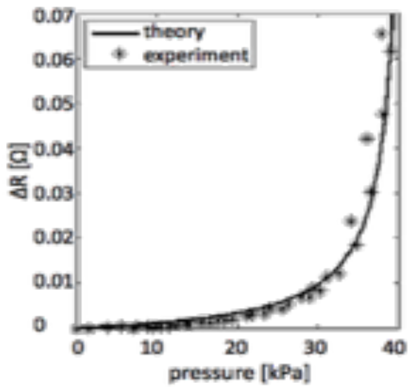


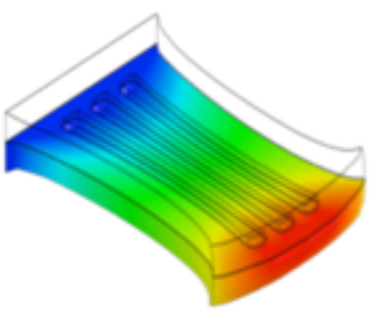
Soft Artificial Skin Sensors

Hyperelastic material with embedded microchannels and conductive liquid

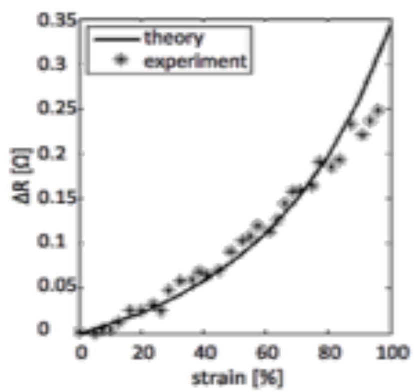


Pressure sensing



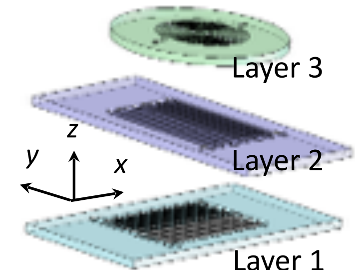


Strain sensing

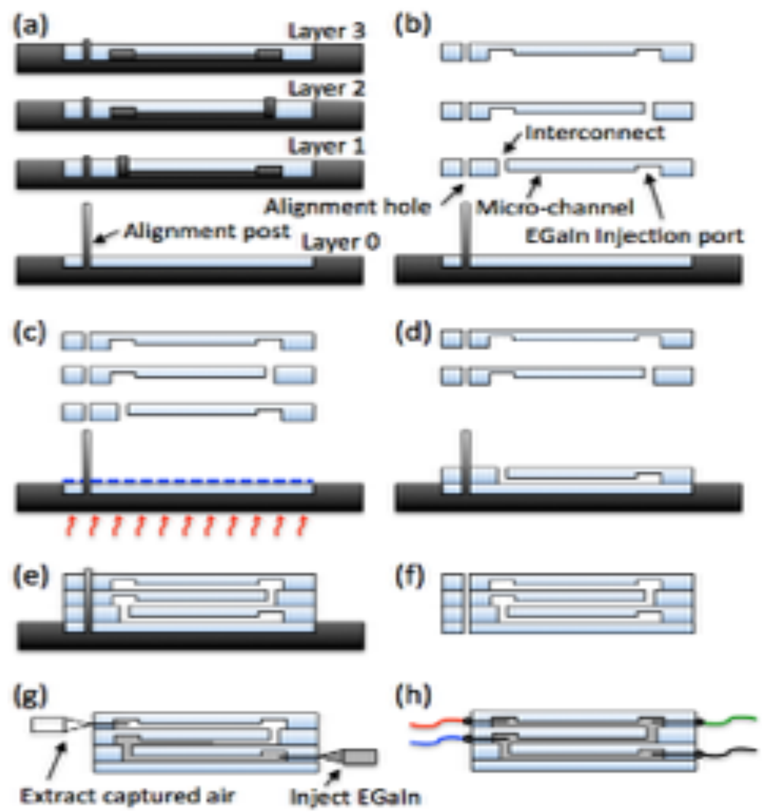


YL Park, C Majidi, RJ Wood et al., ***Journal of Micromechanics and Microengineering***, Vol. 20, No. 12, 2010.
C Majidi, **Y-L Park** et al., *US Patent 8,316,719,* 2012.

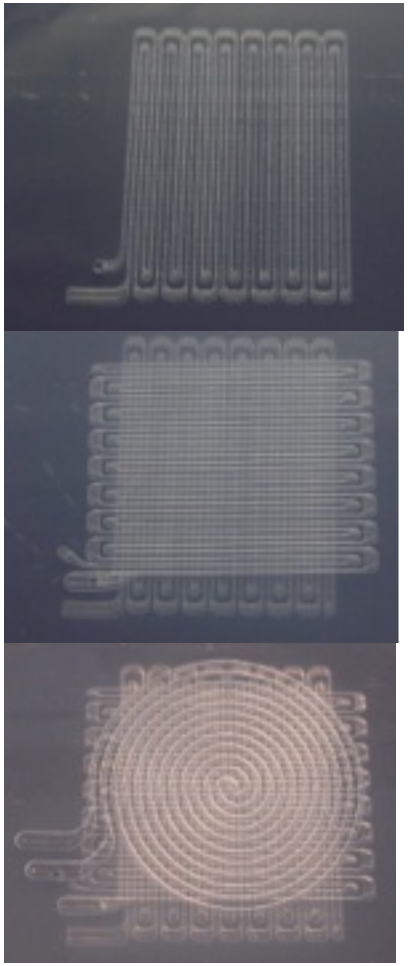
Multi-layered structure for multi-modal sensing

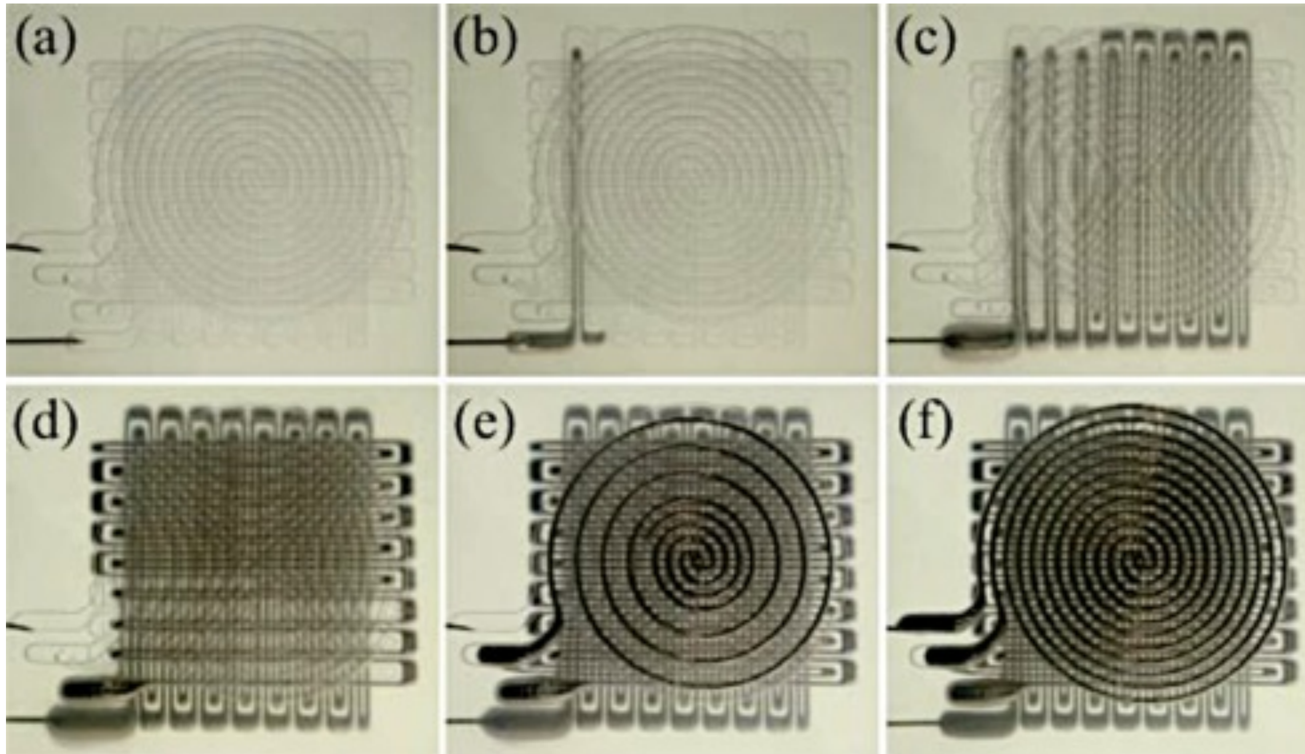


Manufacturing:
Layered molding/casting



EGaIn Injection Process

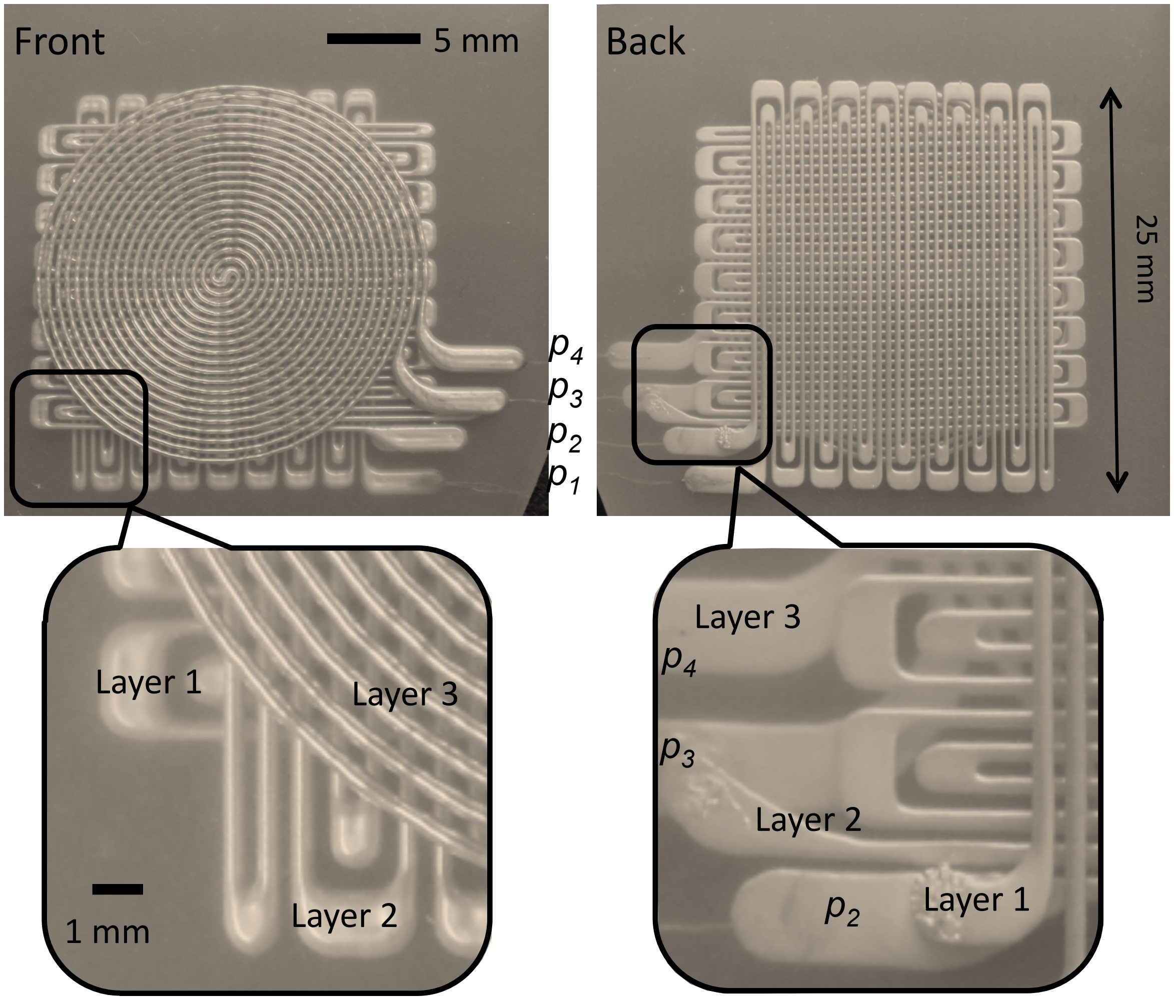


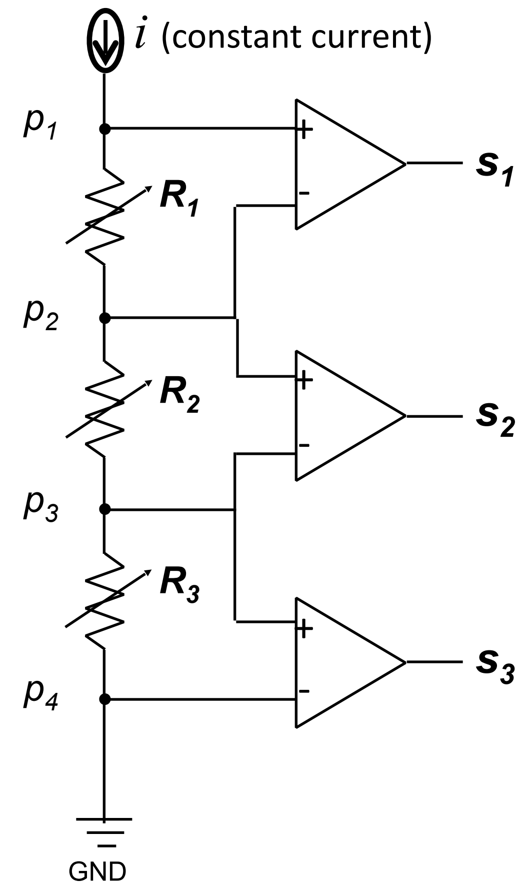


Sensor thickness: Approx. 3.5 mm
Channel size: 200 μm x 200 μm
Entire channel length: Approx. 2 m
Filling time: 1 min

Video Link: http://www.youtube.com/watch?v=-H4sbyaA4gE

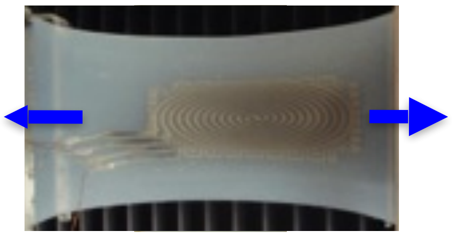
Complete Prototype

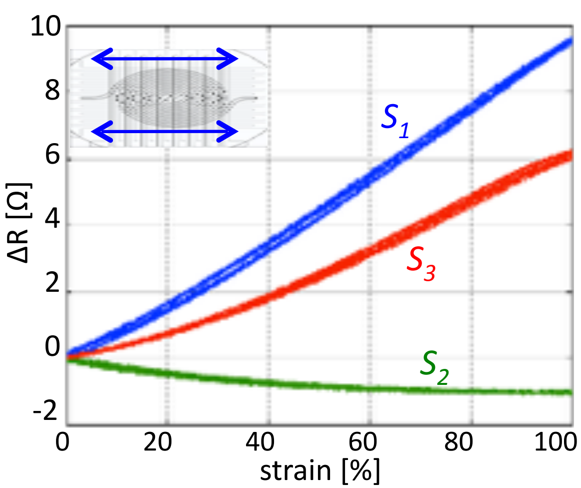




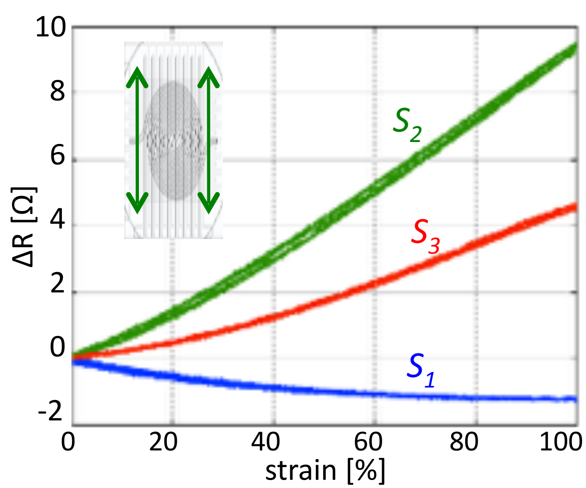
Sensor Calibration

x-axis strain

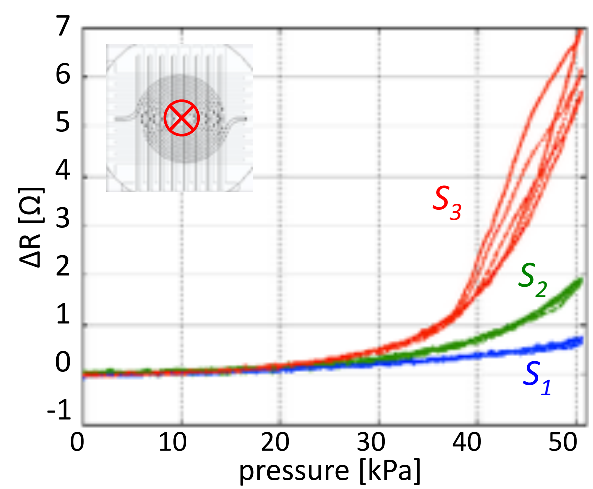




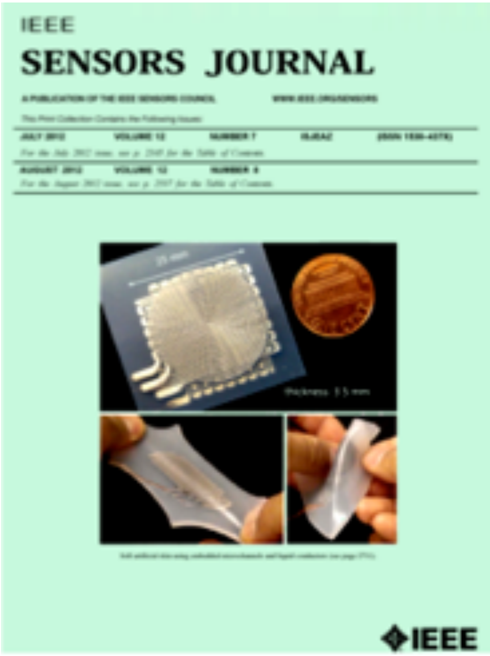
y-axis strain



z-axis pressure



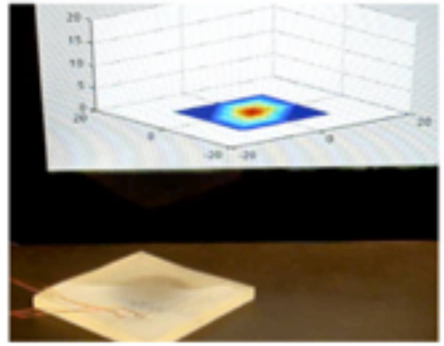
Soft Artificial Skin



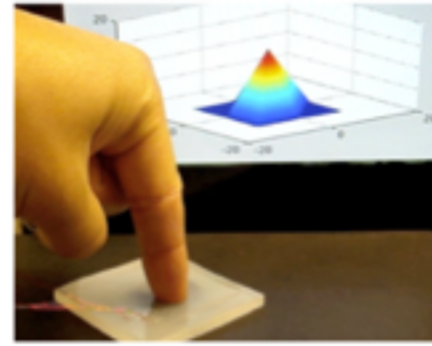
IEEE lifesciences

A Pressure and Strain Sensor fabricated on Soft Artificial Skin

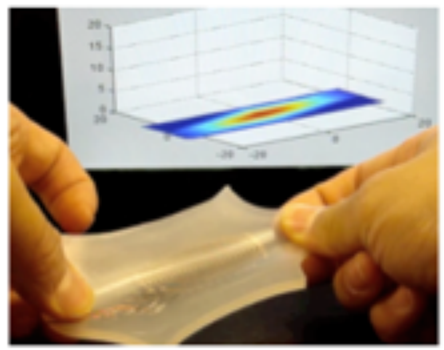
By **Y.-L. Park**, B. Chen, and R. J. Wood



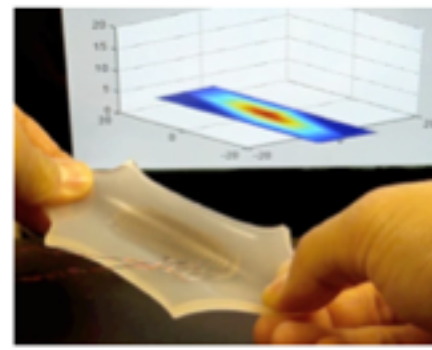
No stimulus



z-axis pressure sensing



x-axis strain sensing



y-axis strain sensing

Video Link: http://www.youtube.com/watch?v=6CLTv-CyMH4

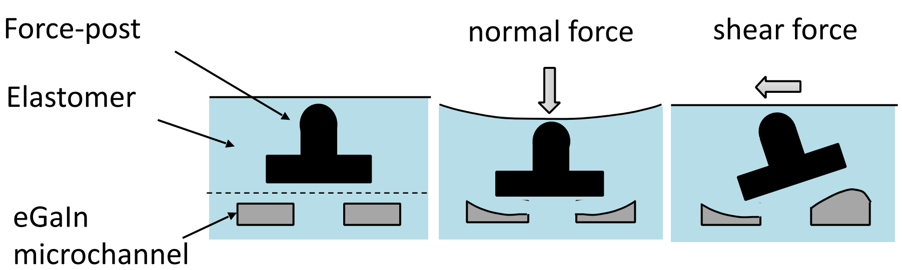
YL Park, B Chen, and RJ Wood, ***IEEE Sensors Journal***, Vol. 12, No. 8, pp. 2711-2718, 2012.

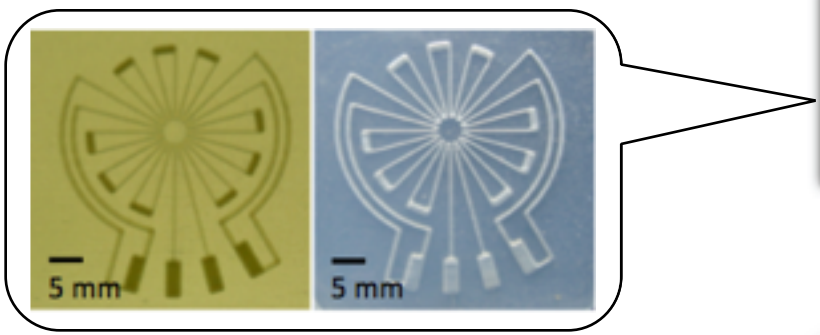
Cover Article, Best Paper of 2012

YL Park, D Tepayotl-Ramirez, RJ Wood, and C Majidi, ***Applied Physics Letters***, Vol. 101, No. 19, 2012.

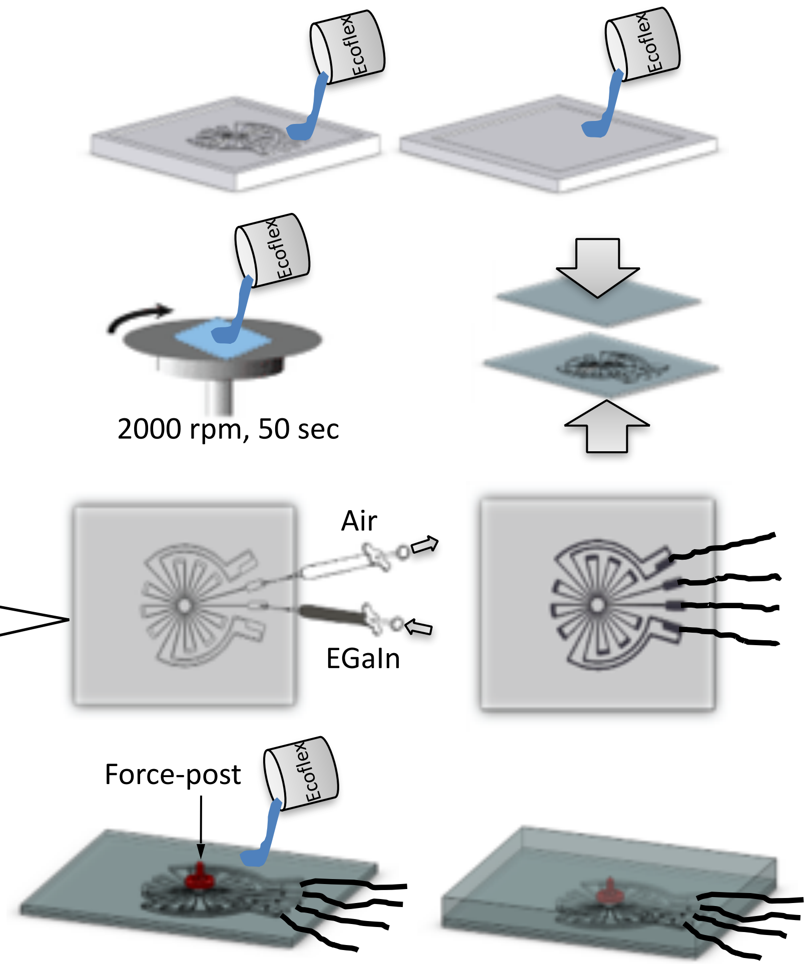
Soft Multi-Axis Force Sensor

Design Concept:





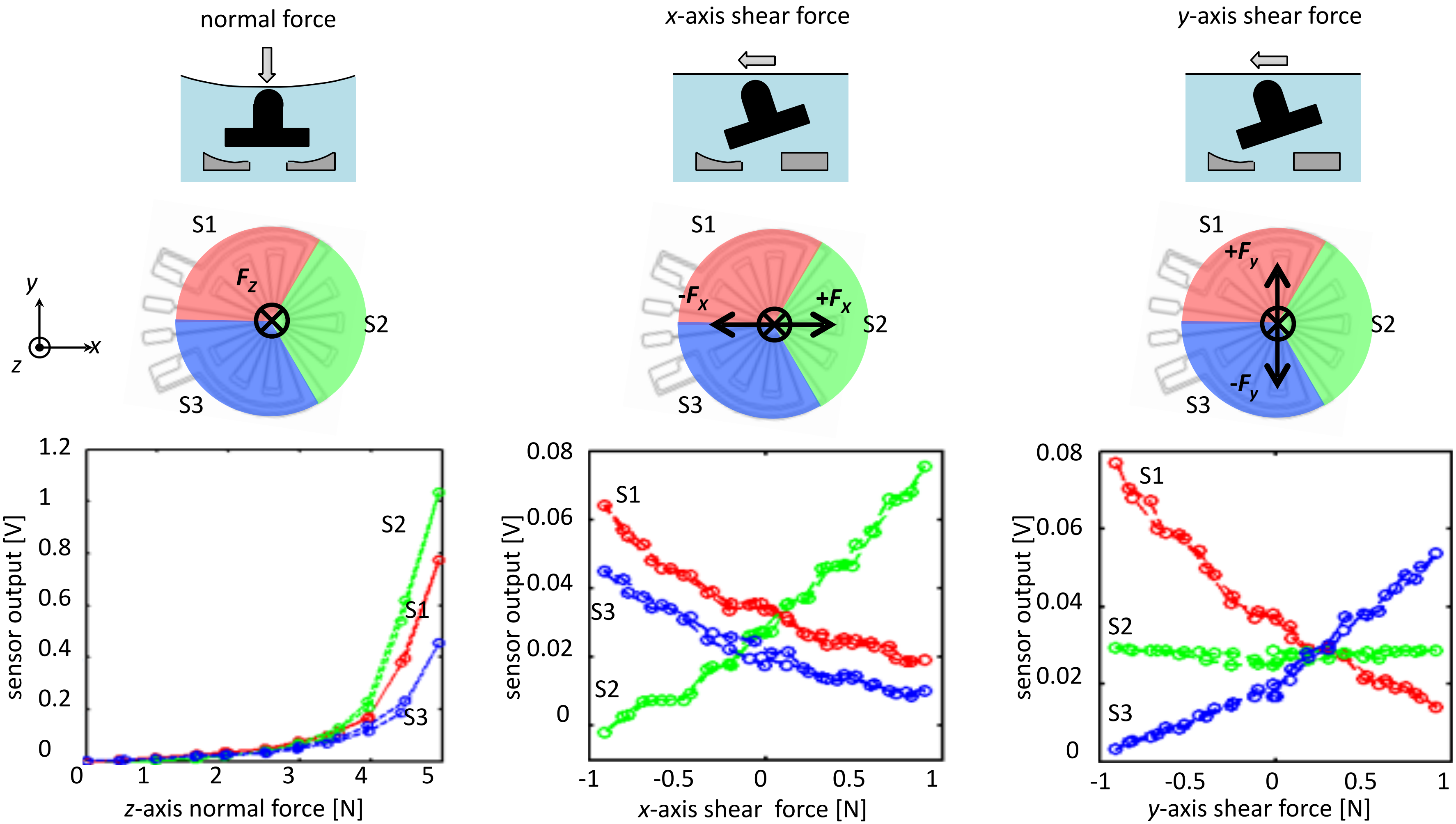
Manufacturing:



D Vogt, **YL Park** (co 1-st author), and RJ Wood, ***IEEE Sensors Journal***, Vol. 20, No. 12, pp. 4056-4064, 2013.

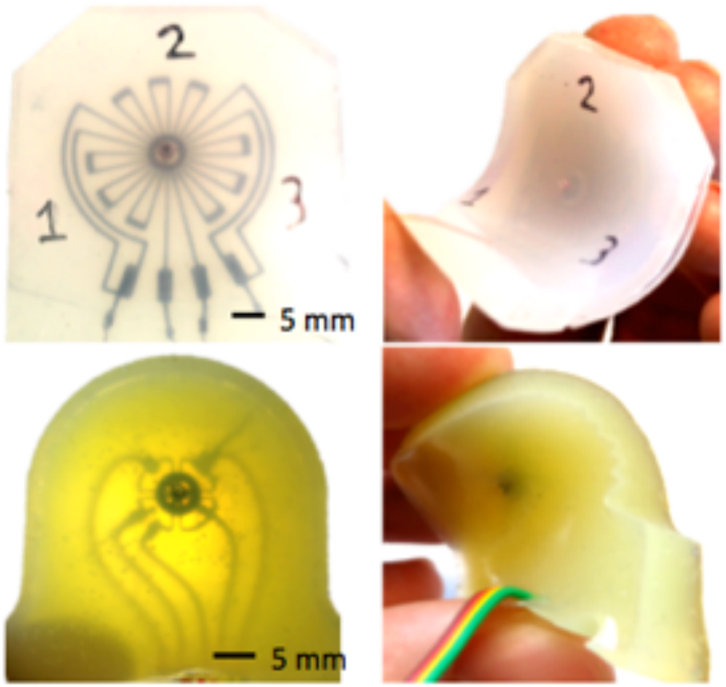
D Vogt, YL Park, and RJ Wood, ***Proc. IEEE Sensors Conf.***, Vol. 13, No. 10, pp. 897-900, 2012.

Sensor Calibration

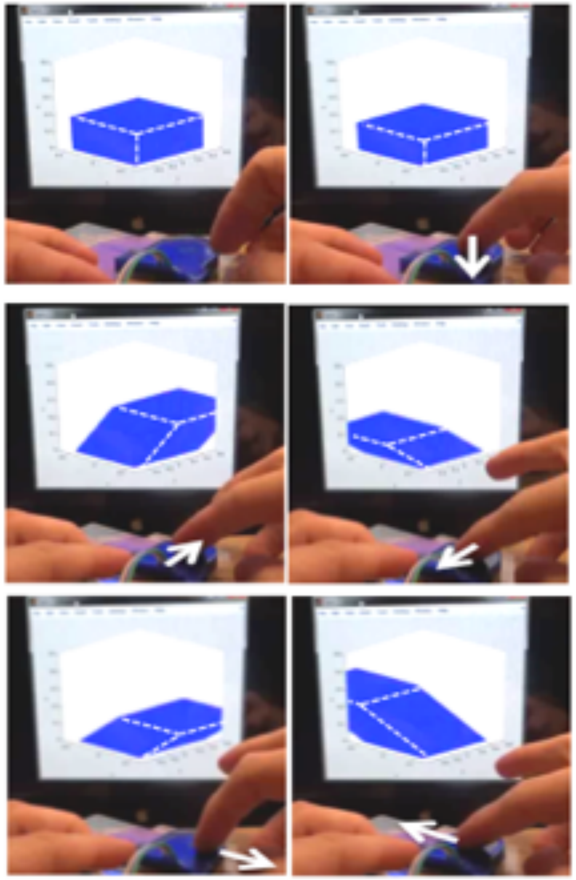


Soft 3-Axis Force Sensor

Complete prototypes



Prototype in action



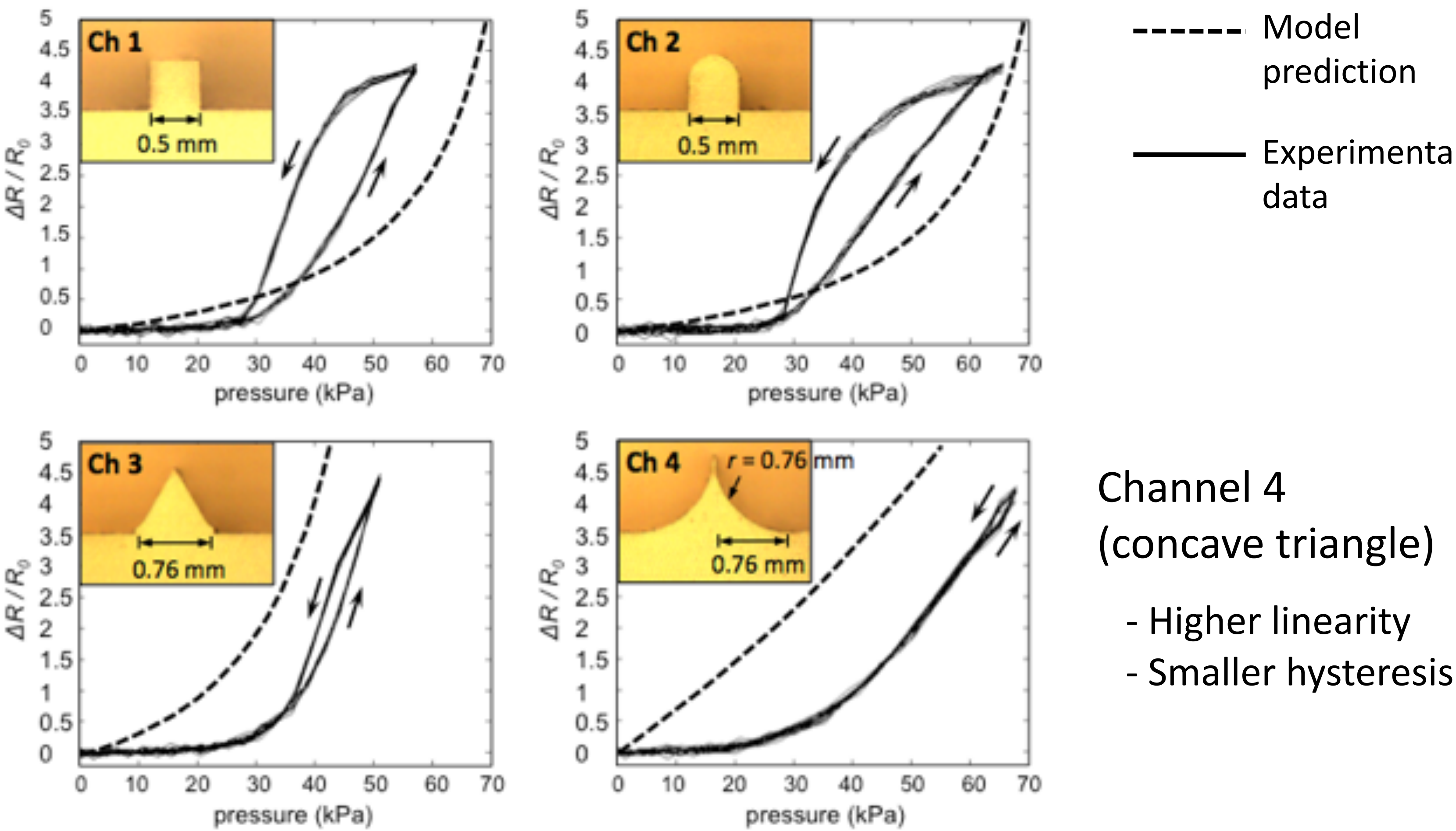
Normal force sensing (***z-axis***)

Shear force sensing (***x-axis***)

Shear force sensing (***y-axis***)

Video Link: http://www.youtube.com/watch?v=BdckdYS5xqY

Improved Pressure Response



Channel 4
(concave triangle)

- Higher linearity
- Smaller hysteresis

Y-L Park, D Tepayotl-Ramirez, C Majidi et al., ***Applied Physics Letters***, Vol. 101, No. 19. 2012.
D Tepayotl-Ramirez, T Lu, **Y-L Park** et al., ***Applied Physics Letters***, Vol. 102, No. 4, 2013

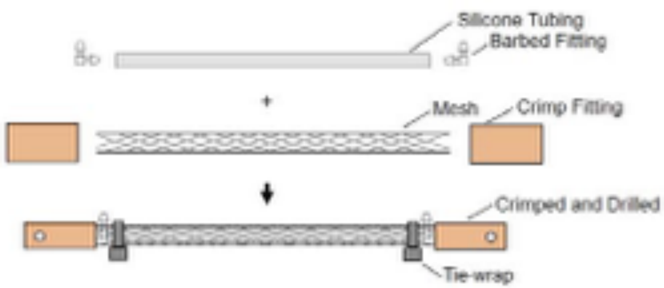
Summary: Soft Sensors

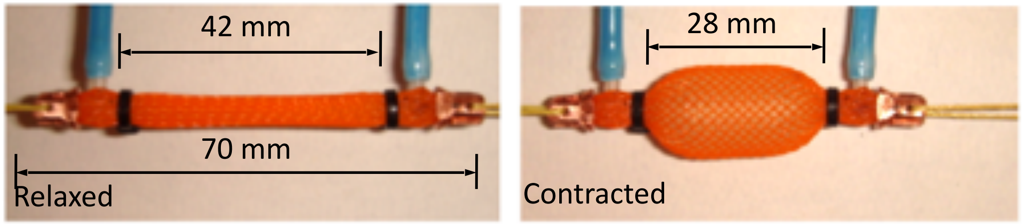
- Objective:
  - Highly flexible and stretchable skin sensors with multi-modalities
- Enabling technologies:
  - Multi-layered soft smart structures
  - Layered molding and casting process
- Results:
  - Stretchable pressure and strain sensor
  - Soft multi-axis force sensor etc.
- Publications:
  - **Y-L Park**, B Chen, RJ Wood et al., *IEEE Sensors Journal, 2012 –* ***Cover Article***.
  - **Y-L Park**, D. Tepayotl-Ramirez, C Majidi et al., *Applied Physics Letters*, 2012.
  - **Y-L Park**, C Majidi, RJ Wood et al., *Journal of Micromechanics and Microengineering*, 2010.
  - D. Tepayotl-Ramirez, T Lu, **Y-L Park** et al., To appear in *Applied Physics Letters*, 2013.
  - **Y-L Park**, D Vogt, and RJ Wood, IEEE Sensors Journal, 2013 – in review
  - D Vogt, **Y-L Park**, and RJ Wood, Proc. *IEEE Sensors Conf.*, 2012.
  - **Y-L Park**, B Chen, and RJ Wood, Proc. *IEEE Sensors Conf.*, 2011.

- MRI-Compatible Shape Sensing Interventional Tools
- MRI-Compatible Robotic End-Effector
- Soft Sensors
- **Soft Actuators**

Pneumatic Artificial Muscles (PAM)

Miniaturized McKibben muscle

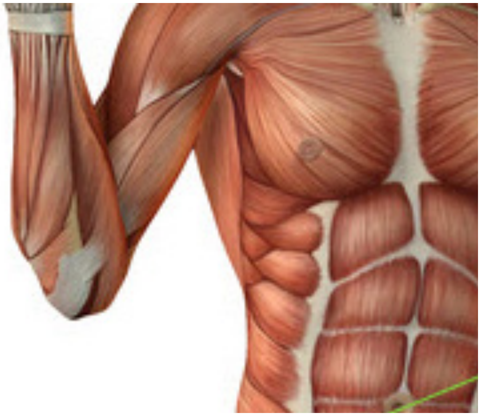


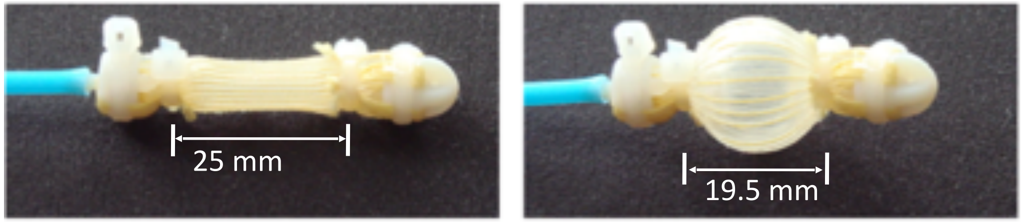


Y-L Park, B Chen, C Majidi et al., *IEEE/RSJ IROS*, 2012.

Video Link: http://www.youtube.com/watch?v=zGDjQ_4hSdI

Bio-Inspired Elastomer muscle

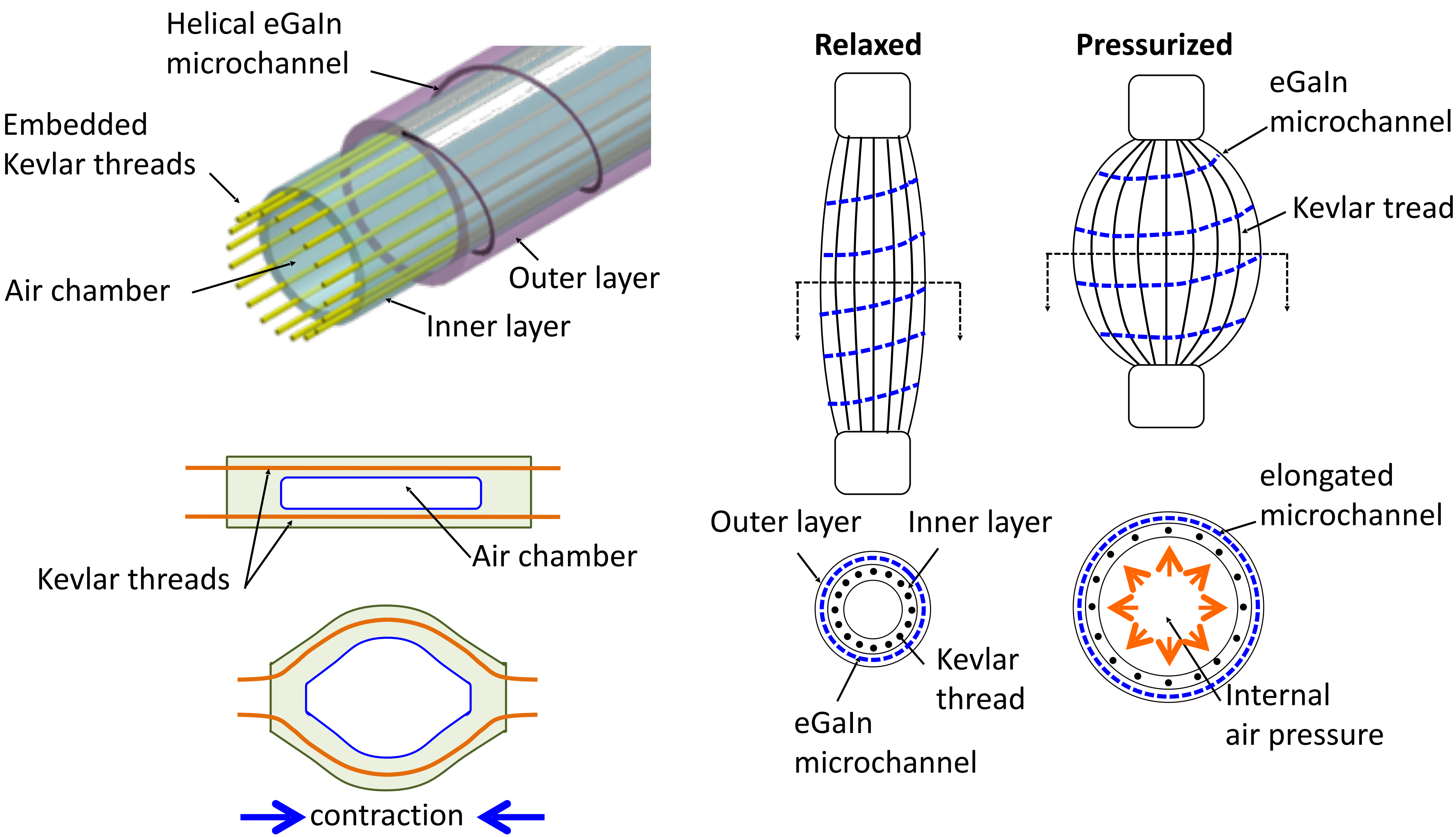




EC Goldfield, **Y-L Park**, RJ Wood et al., *Ecological Psychology, 2012*.

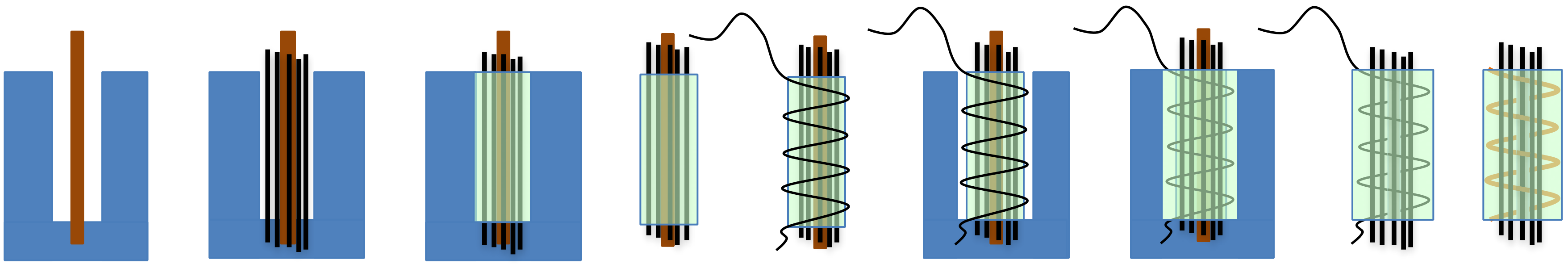
Video Link: http://www.youtube.com/watch?v=tatgfRWtiT4

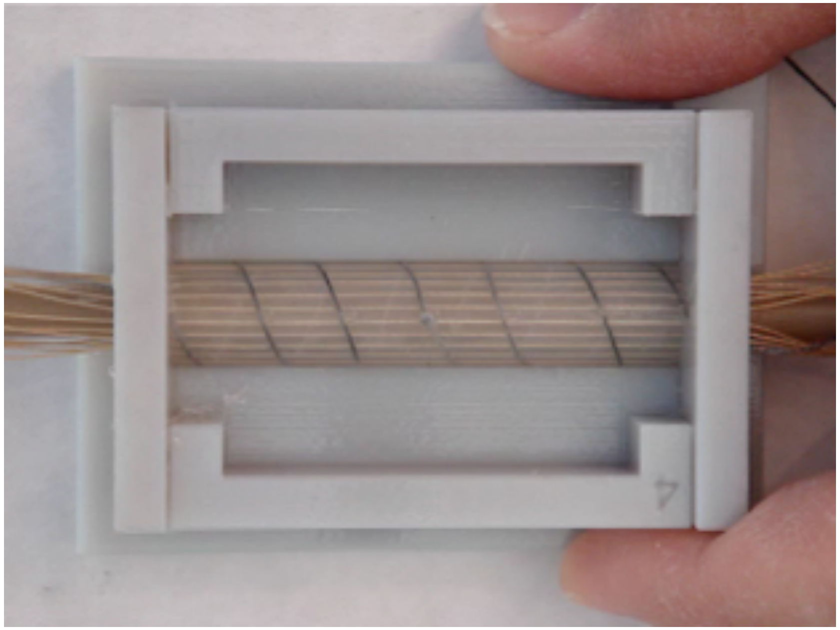
Prototype Design



3-D Manufacturing

Fabrication – Helical microchannel





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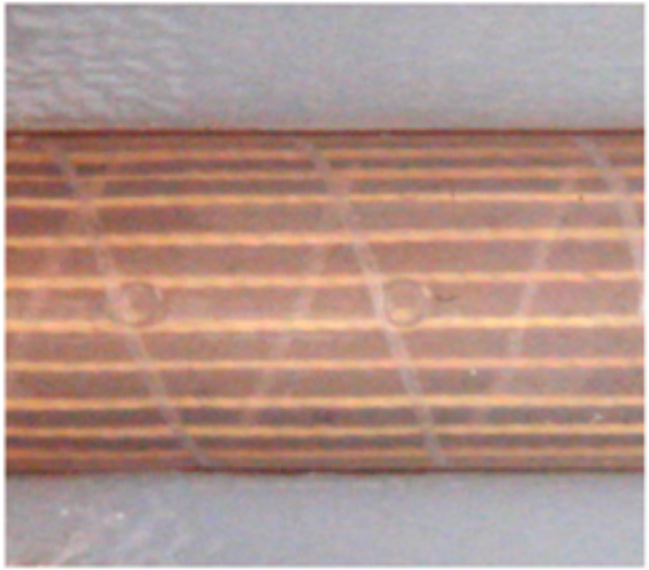
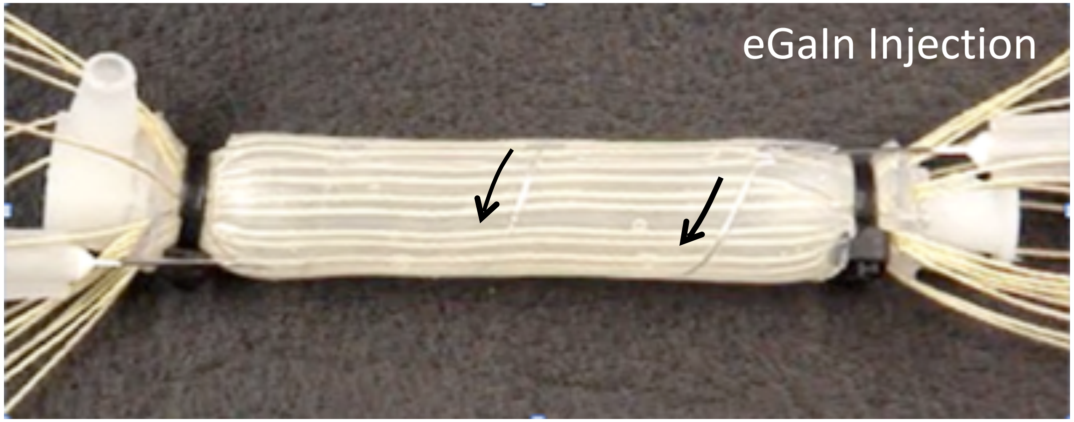
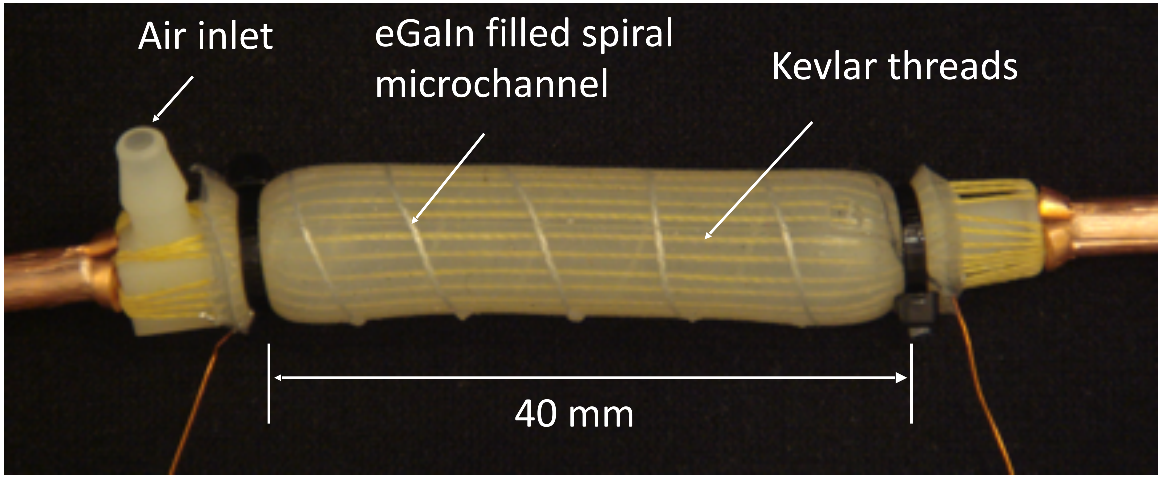
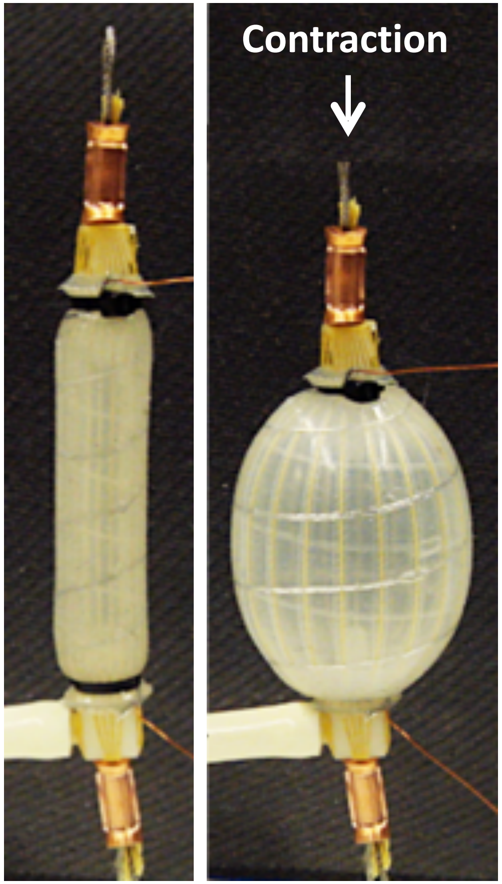


Actual Prototype

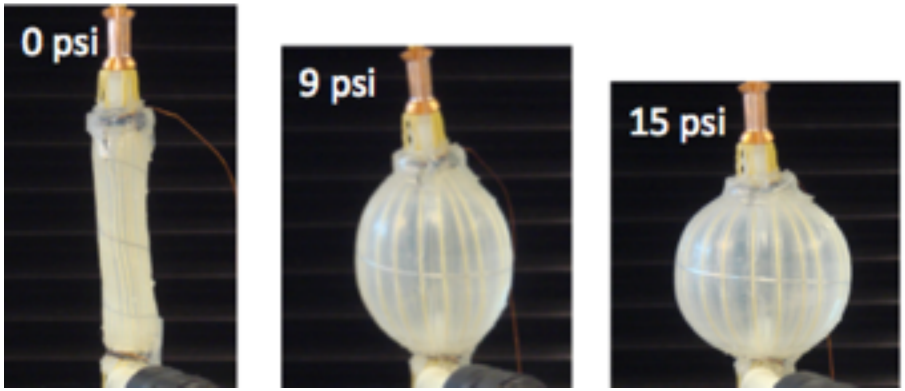


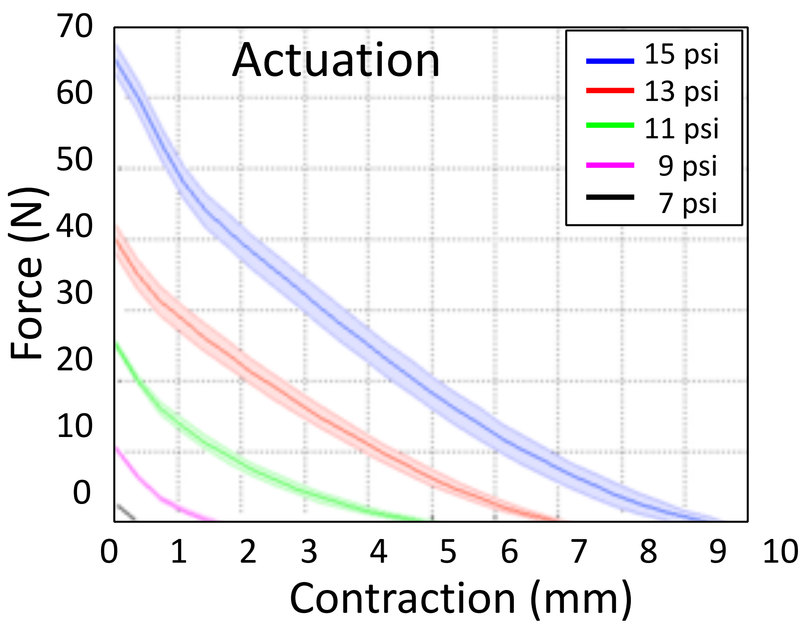


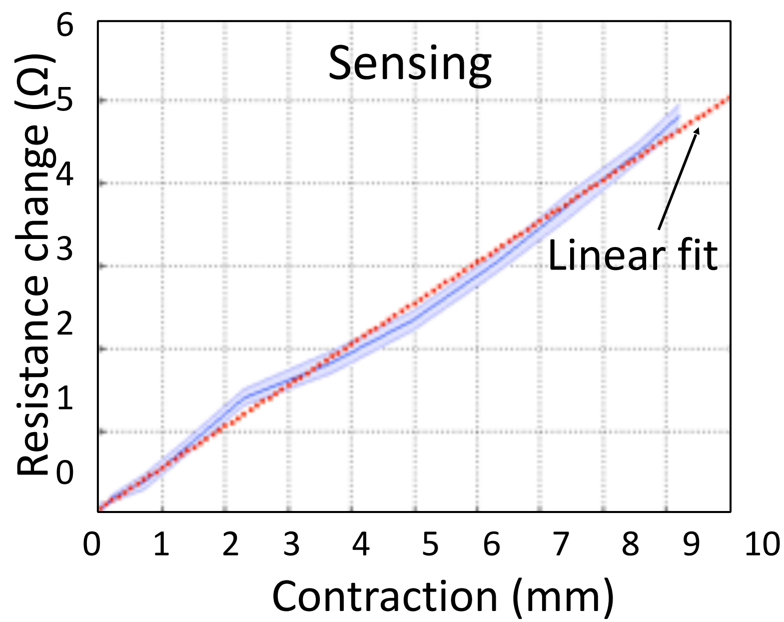


Y-L Park and RJ Wood, ***IEEE Sensors Conf.***, 2013.

Characterization

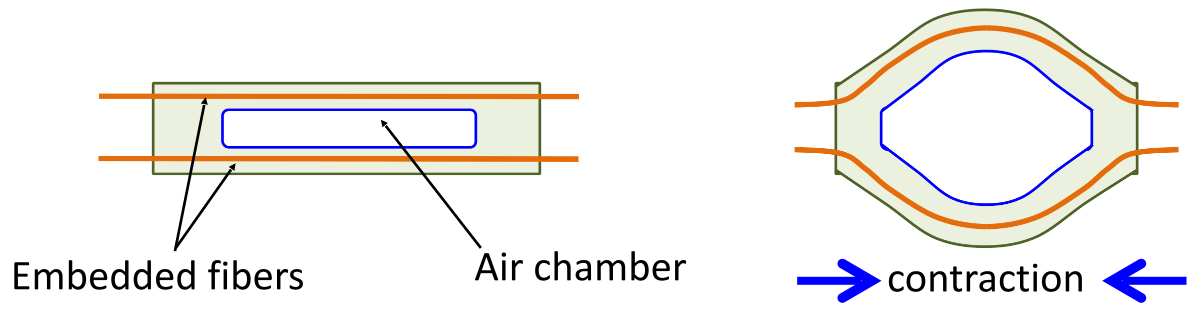




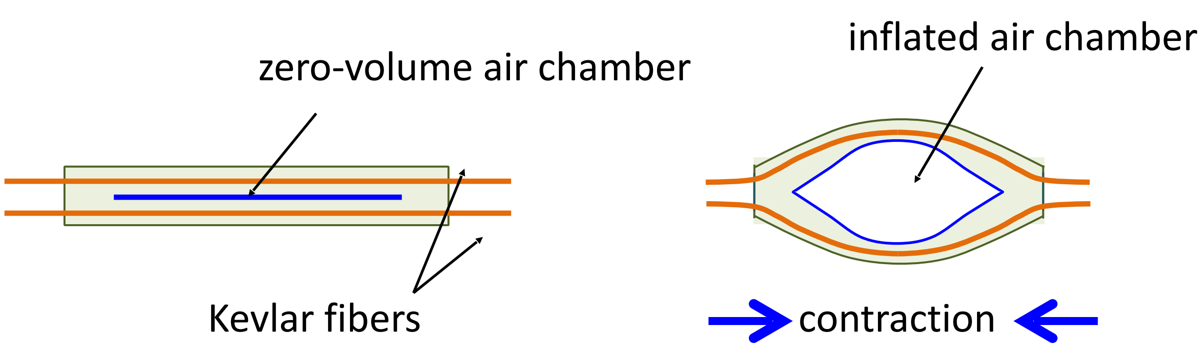


Flat Pneumatic Artificial Muscle

Conventional Design

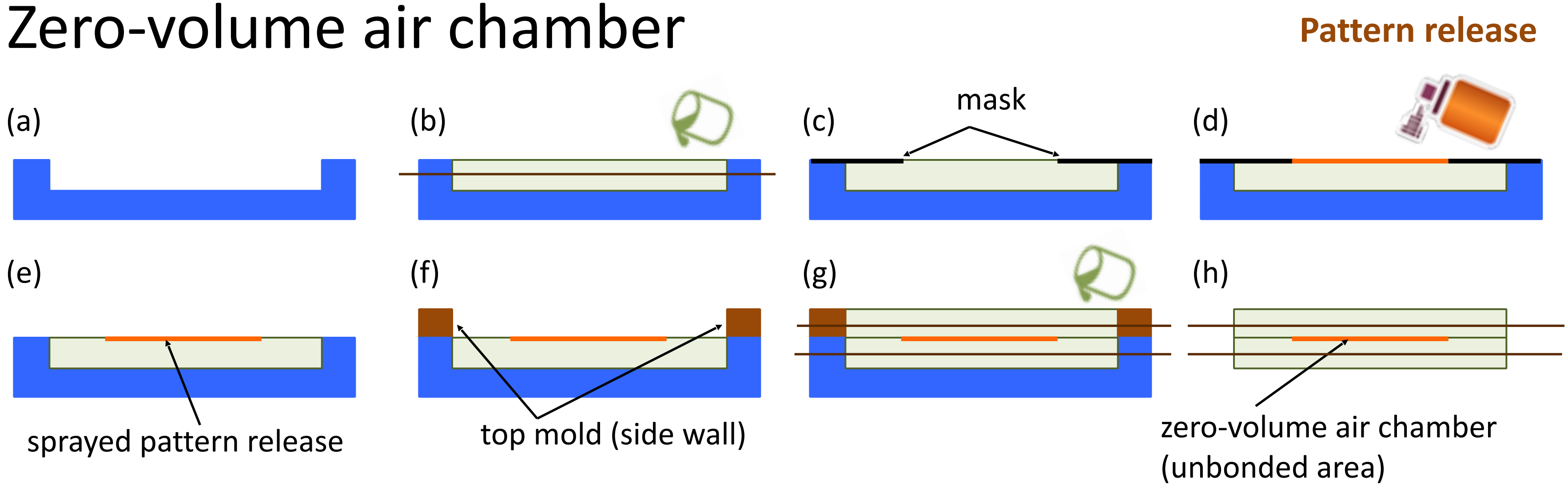


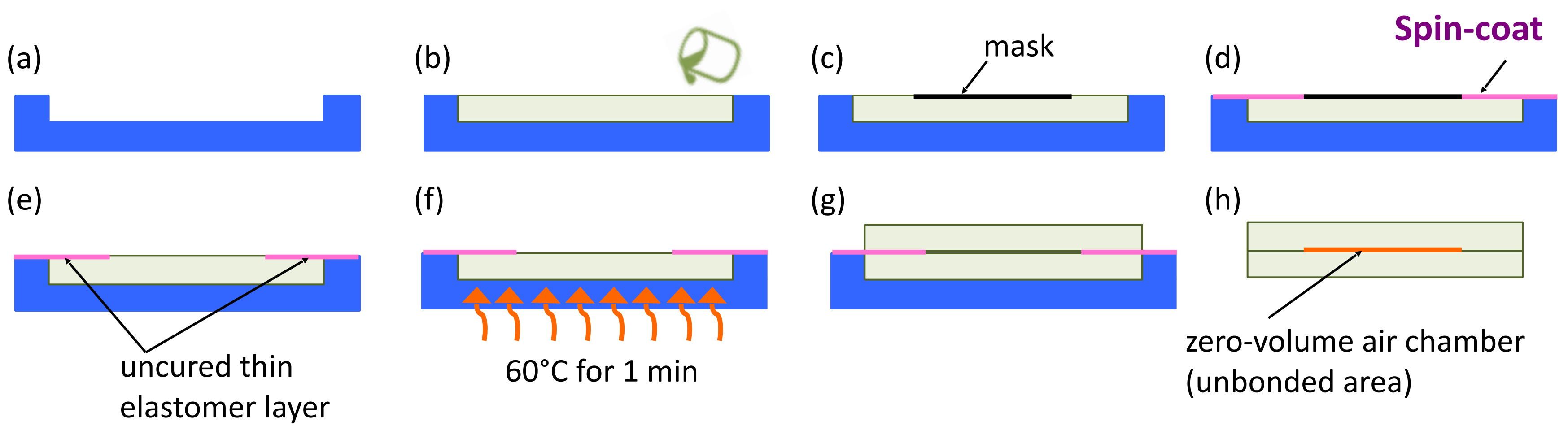
New Design: Zero-volume chamber



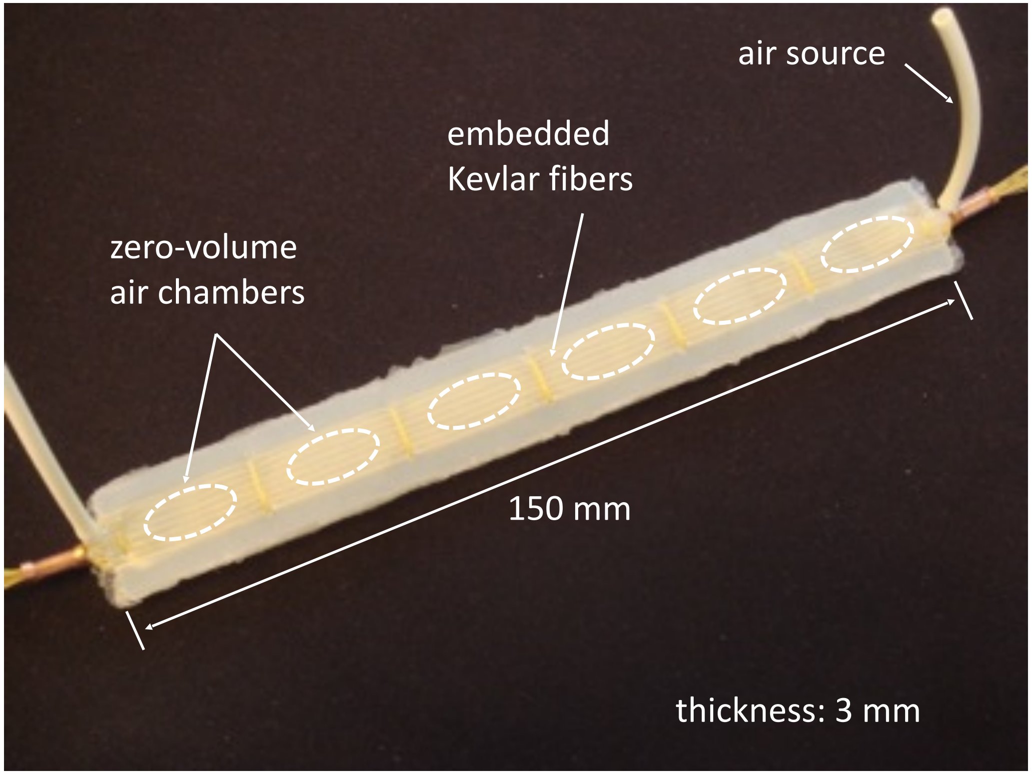
Manufacturing Process

Zero-volume air chamber

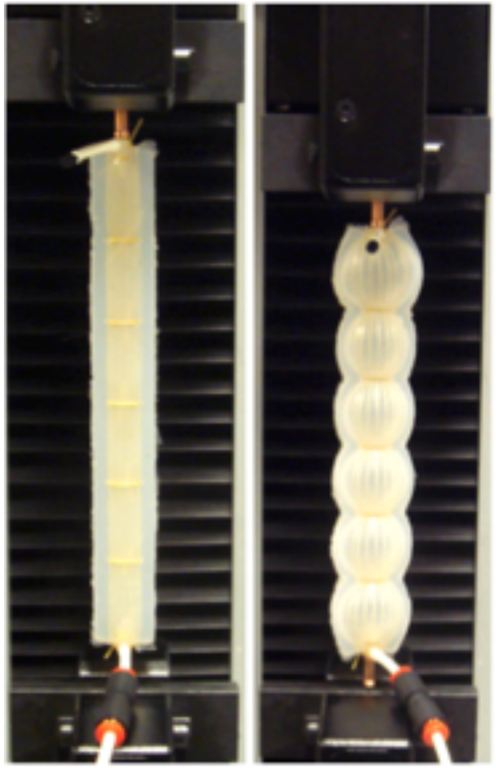




Complete Prototype



Y-L Park, J Santos, RJ Wood et al., ***IEEE ICRA'14***, 2014.



Air pressure: 15 psi
Max. contraction: 25%

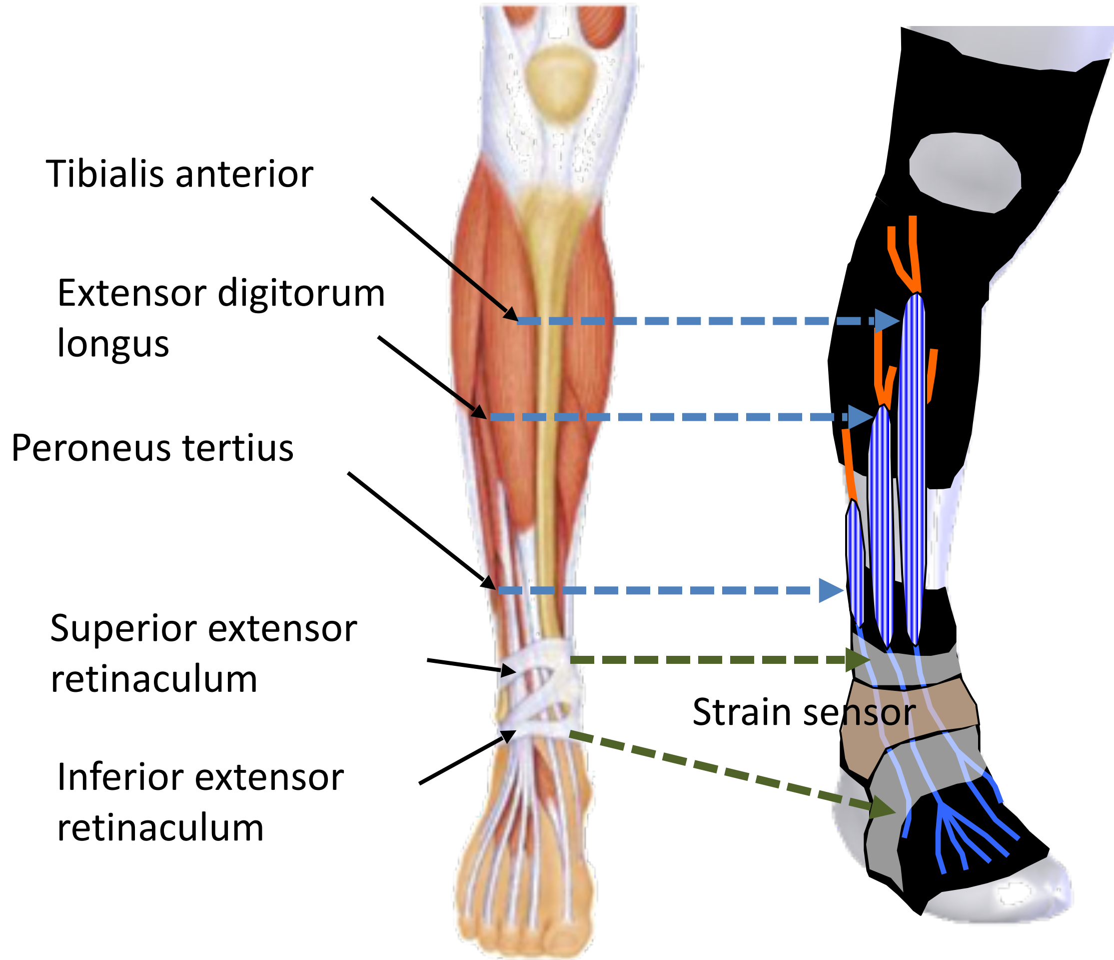
Application – Active Soft Orthotics (1)

Motivation: Drop-foot

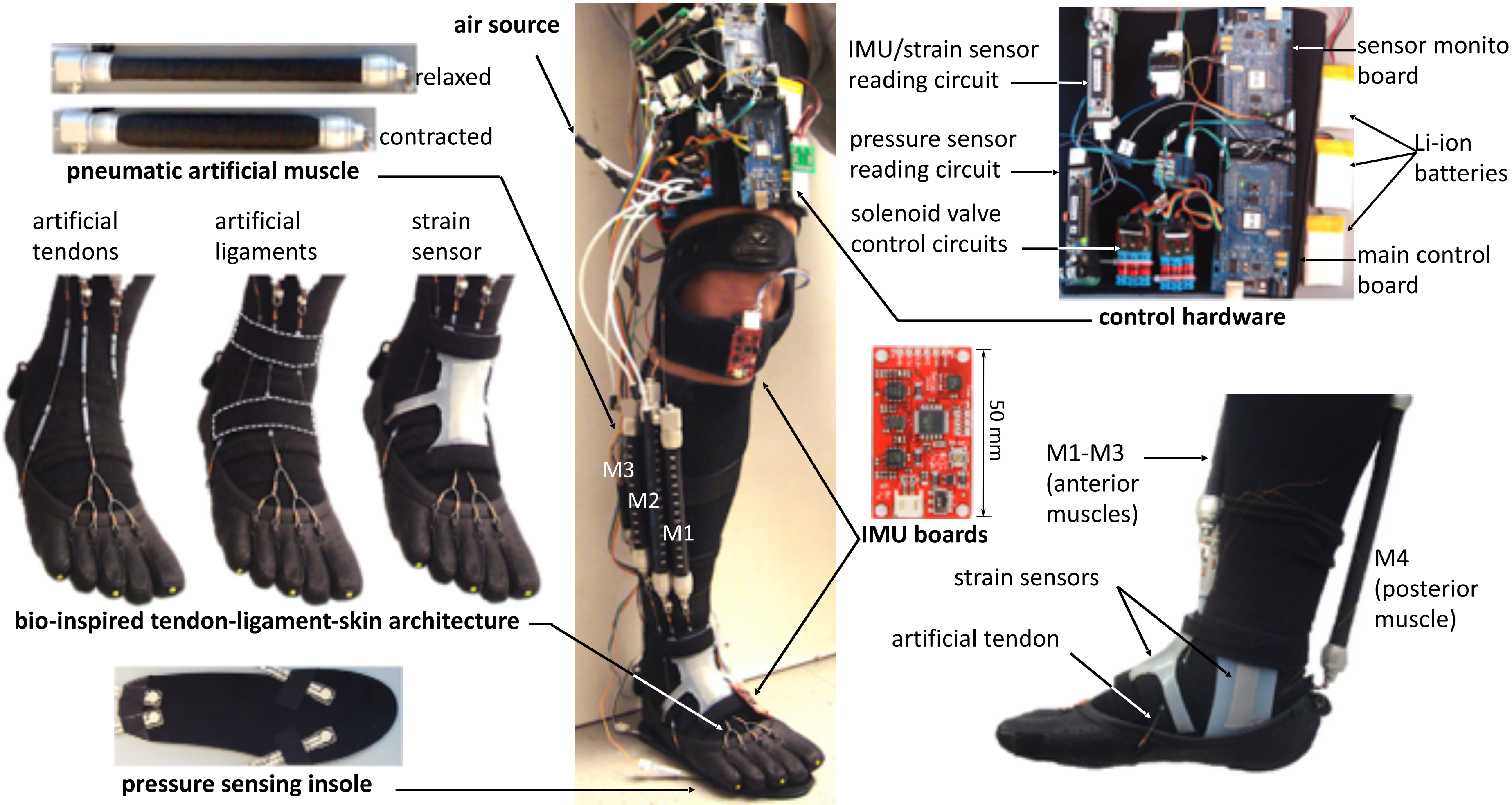
<http://www.neurosurgical.com>

<http://shopshacksite.com>

Bio-Inspired Design



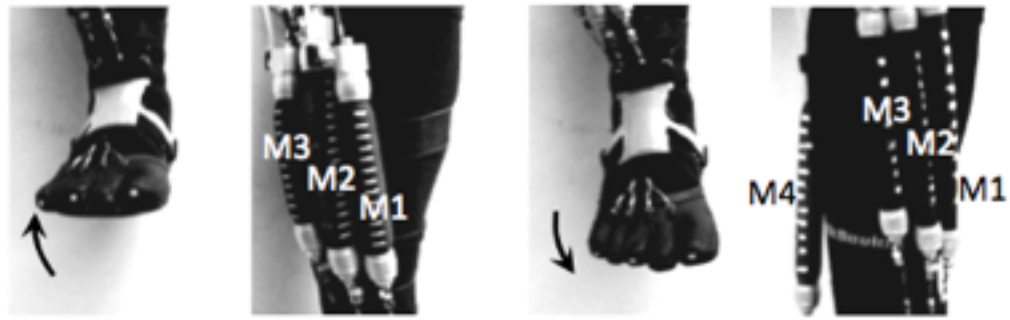
Application – Active Soft Orthotics (2)



YL Park, B Chen, R Nagpal et al., ***Biomimetics & Bioinspiration**, 2014*.
YL Park, B Chen, R Nagpal et al., *IEEE IROS*, 2011.

Application – Active Soft Orthotics (3)

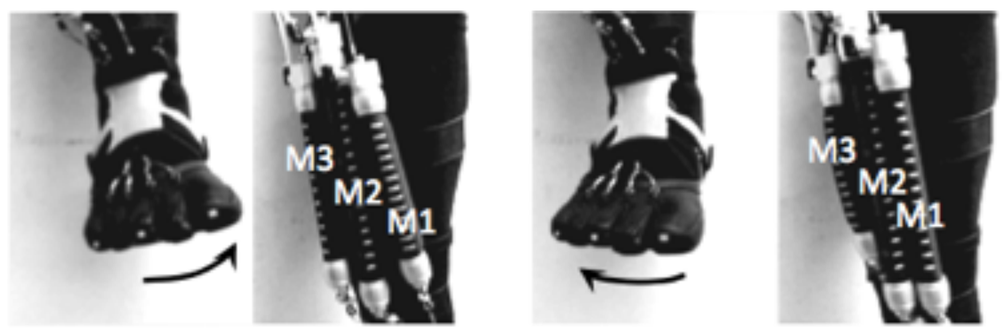
Active Sagittal Motions



Dorsiflexion

Plantarflexion

Active Mediolateral Motions

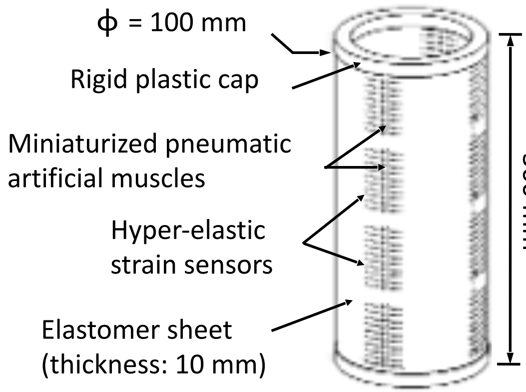


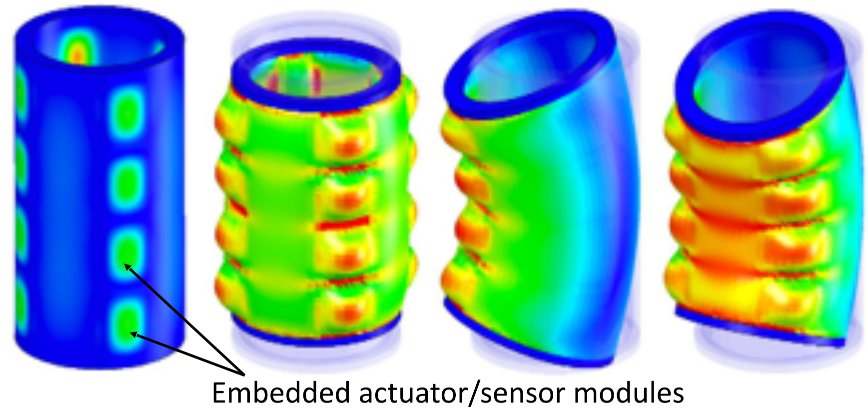
Inversion

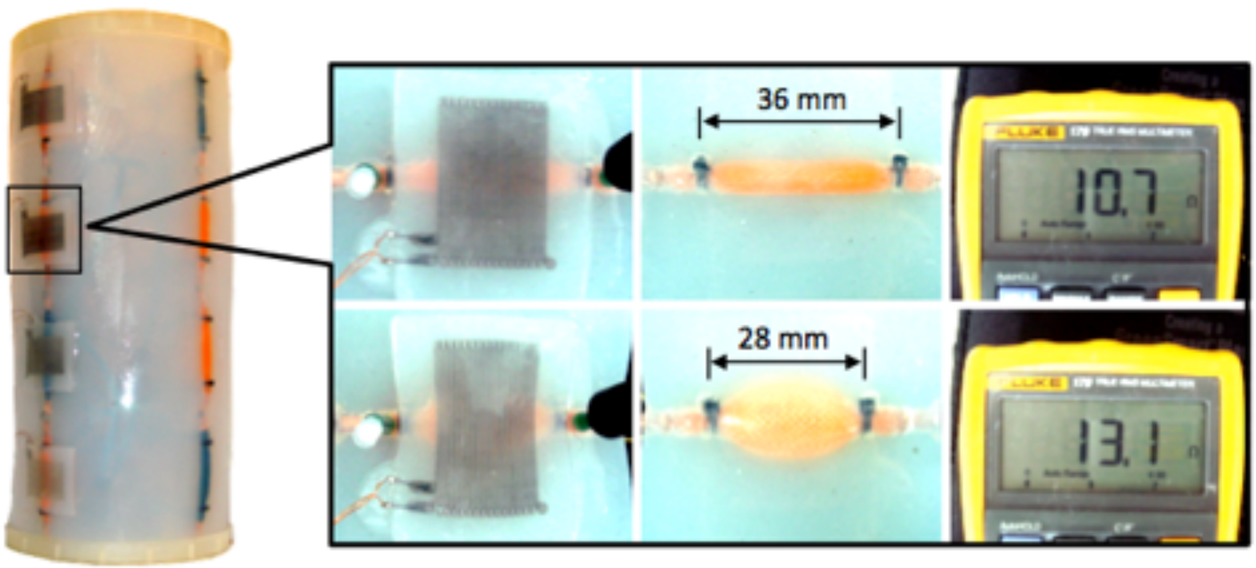
Eversion

Video Link: http://www.youtube.com/watch?v=IbXRiTbuDvY

Application – Programmable Second Skin (1)



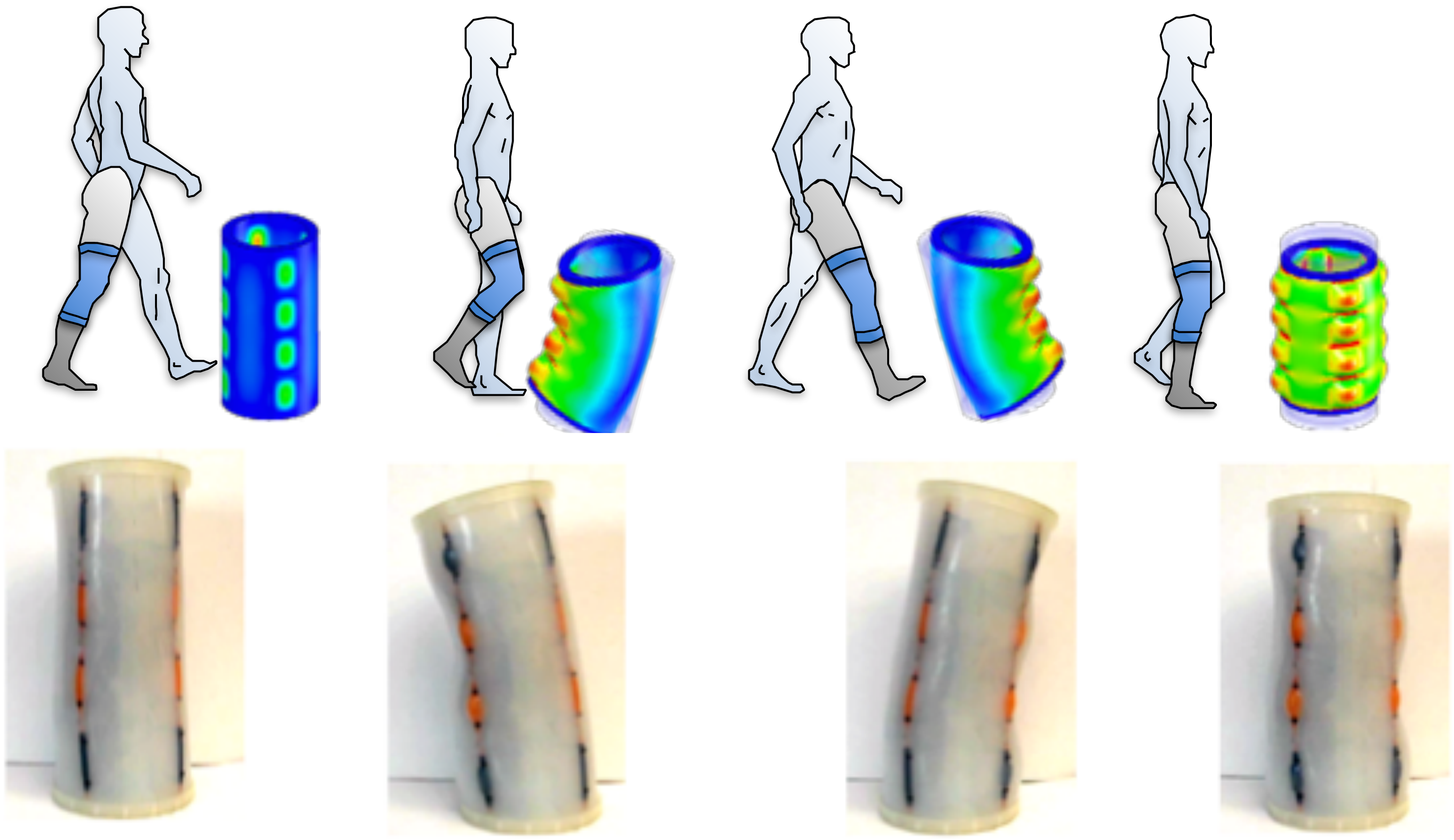




YL Park, B Chen, C. Majidi et al., ***Proc. IEEE/RSJ IROS***, pp. 1595-1602, 2012.

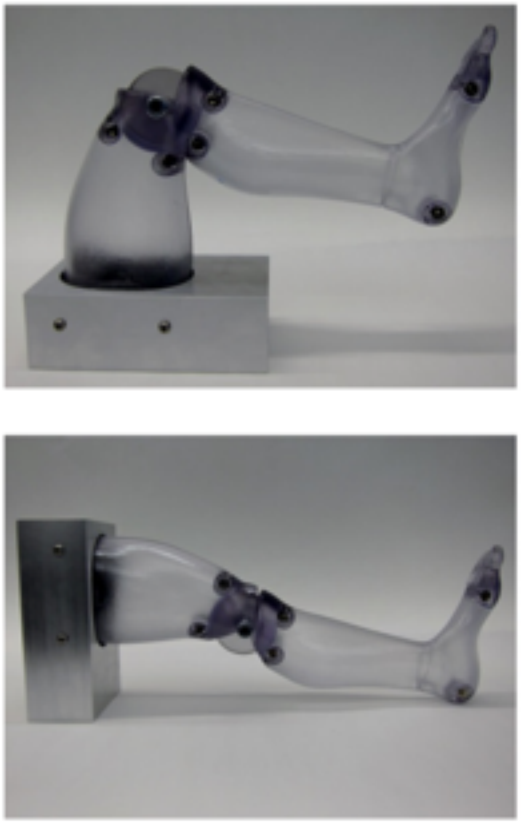
EC Goldfield, **YL Park**, B Chen et al., ***Ecological Psychology***, Vol. 24, No. 4, pp. 300-327, 2012.

Application – Programmable Second Skin (2)

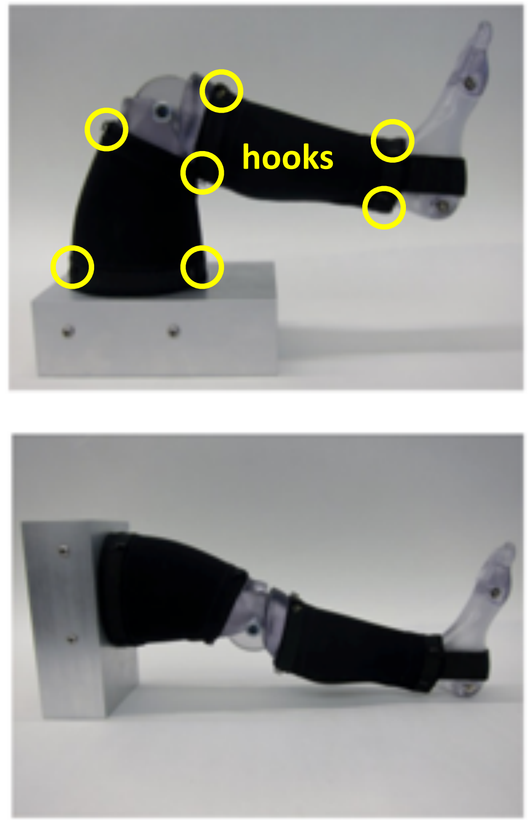


Video Link: http://www.youtube.com/watch?v=38D8hayhUJ0

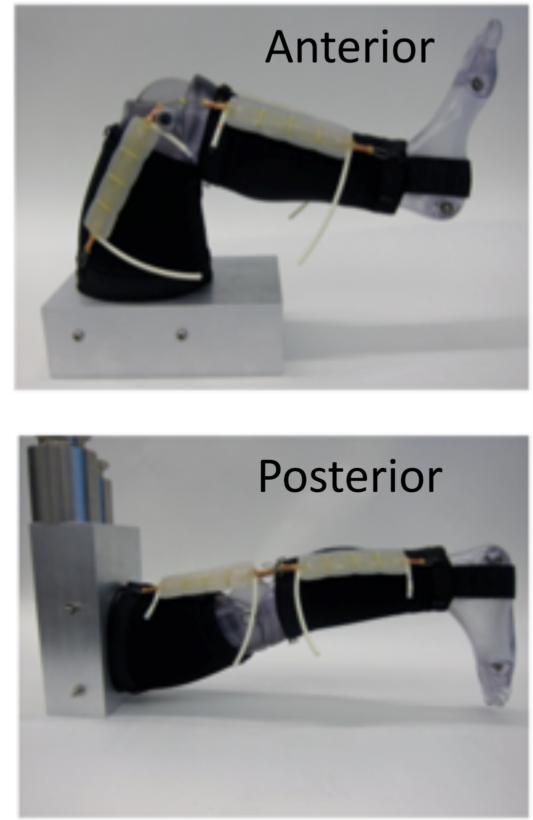
Application – Soft Knee Orthotic (1)



Articulated leg model (3D printed)

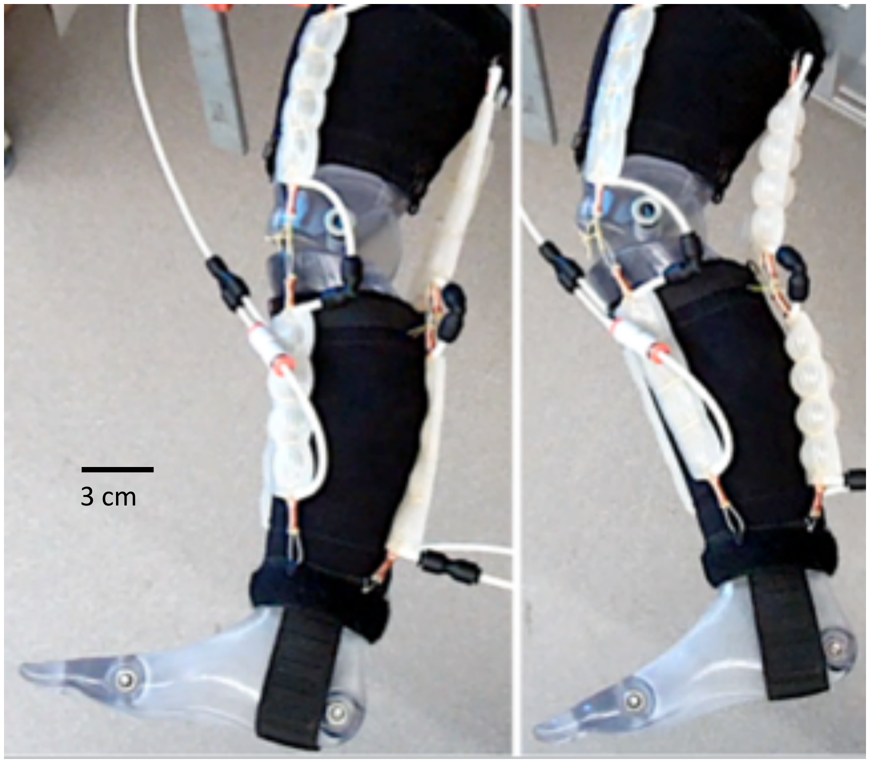


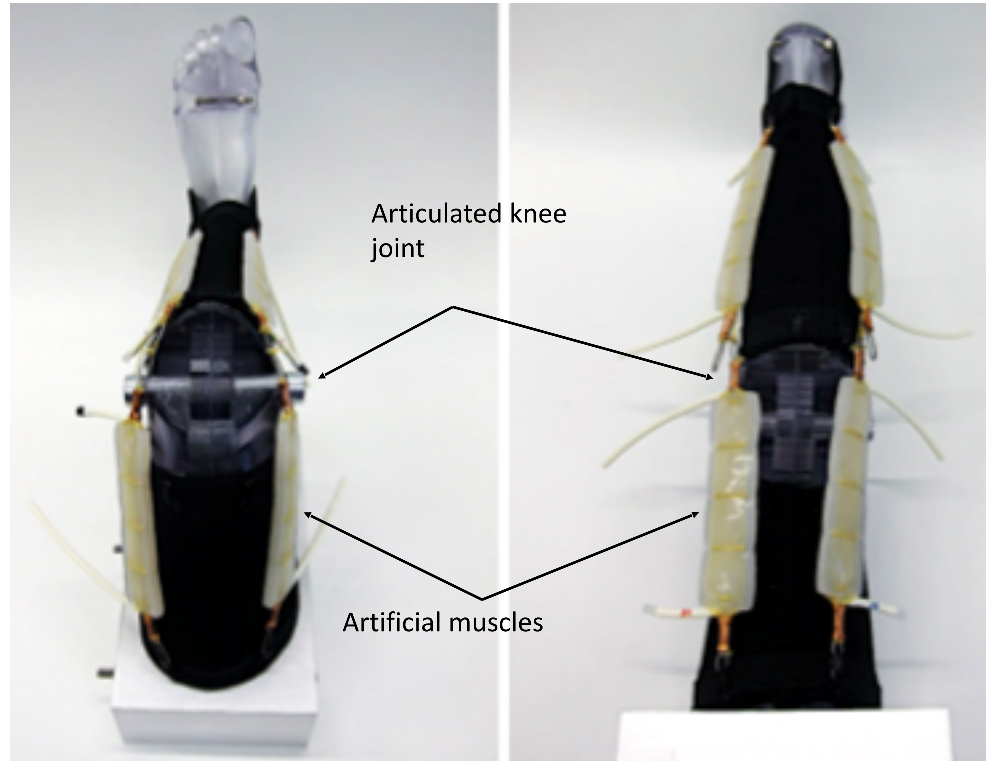
Leg sleeves



Muscle installation

Application – Soft Knee Orthotic (2)





Y-L Park, J Santos, RJ Wood et al., ***IEEE ICRA'14***, 2014.

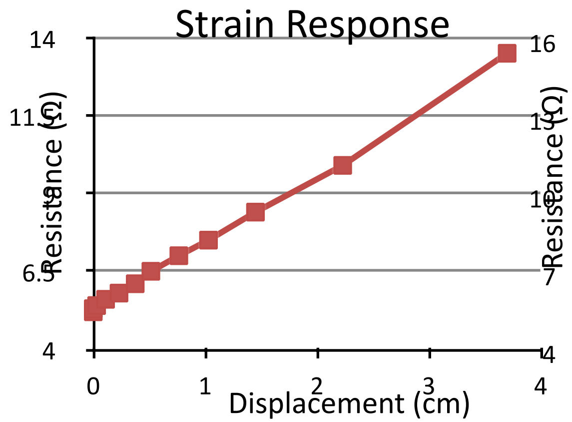
Video Link: http://www.youtube.com/watch?v=pWzoXk7KUmU

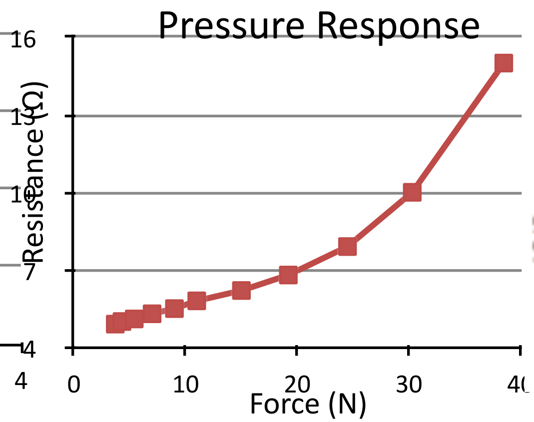
Application - Soft Motion Sensing Suits

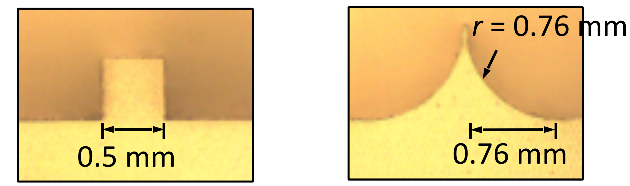
Y Menguc, **Y-L Park**, C Walsh et al. ***Proc. IEEE ICRA'13***, 2013.
Y Menguc, **Y-L Park**, C Walsh et al., ***International Journal of Robotics Research***, 2014.

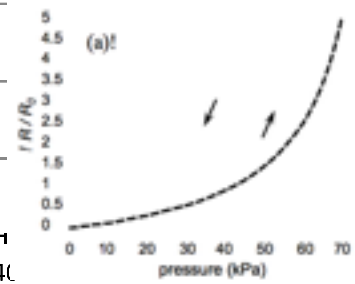
Ongoing & Future Work

- Senor Response Improvement



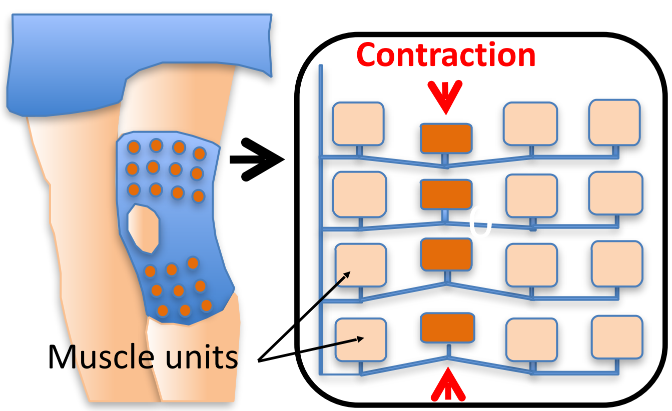






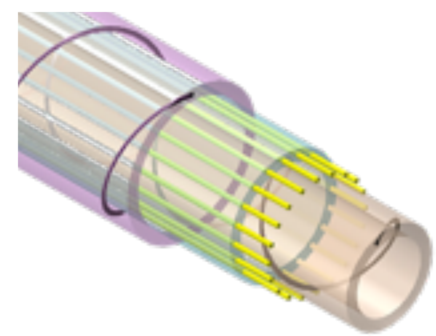
YL Park, C Majidi et al., ***APL***, 2012.

- Modularized Muscle Design & Control



YL Park, B Chen, C Majidi et al., ***IEEE IROS***, 2012.

- Automated Manufacturing of 3D Muscles



YL Park, RJ Wood, ***IEEE Sensors Conf.***, 2013.

Summary: Soft Actuators

- Objective:
  - Compact, soft pneumatic artificial muscle with integrated sensing
- Enabling technologies:
  - Bio-inspired design & manufacturing
  - Multi-layered structure
- Results:
  - Flat pneumatic muscles
  - Sensor integrated pneumatic muscles
- Applications:
  - Soft Wearable Robots for Active Assistance and Rehabilitation

Acknowledgement

- Affiliation & Collaboration:

Carnegie Mellon University

THE ROBOTICS INSTITUTE

Mechanical Engineering

Biomimetics Dexterous Manipulation Laboratory

IFOS INTELLIGENT FIBER OPTIC SYSTEMS

HARVARD School of Engineering and Applied Sciences

WYSS INSTITUTE for Biologically Inspired Engineering

HARVARD MICROROBOTICS LABORATORY

Self-Organizing Systems Research Group

Boston Children's Hospital

- Funding:

NASA

NATIONAL INSTITUTES OF HEALTH

USAMRAA

NSF

WYSS INSTITUTE for Biologically Inspired Engineering

More Questions…

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