# Soft Micro/Nano-structured Sensors for Flexible and Wearable Physical Sensing

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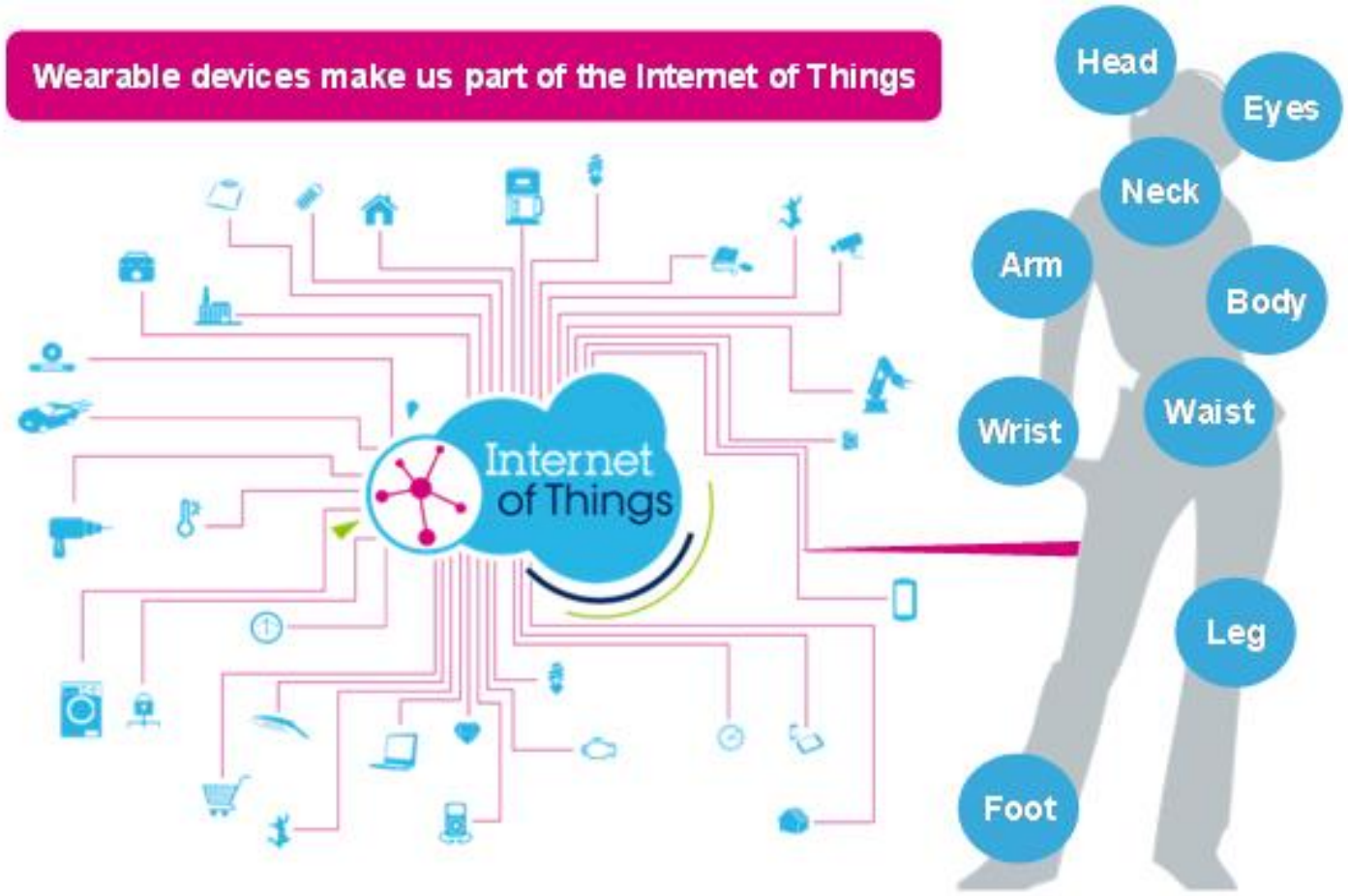
**Korea Advanced Institute of Science and Technology (KAIST)**

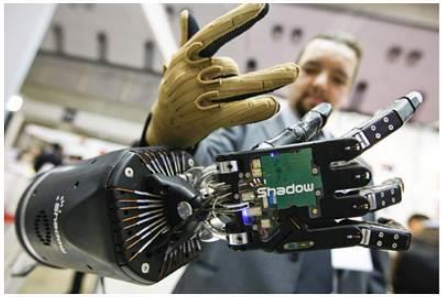
# Sensing in Flexible / Wearable Electronics




**Human Health Information → Wearable Sensors → IoT**

# Wearable Human Motion Detection

Entertainment



Smart glove; surgical robot, entertainment

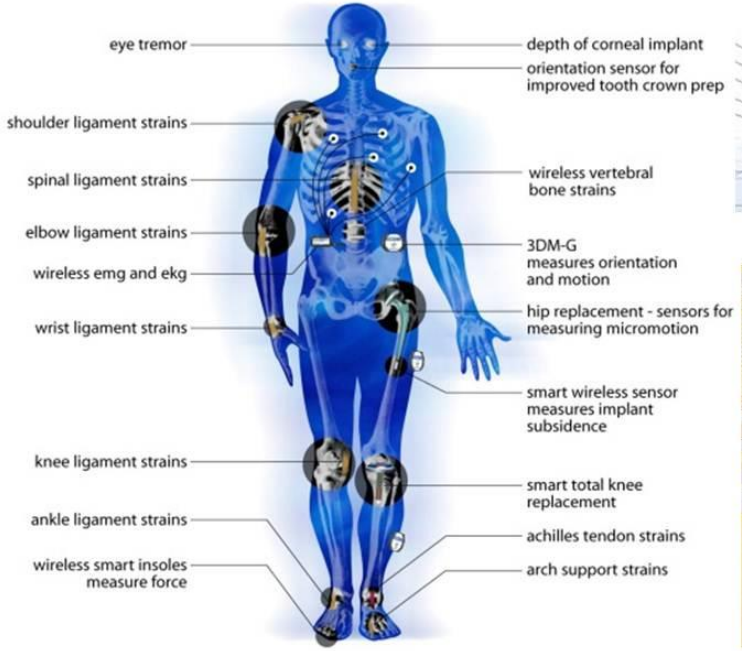
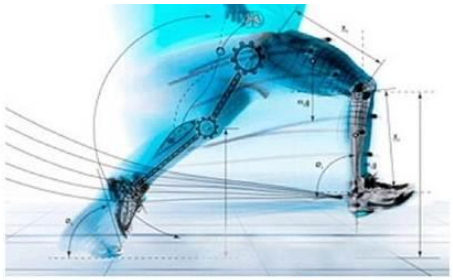



Image courtesy of Microstrain, Inc.



Sports dynamics

Personal health care; rehabilitation

- Optical motion capture
- Goniometer
- MEMS Accelerometer
- Infrared imaging
- Electrostatic detection
- Stretchable physical sensing

# Wearable Human Motion Detection

- **Critical requirements for wearable / stretchable motion sensing:**
  - ✓ **High Sensitivity**
  - ✓ **Quick response**
  - ✓ **High stretchability**
  - ✓ **High durability**
  - ✓ **Small hysteresis**

**Elastomer with high stretchability and flexibility**

**Electrically or optically sensitive materials**

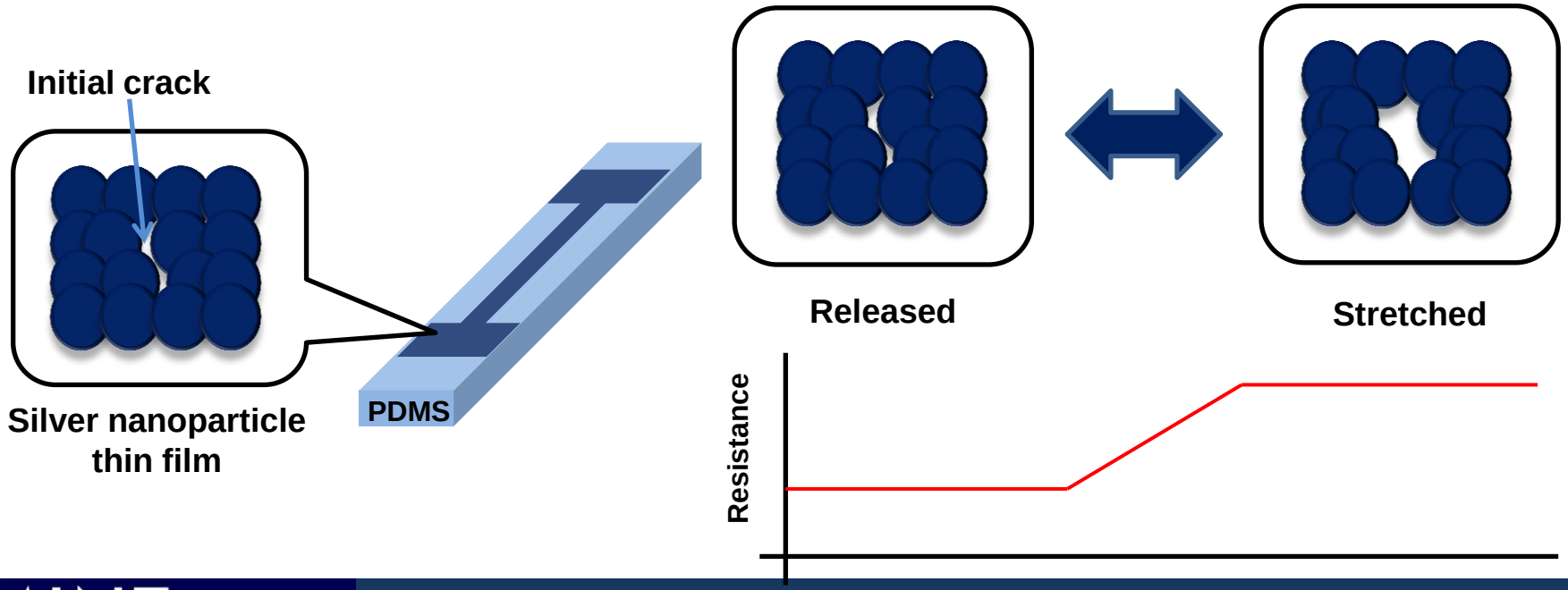
# Stretchable Strain Sensor based on Metallic Nanoparticles

J. Lee, I. Park, et al., Nanoscale 6, 11932-11939 (2014)

# Stretchable Strain Sensor based on Metallic Nanoparticles

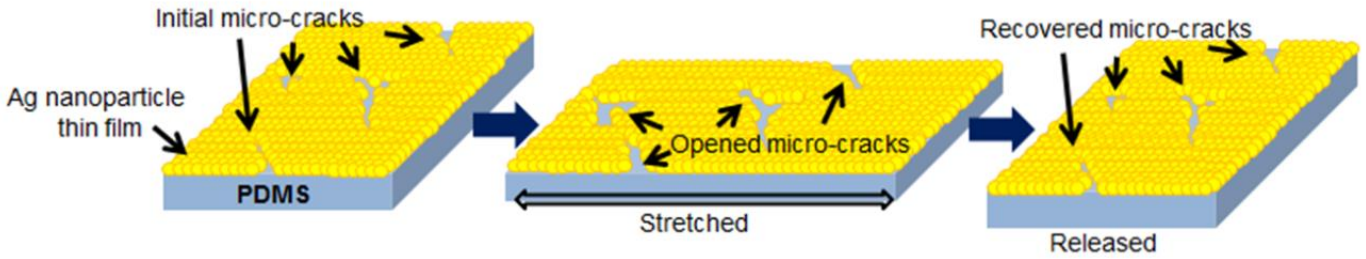
**Stretchable strain sensing based on cracking of metal nanoparticle thin film on PDMS**

- ✓ **Simple & easy fabrication process**
- ✓ **Low-cost process**
- ✓ **High sensitivity (Maximum gauge factor ~ 10 in tensile strain)**
- ✓ **Sensitive to compressive strain (Maximum gauge factor ~ 13.6)**
- ✓ **High stretchability (50% tensile strain)**

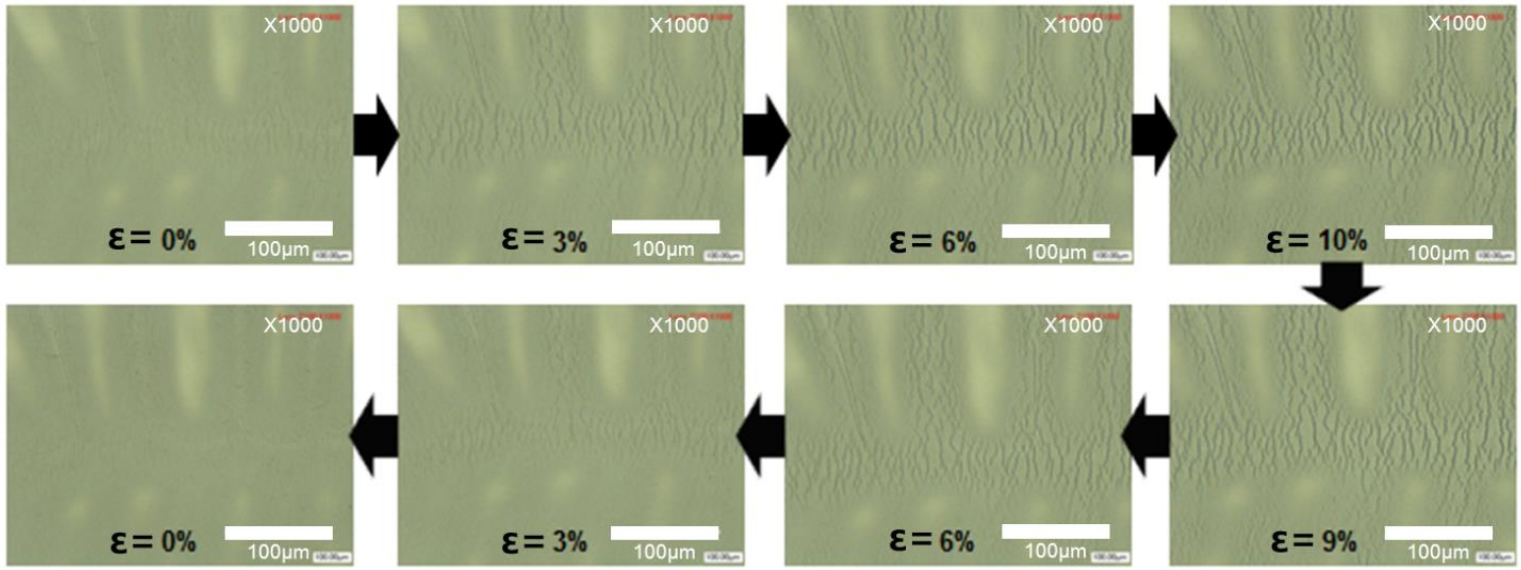


# Reversible Opening & Closure of Micro-Cracks

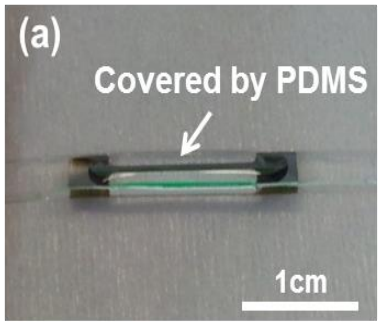
## Schematic of mechanism: stretchable strain sensor

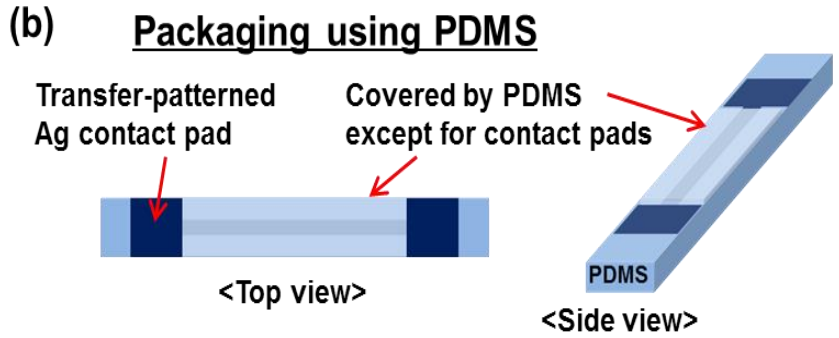


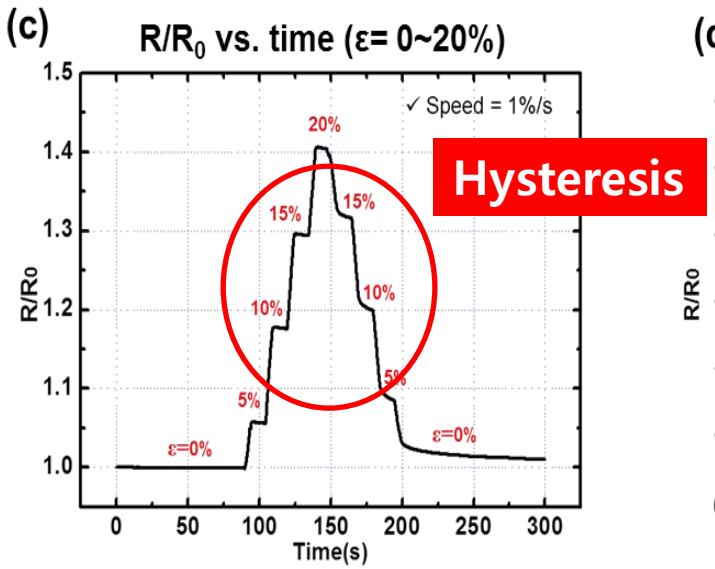

## Microscopic images of strain sensor upon strain cycle

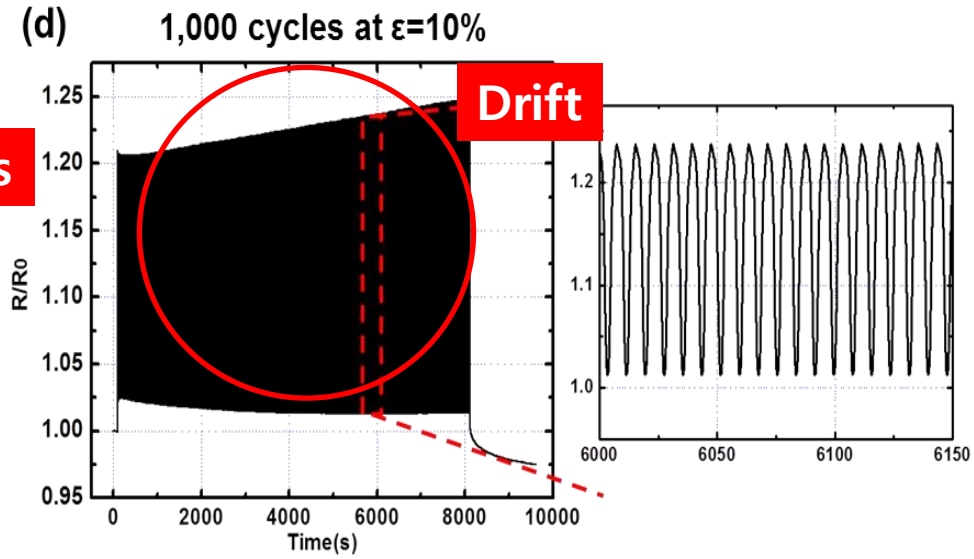


# Stretchable Strain Sensing by AgNP Thin Film Sensor

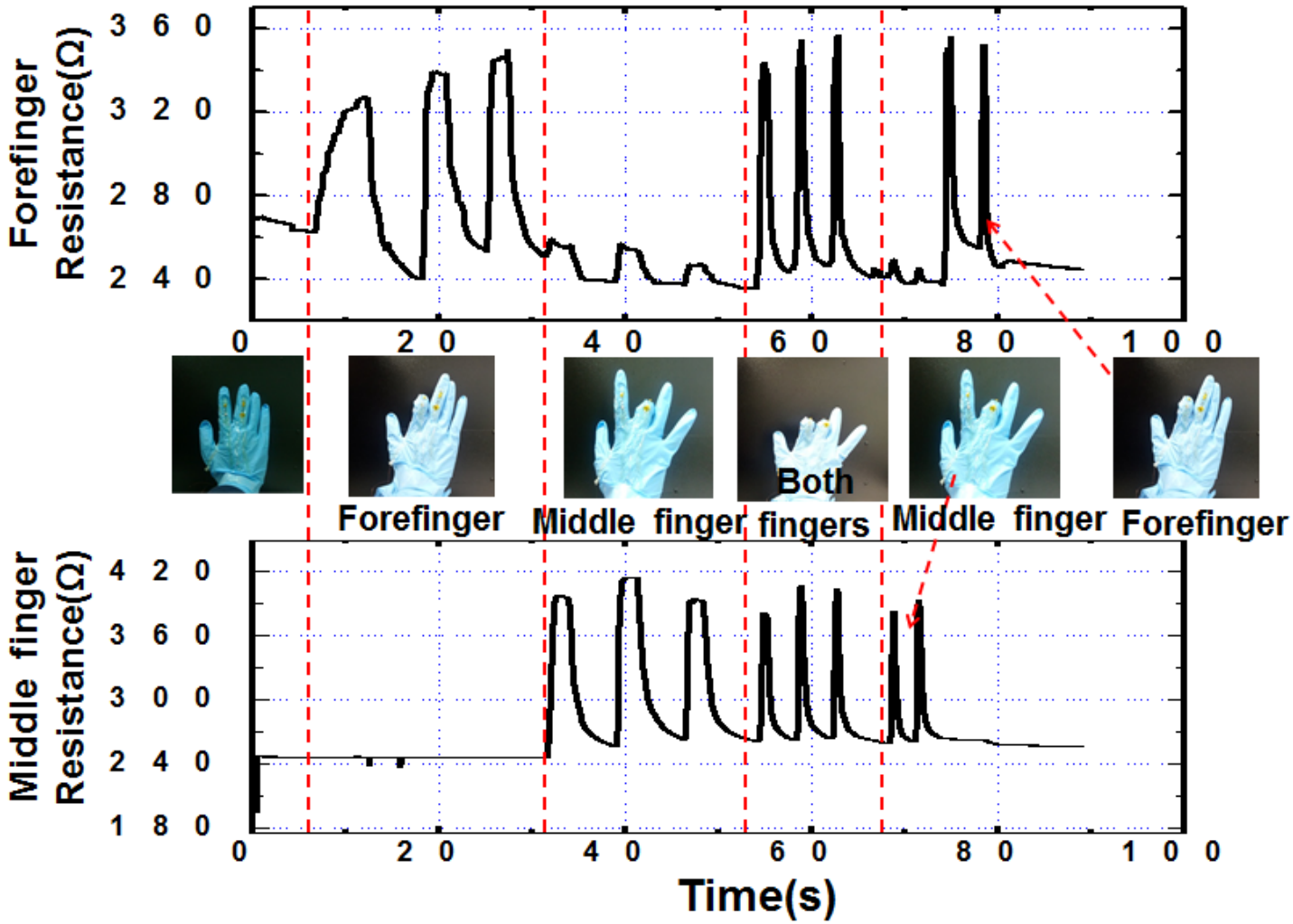


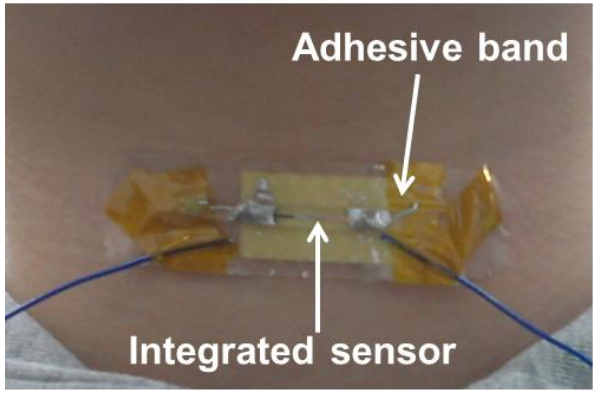



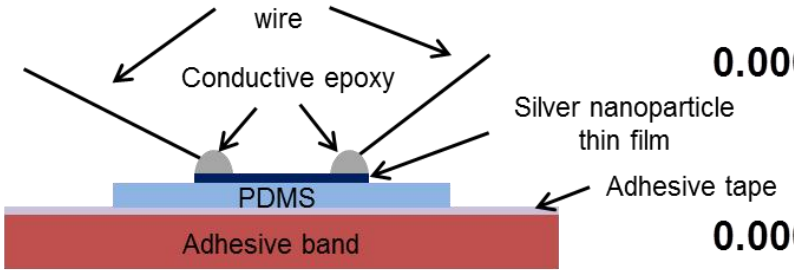



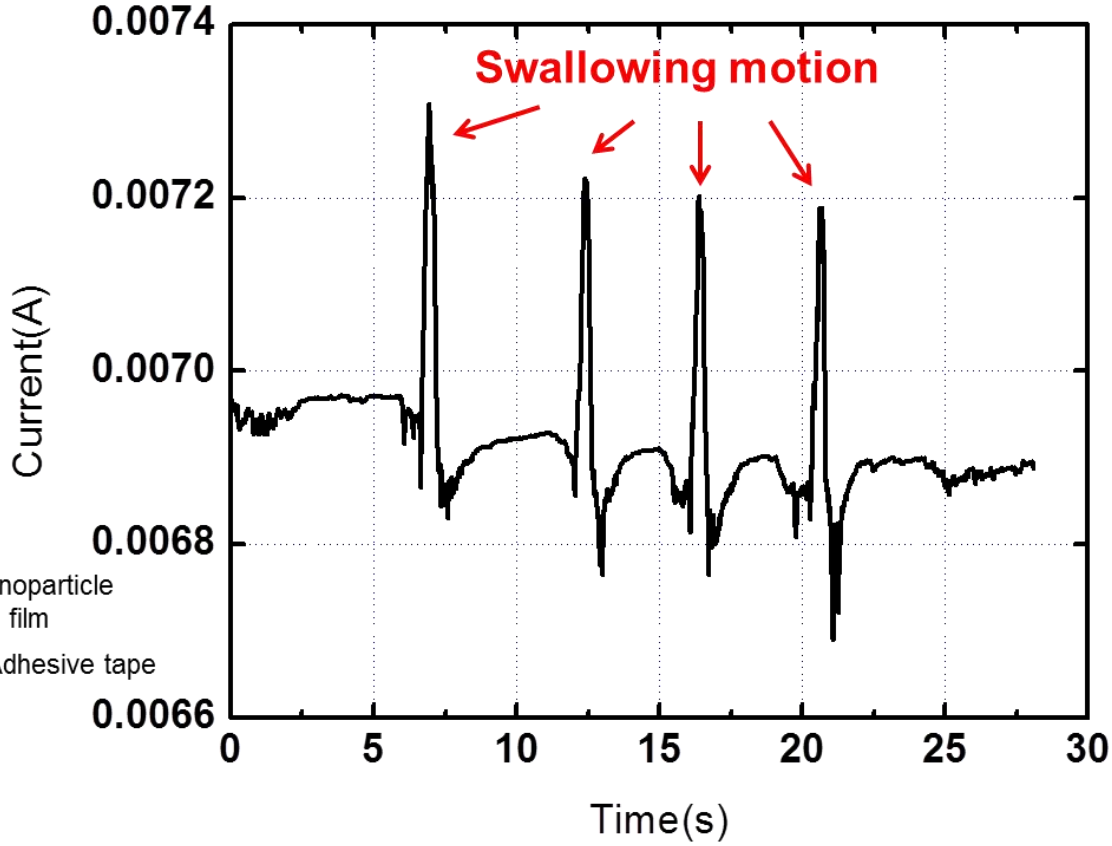
# Human Finger Motion Detection



# Detection of Swallowing Motion in Adam's Apple



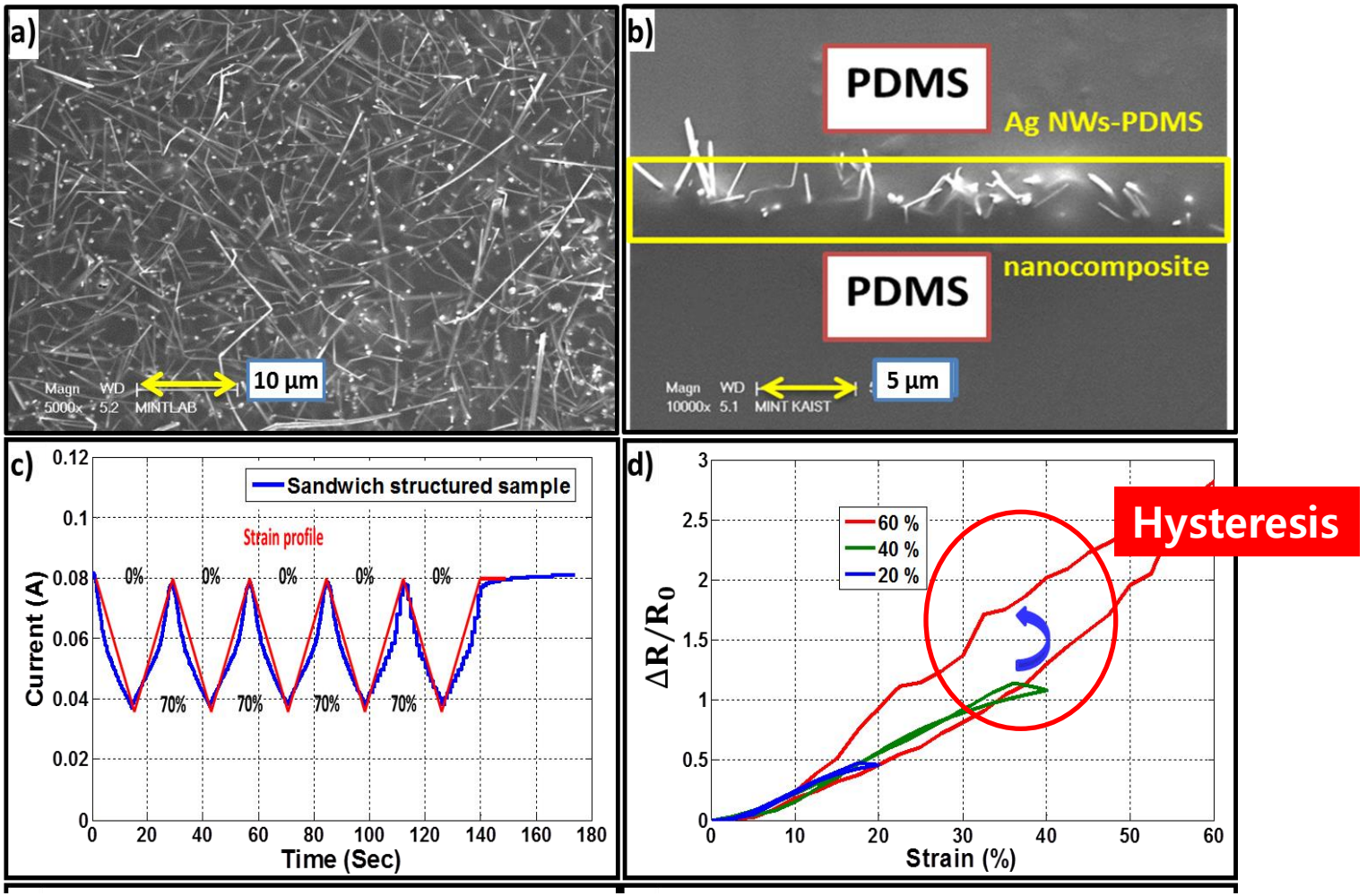



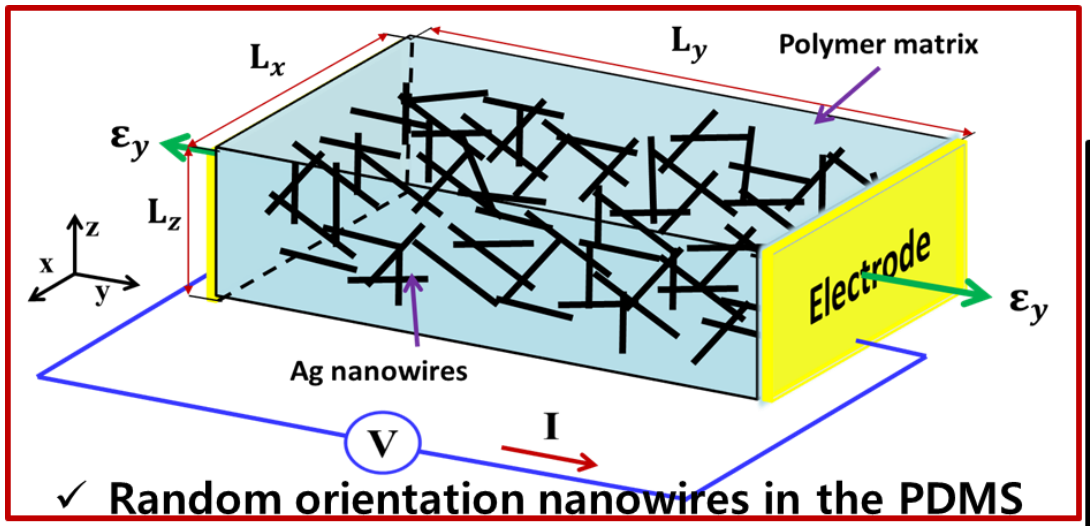
# Silver Nanowire – Elastomer Composite : Stretchable Strain Sensor

**M. Amjadi, I. Park, et al., ACS Nano 8, 5154-5163 (2014)**

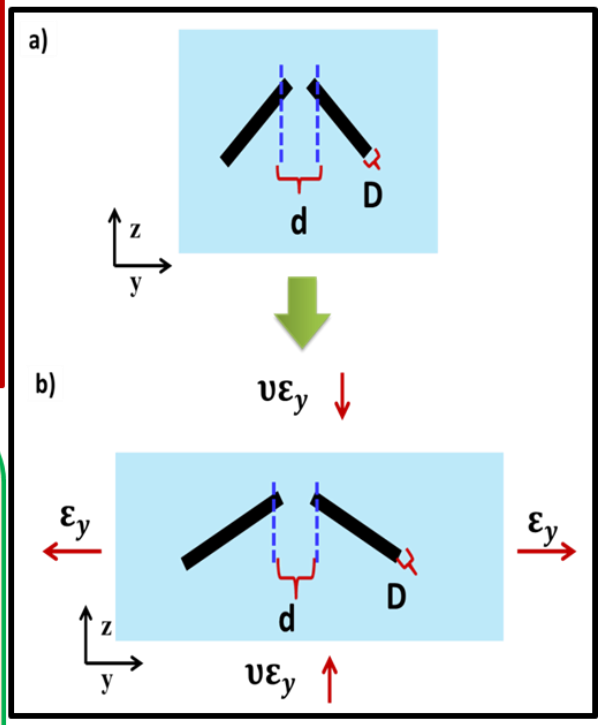
# Silver Nanowire – Elastomer Composite : Stretchable Strain Sensor



# Silver Nanowire – Elastomer Composite : Stretchable Strain Sensor

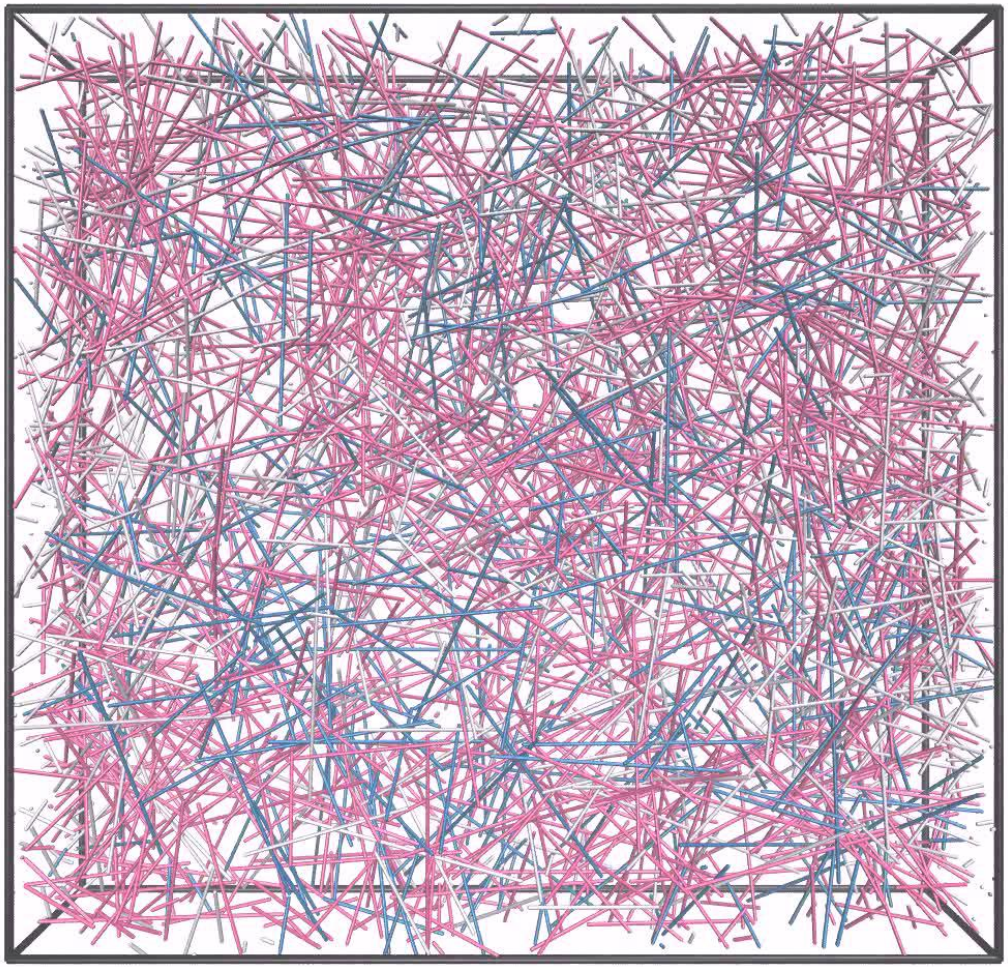



- ✓ Random orientation nanowires in the PDMS matrix
- ✓ 1,500 Ag nanowires with a constant diameter (D=150 nm) and length (L=20 μm) within the PDMS matrix ($L_y = 62\ \mu m, L_x = 62\ \mu m$ and $L_z = 5\ \mu m$)
- ✓ Position and orientation of each nanowire by its special coordinates
- ✓ Re-positions and re-orientations by the mechanical strain using the 3D fiber reorientation model

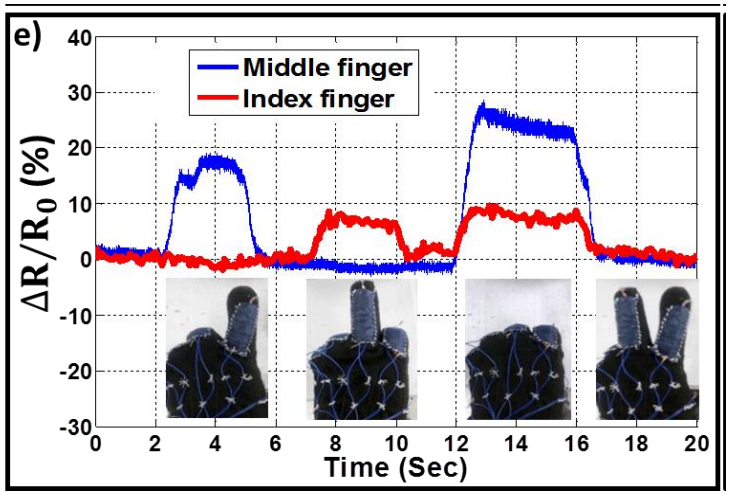


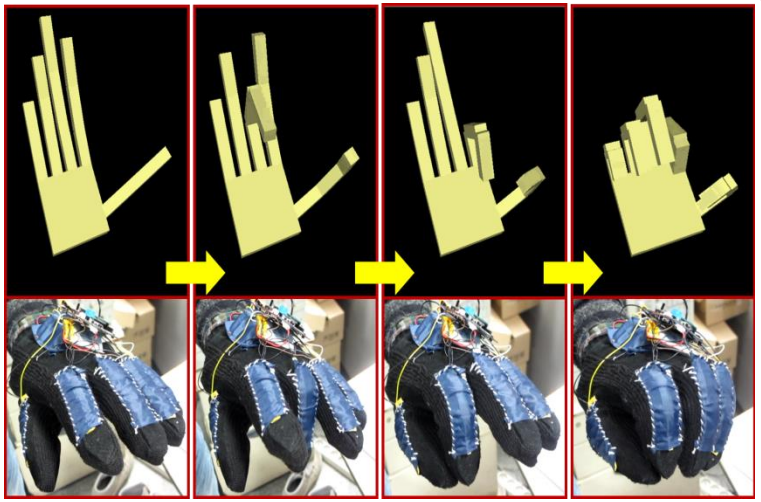
# Silver Nanowire – Elastomer Composite : Stretchable Strain

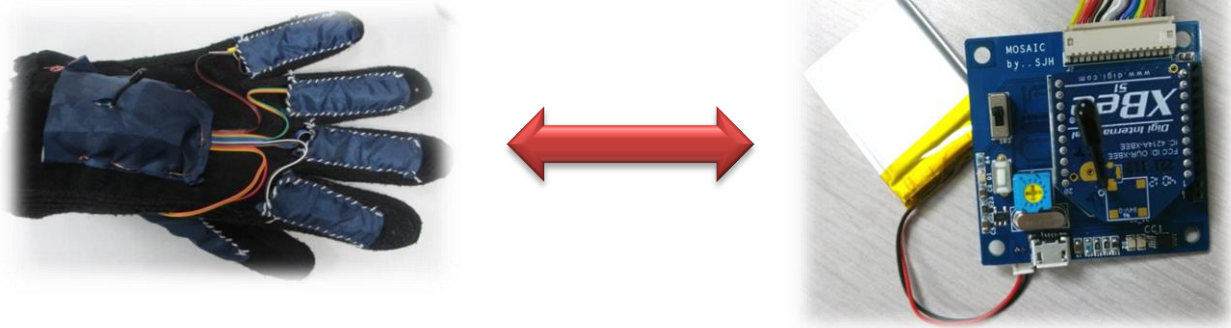




# Wireless Smart Glove System for Human Motion Detection

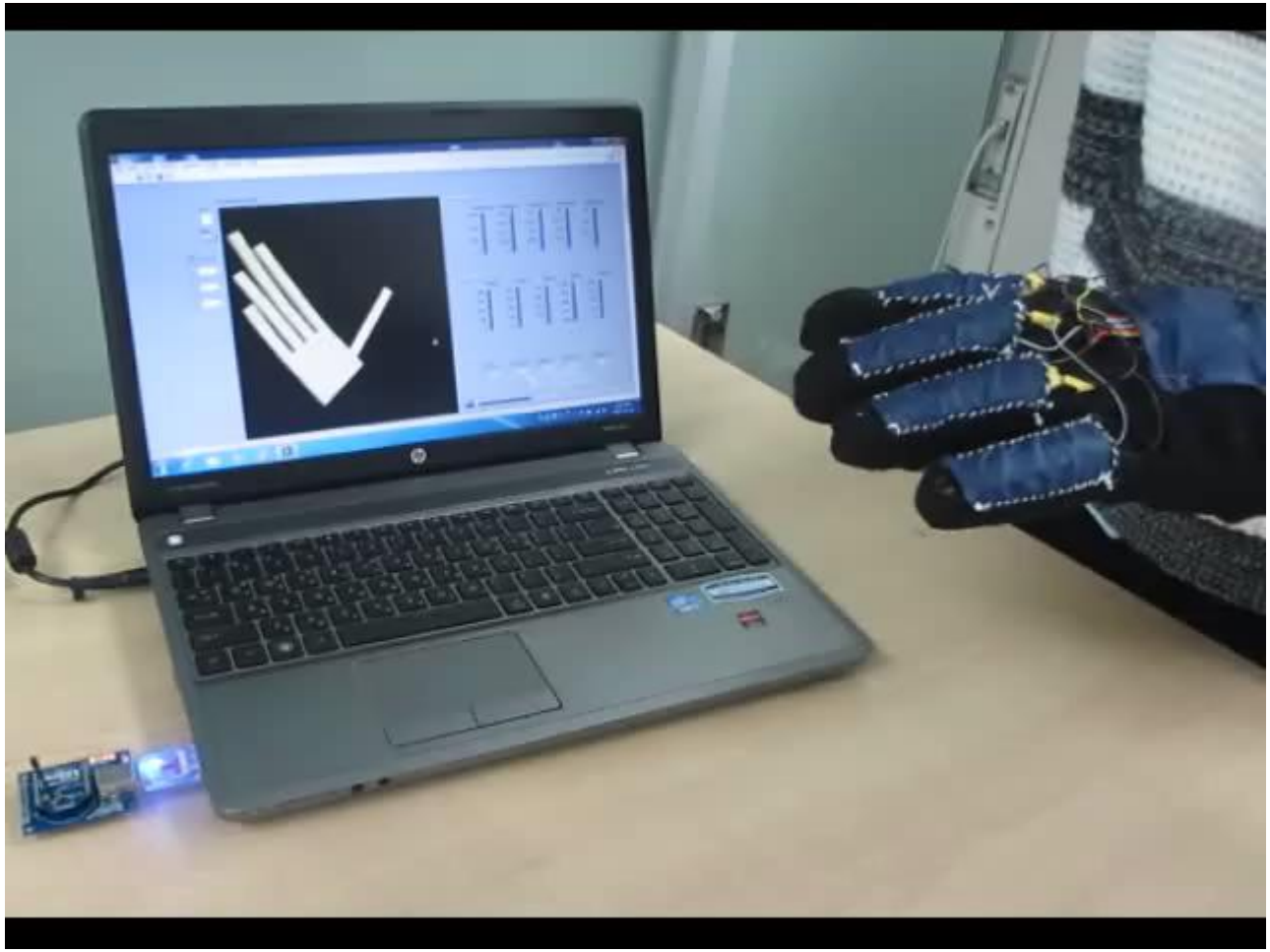




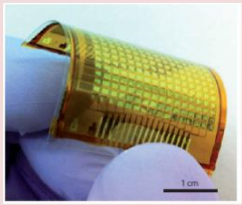
- Excellent agreement between loading profile and sensor response.
- Wireless communication system for DAQ and data transmission.
- Integrated glove and communication system.

# Wireless Smart Glove System for Human Motion Detection

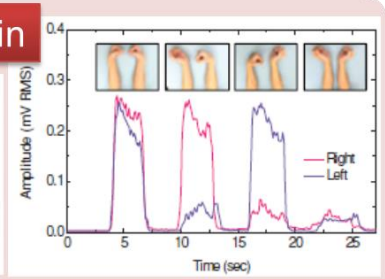


# Flexible Pressure Sensors

## Electronic skin

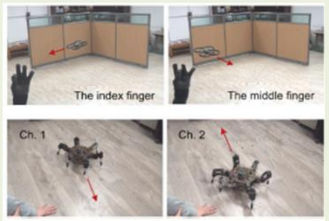


Chuan Wang et al.,
*Nat. Mater.*, 2013



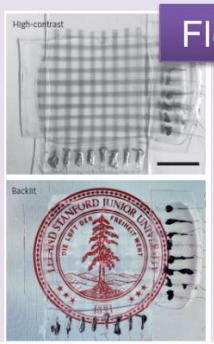

Jae-Woong Jeong et al.,
*Adv. Mater.*, 2013

## Electronic textiles

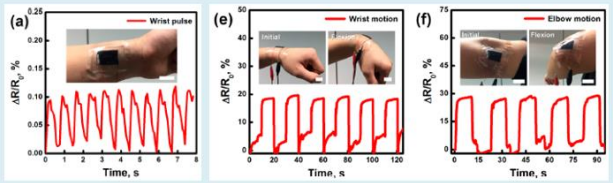

Jaehong Lee et al.,
*Adv. Mater.*, 2015

## Flexible touch displays



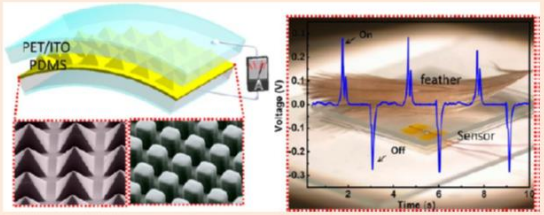
Darren J. Lipomi et al.,
*Nat. Nano.*, 2011

## Mobile healthcare aids



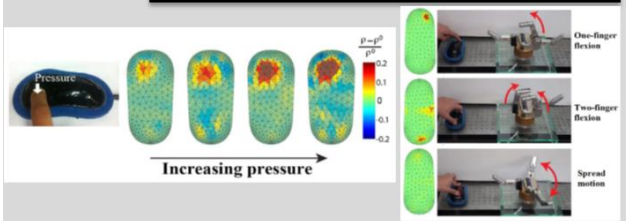

Kang-Hyun Kim et al.,
*ACS Appl. Mater. Inter.*, 2017

## Soft robotics




Feng-Ru Fan et al.,
*Nano Lett.*, 2012

## Human-machine interfaces




Hyosang Lee et al.,
*Sci. Rep.*, 2017

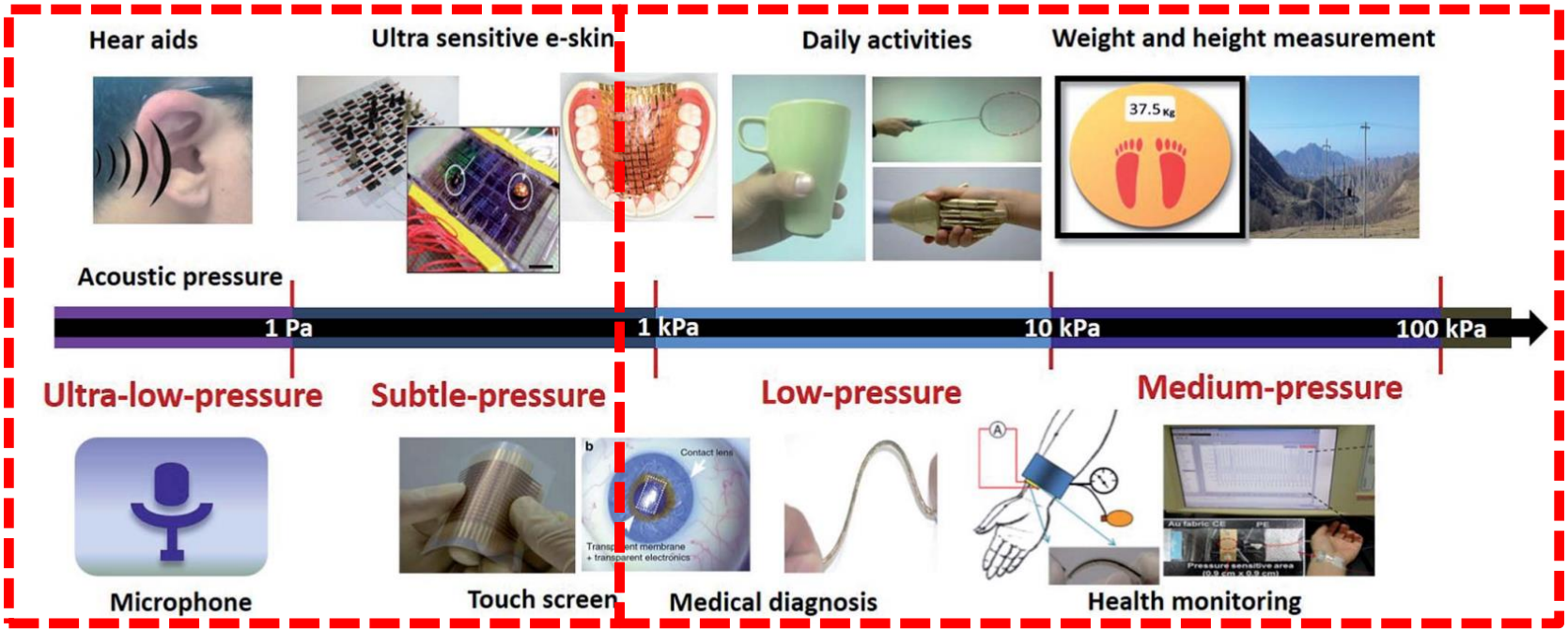
➔ **Rigid sensors have limitations in deformability and conformability to arbitrary surfaces** for wearable device applications.

➔ **Flexibility of pressure sensors is required** for advanced future applications in terms of human-motion-induced pressure sensing .

# Flexible Pressure Sensors

Rare but important for advanced applications

Daily-life applications




Yaping Zang et al., *Mater. Horiz.*, 2015

➔ Flexible pressure sensors must satisfy:

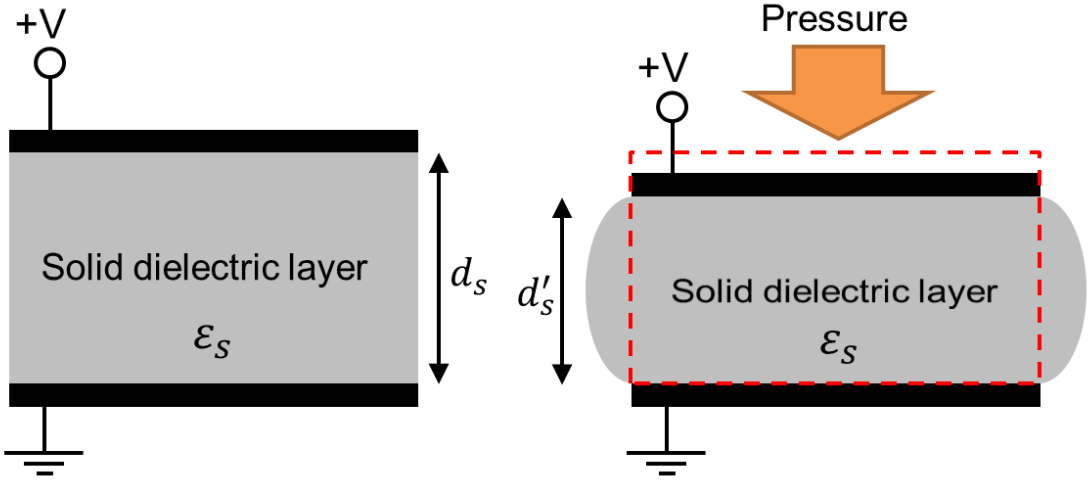
(1) **high sensitivity** for low pressure sensing

(2) **wide span** up to medium-pressure for tactile pressure sensing

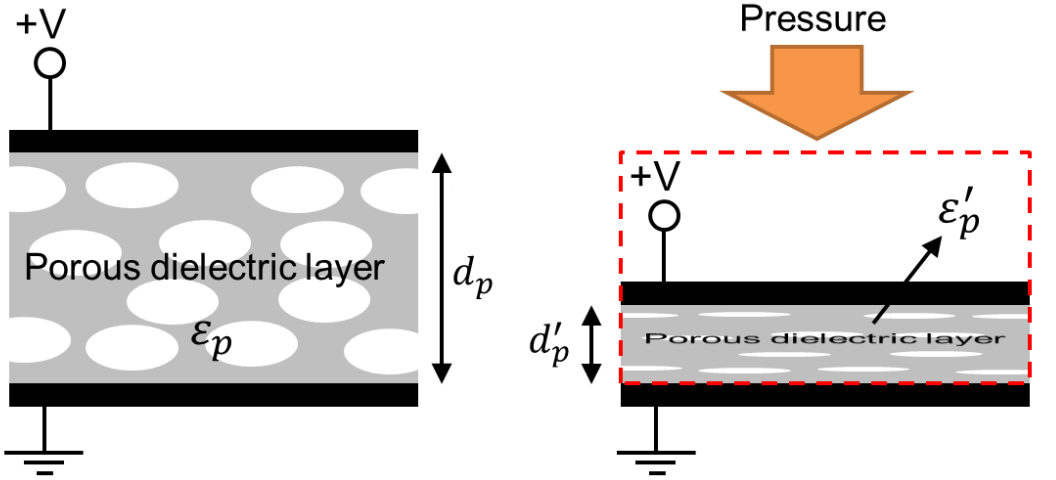
# Microporous Elastomer as Capacitive Sensing Element

D. Kwon, I. Park, et al., ACS Appl. Mater. Inter. 8, 1901 (2016)

# Microporous Elastomer as Capacitive Sensing Element




$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

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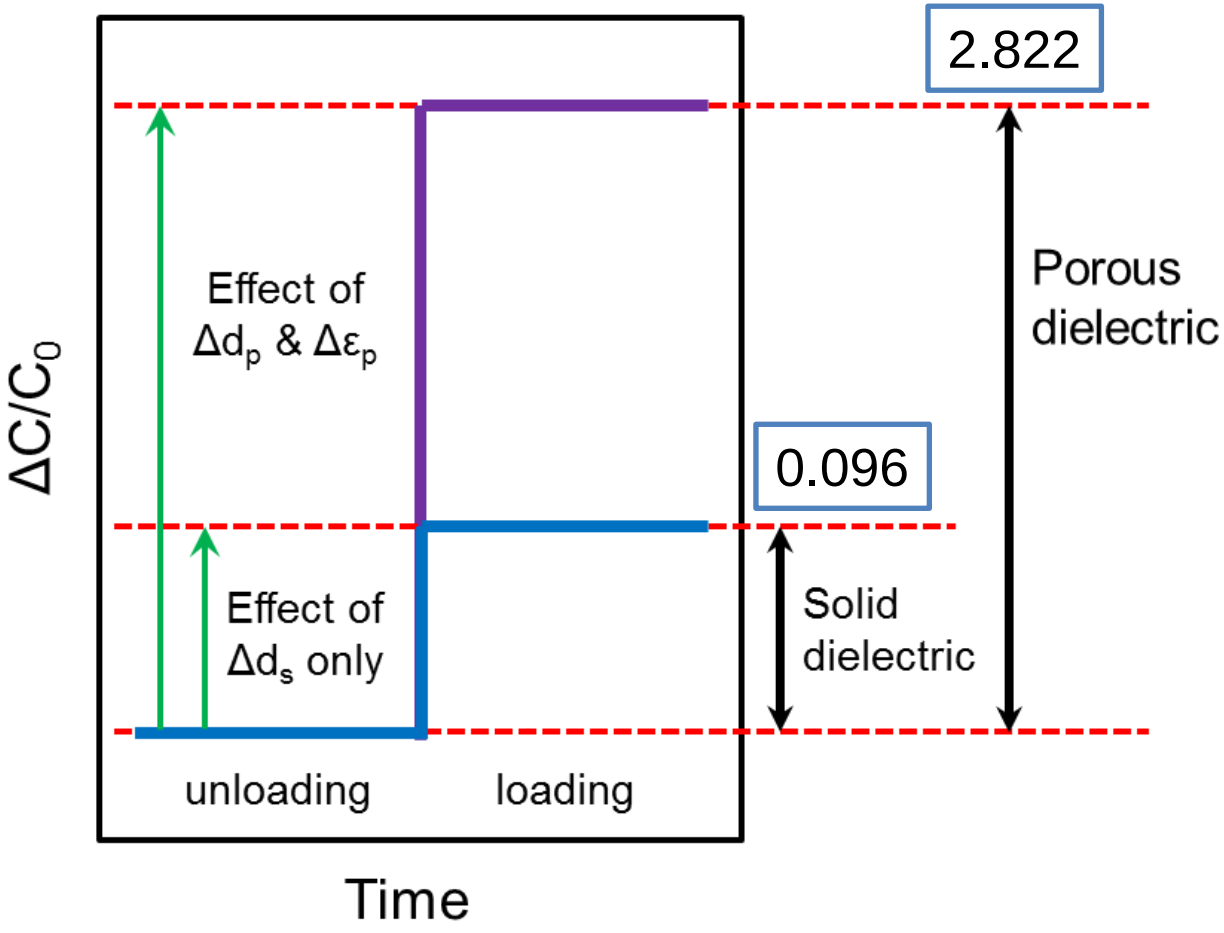
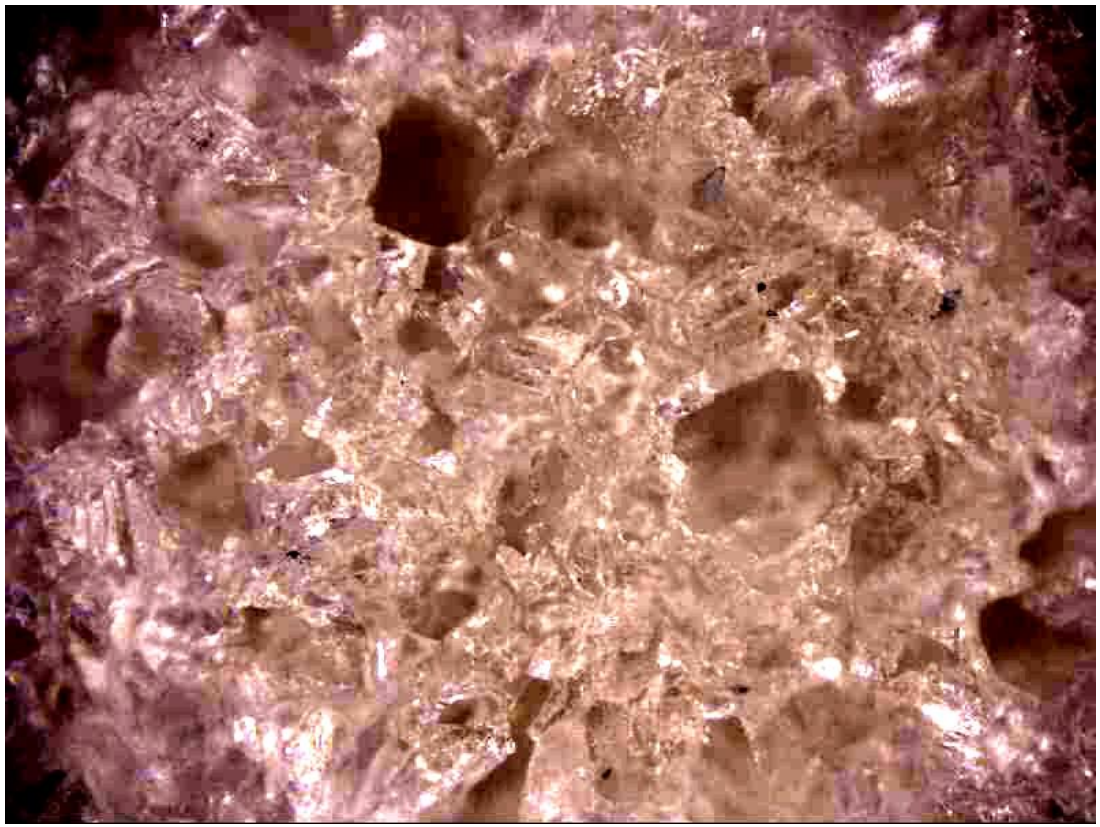
# Microporous Elastomer as Capacitive Sensing Element

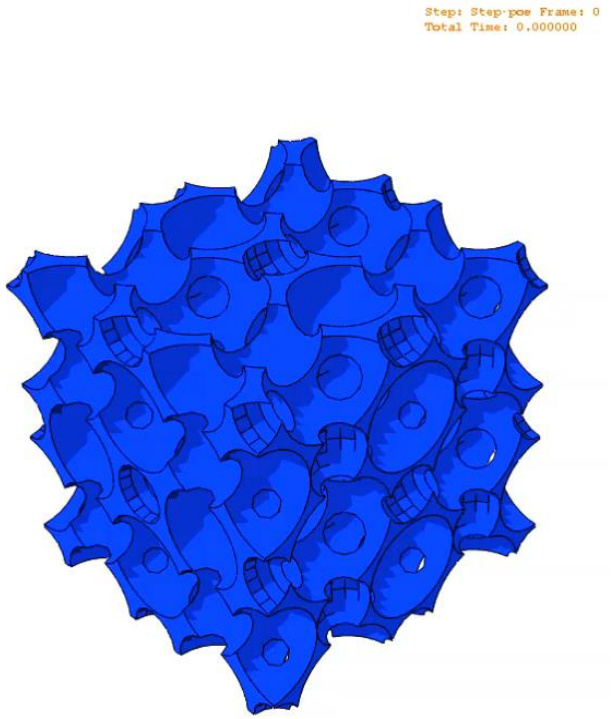



Ex)
- ✓ Material: Ecoflex
- ✓ Solid dielectric: 0% porosity
- ✓ Porous dielectric: ~80% porosity
- ✓ Pressure: 5kPa

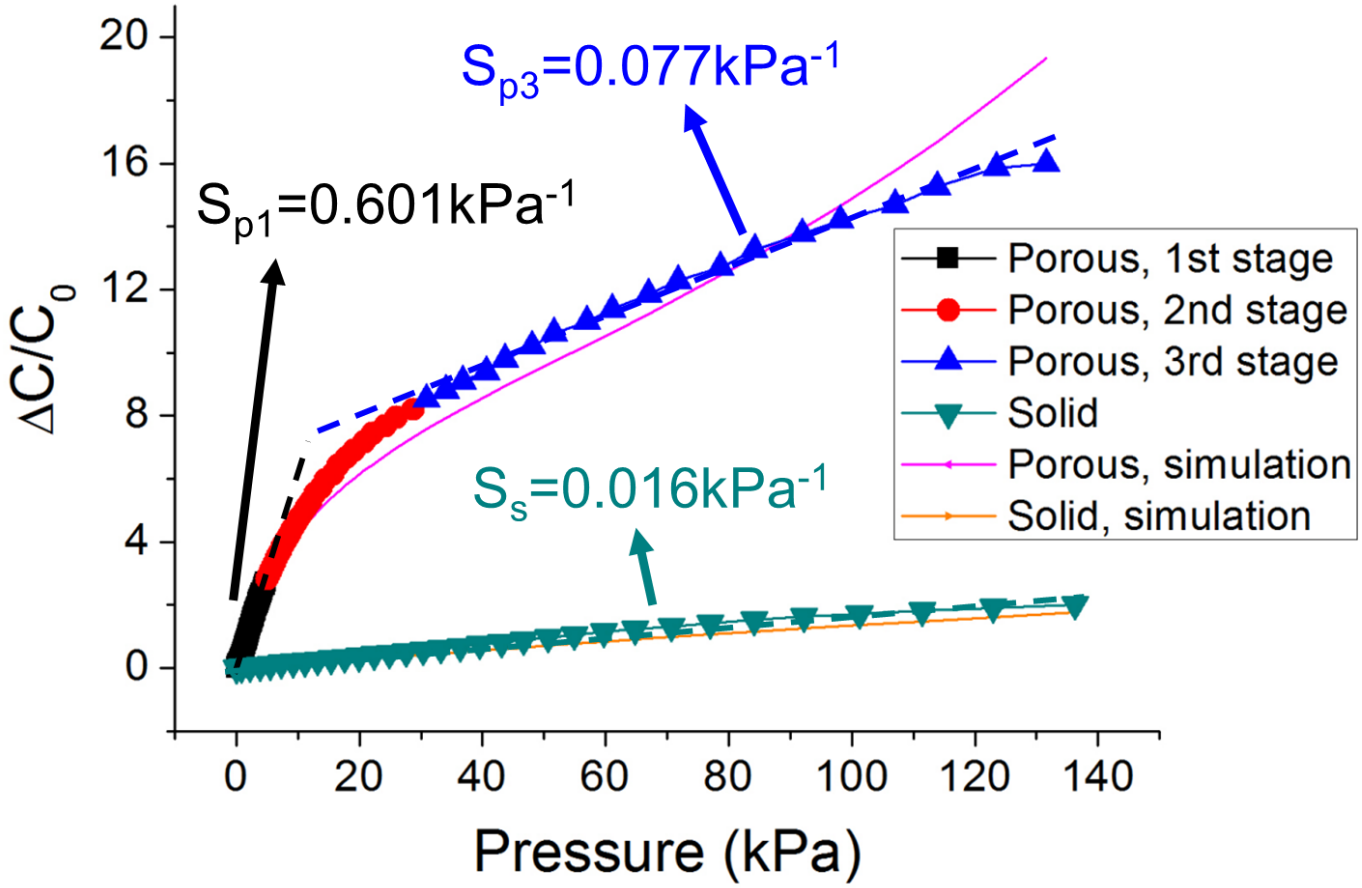
$$2.822 / 0.096 = 29.4$$

# Microporous Elastomer as Capacitive Sensing Element





# Microporous Elastomer as Capacitive Sensing Element



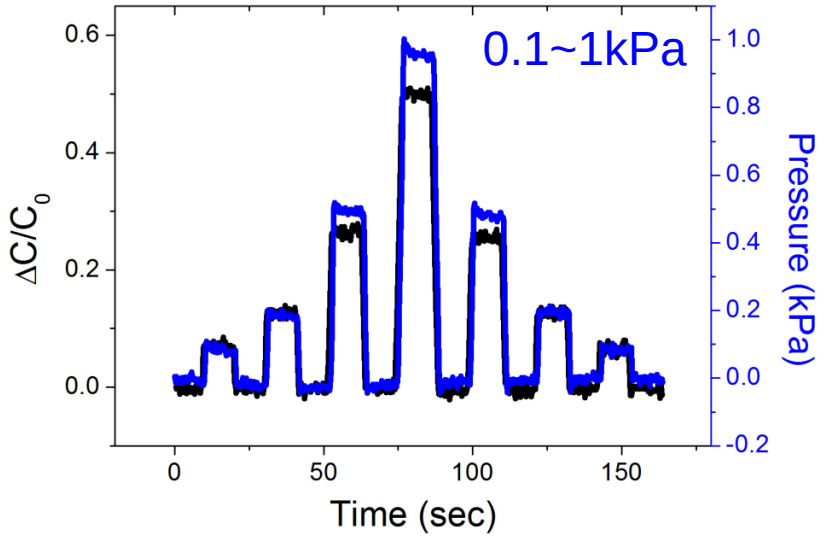

- ✓ 1st stage: 0~5kPa
- ✓ 2nd stage: 5~30kPa
- ✓ 3rd stage: 30~140kPa

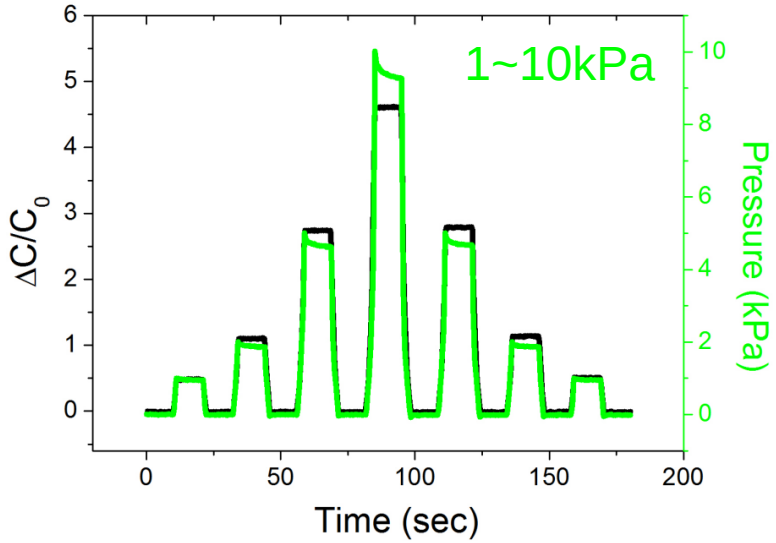
$S_{p1} / S_s = 37.56$

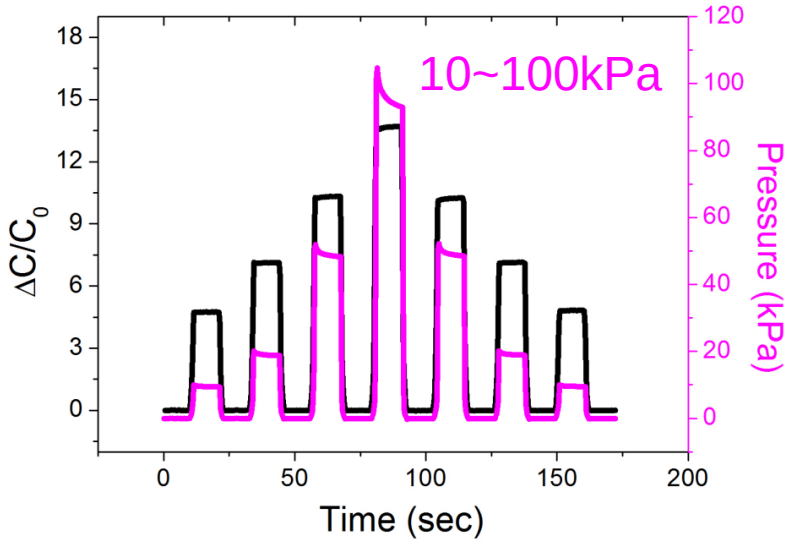
$S_{p1} / S_{p3} = 7.81$

➔ High sensitivity: 0.077~0.601kPa$^{-1}$
➔ Wide span: whole tactile pressure range (~100kPa)

# Microporous Elastomer as Capacitive Sensing Element

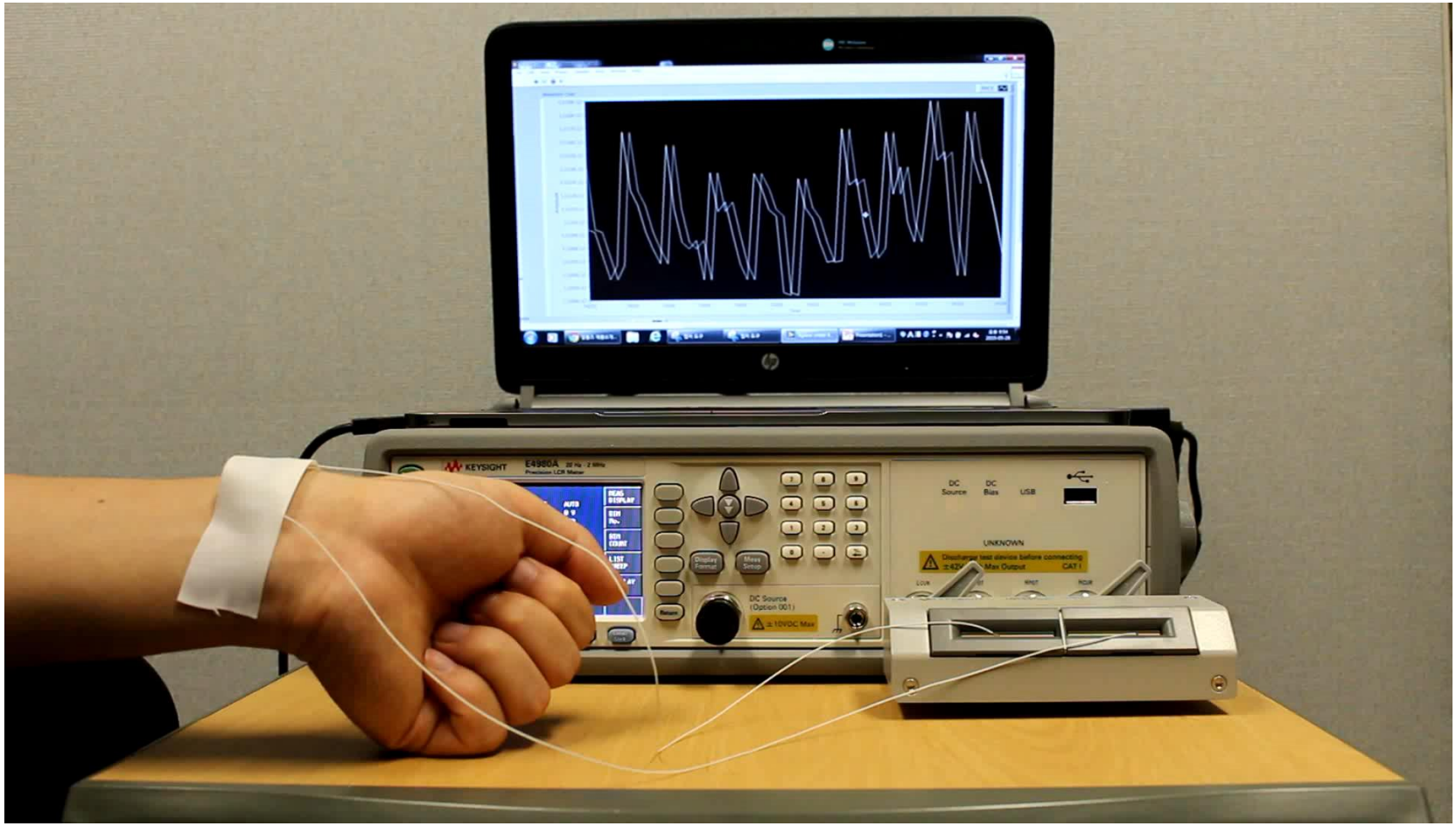


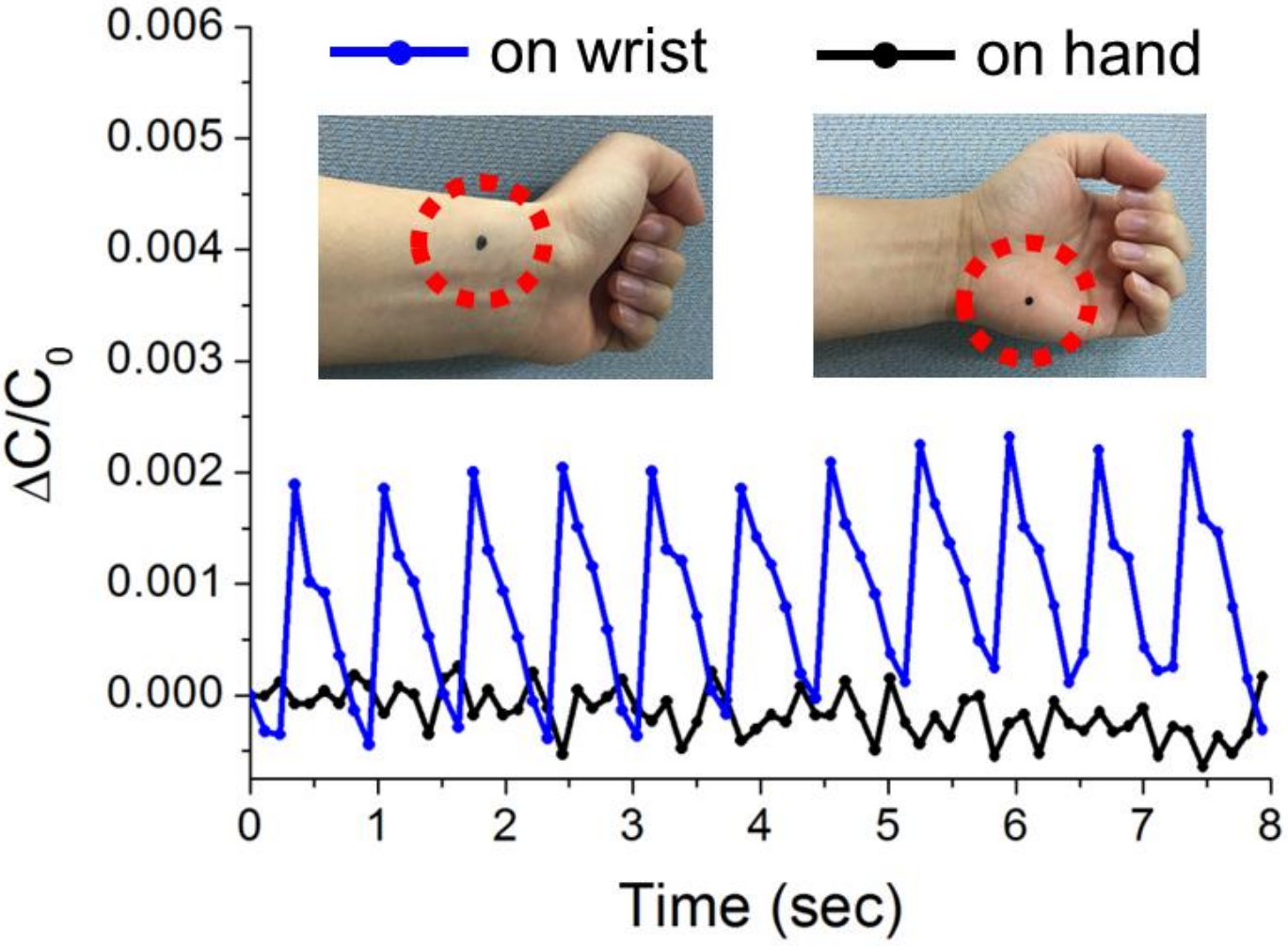




- ✓ Dynamic pressure response in different pressure scale
- ➔ Great match between input & output profile

# Microporous Elastomer as Capacitive Sensing Element



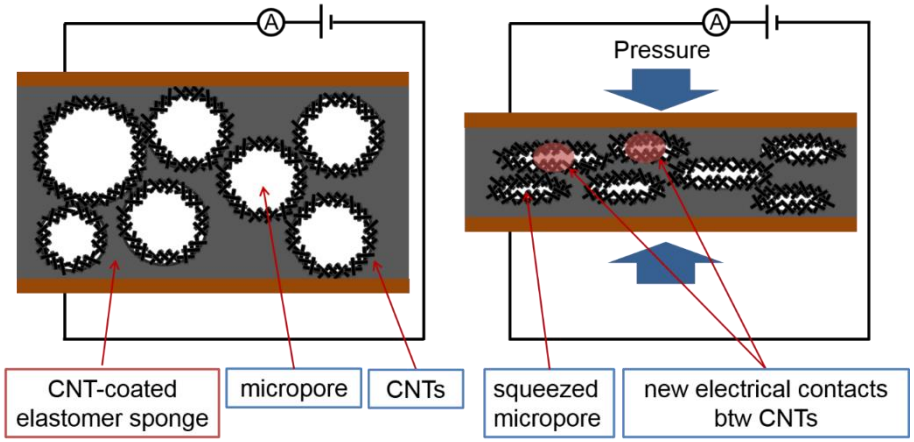
# Microporous Elastomer as Capacitive Sensing Element

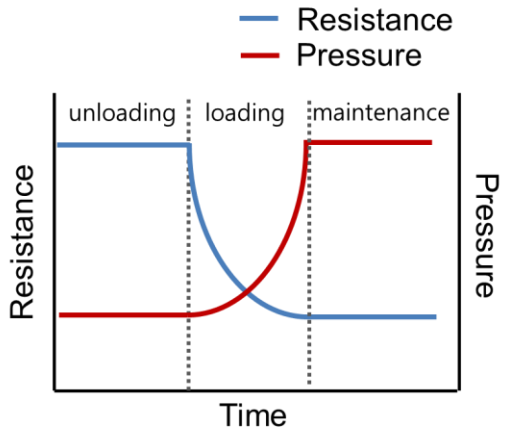


# Piezoresistive Pressure Sensors using Microporous Elastomer

S. Kim, I. Park, et al., in review (2018)

# Piezoresistive Pressure Sensors using Microporous Elastomer

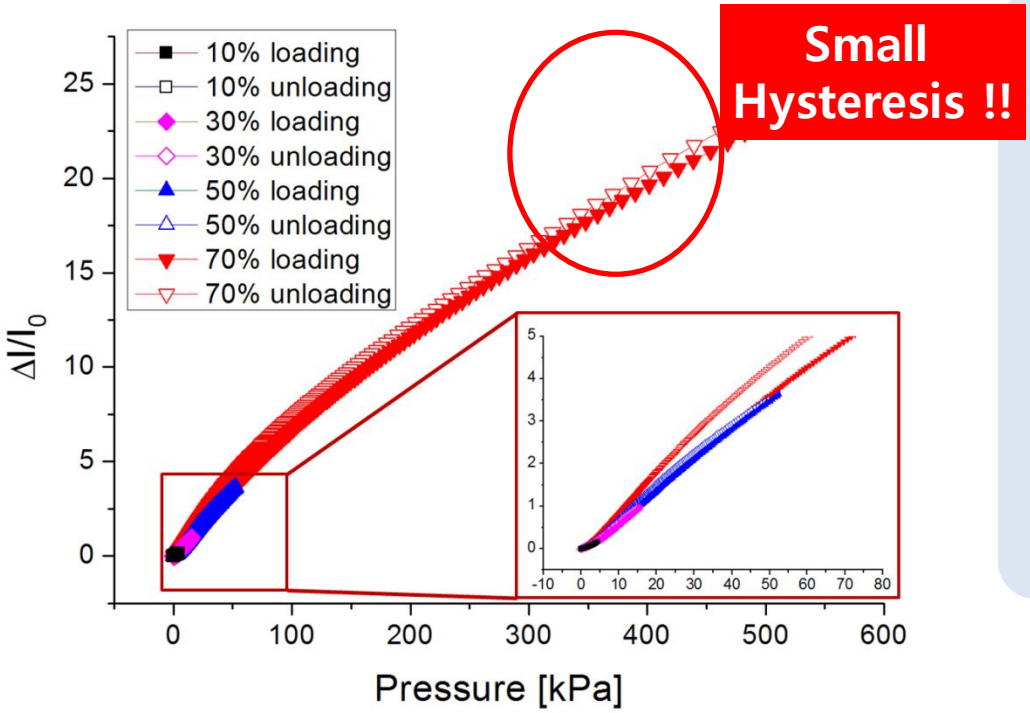



- Flexible CNT-coated porous elastomer structure acts as a sensing structure of pressure sensor.
- CNT-coated porous elastomer structure has many interconnected micro pores which have CNT-coated surfaces, and they forms electrical path ways.
- When pressure is applied, as micro pores are squeezed.
  → New electrical contact between CNT networks is generated.
  → Resistance of the pressure sensor is decreased.

# Piezoresistive Pressure Sensors using Microporous Elastomer

- **Hysteresis due to Viscoelasticity**

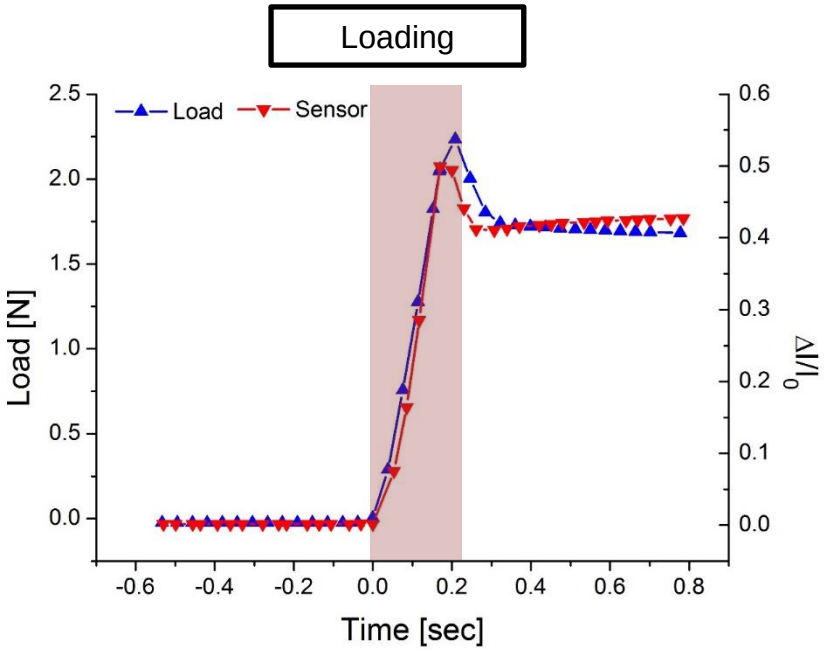


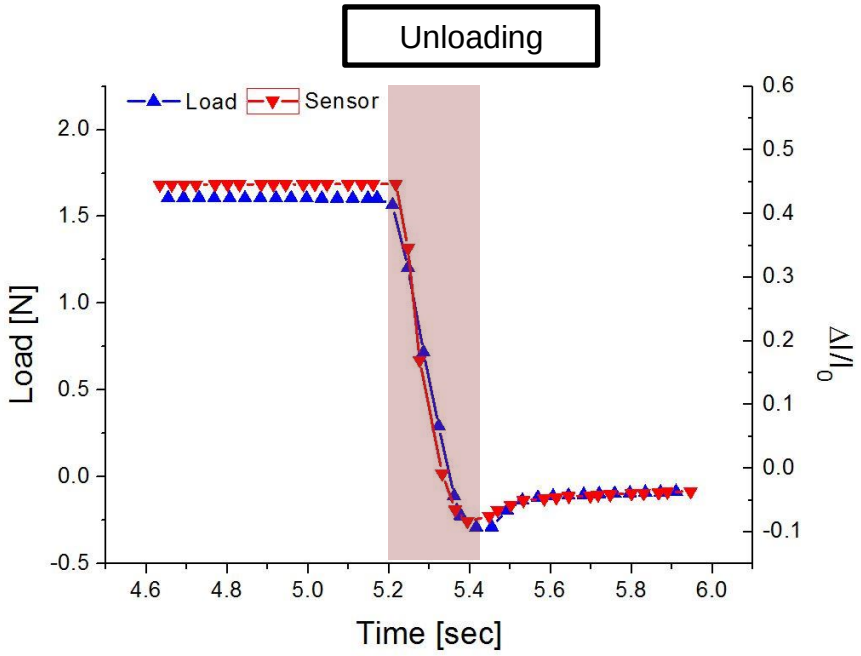

- Hysteresis profiles of loading/unloading of 10-70% of compressive strain.
- Porous elastomer structure could minimize the viscoelastic property of elastomer.

→ No significant hysteresis is observed between loading and unloading state.

# Piezoresistive Pressure Sensors using Microporous Elastomer

- **Transient Response**



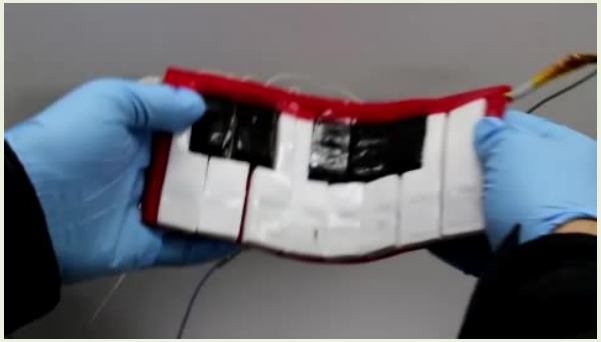

Load input (Load-cell 2580 series)

Sensor signal output

The response of the sensor has as fast response time as that of commercial load-cell.

# Application to Flexible Piano

Movie1: Flexibility



Movie 3: Sound volume control

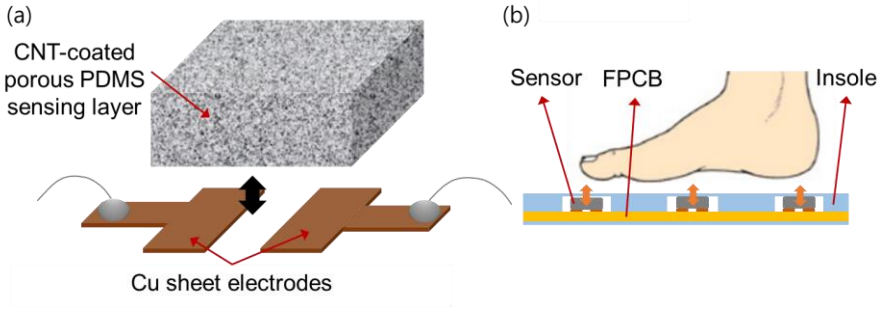
Movie 5: Harmony

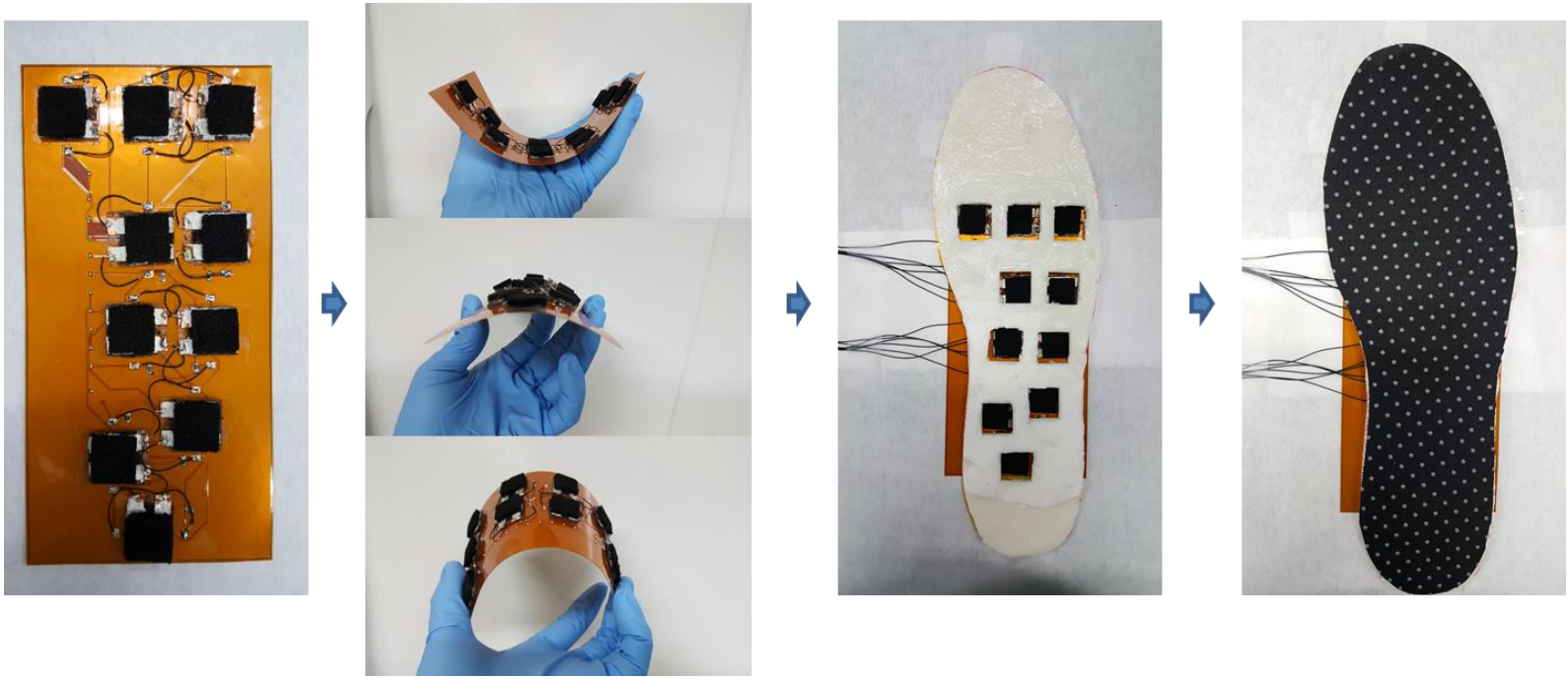
Movie 2: Do to Do

Movie 4: Fast response

Movie 6: Music rendering

# Application to Smart Shoes

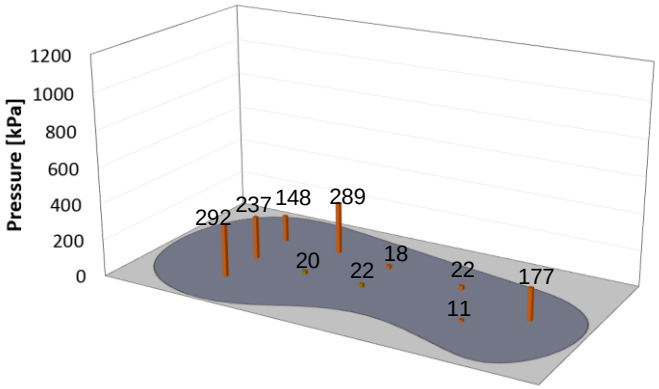


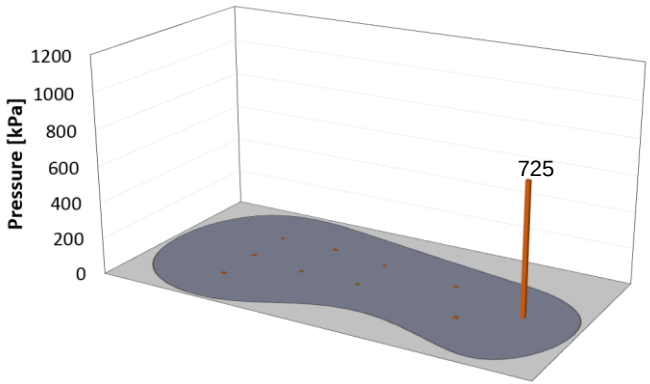
# Application to Smart Shoes

<Standing stance>

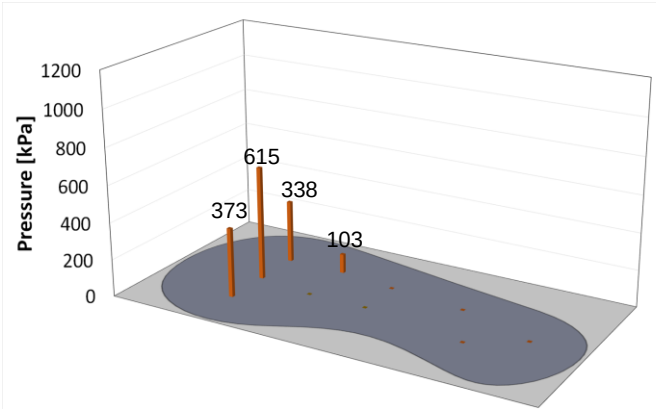
| 위치 좌표 | Average[kPa] |
|---|---|
| sensor1 | 292 |
| sensor2 | 237 |
| sensor3 | 148 |
| sensor4 | 289 |
| sensor5 | 18 |
| sensor6 | 22 |
| sensor7 | 11 |
| sensor8 | 177 |
| sensor9 | 20 |
| sensor10 | 22 |



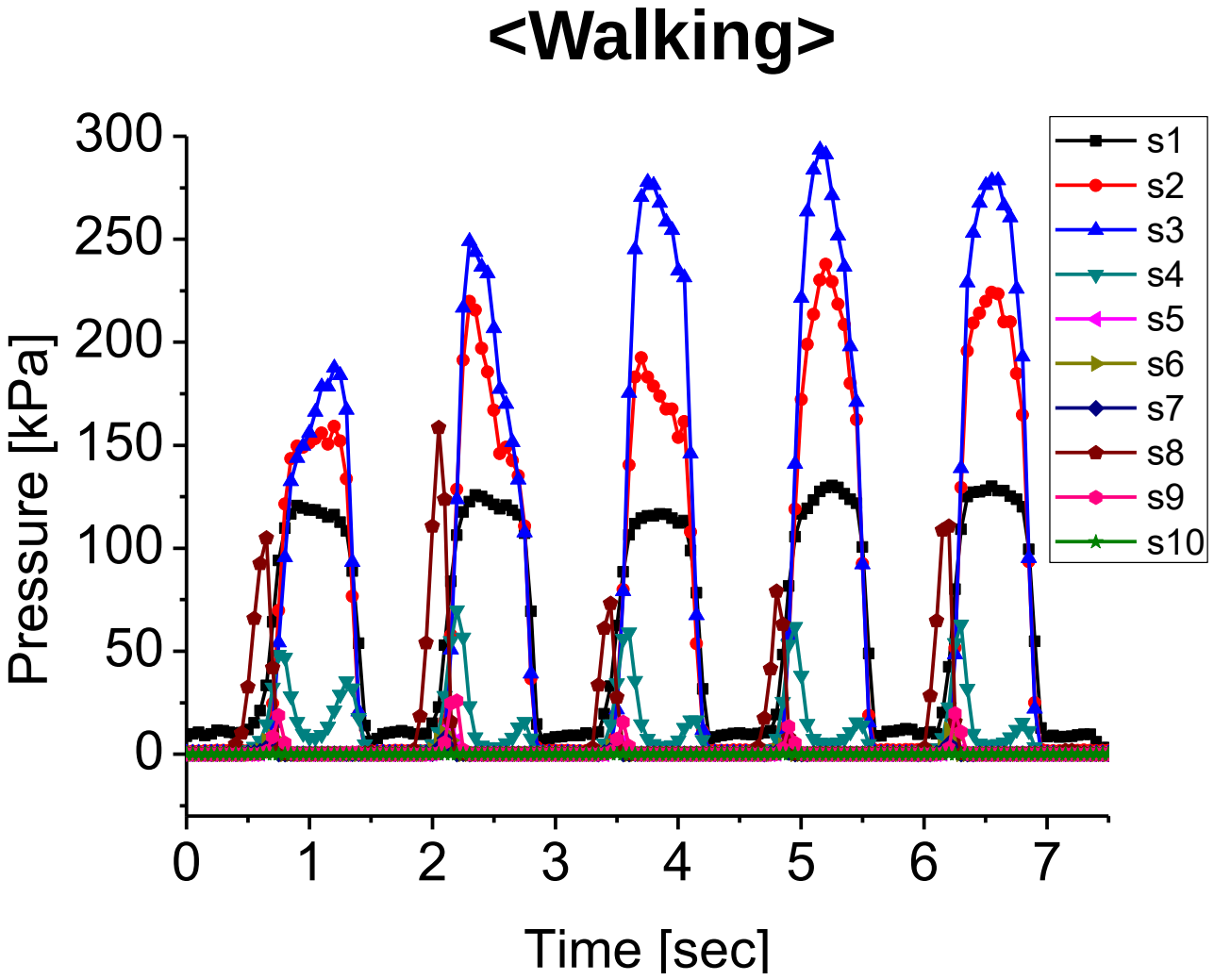

<Step starting motion>



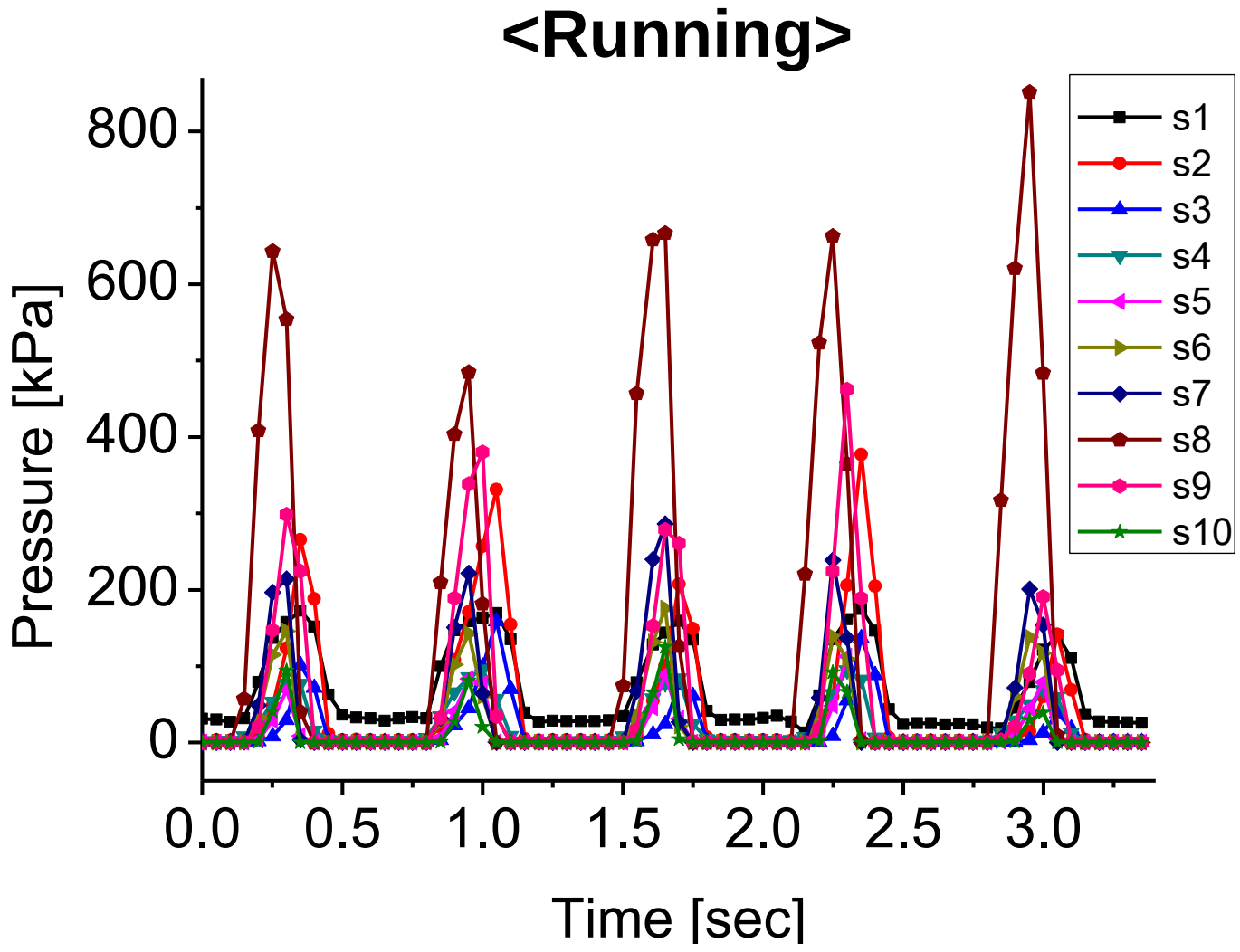

<Step end motion>



# Application to Smart Shoes



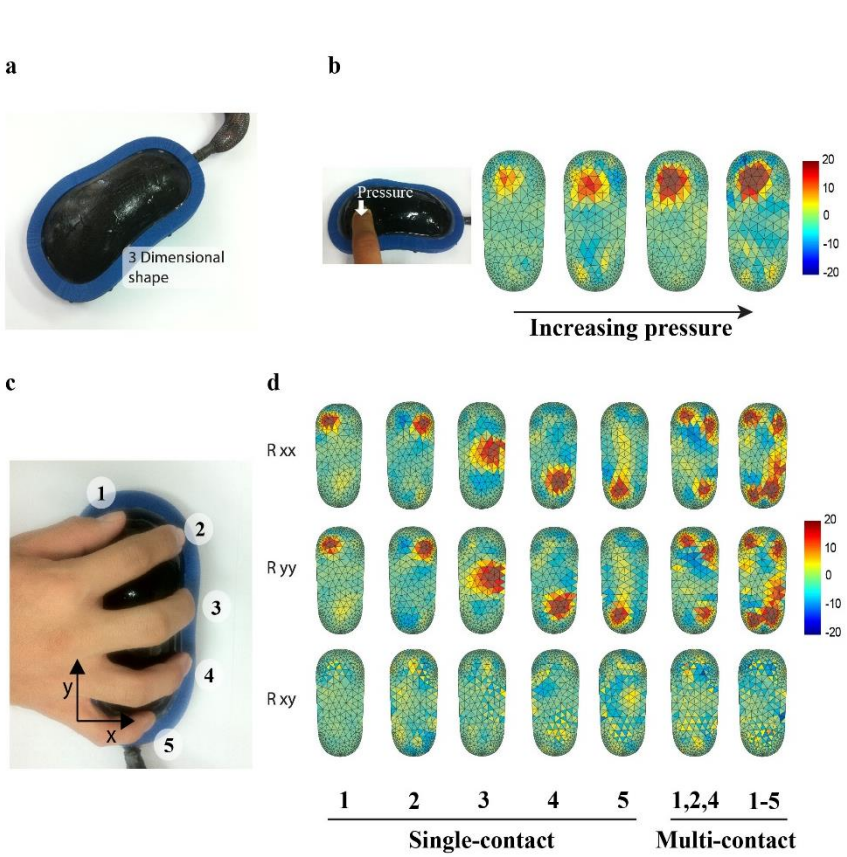
# Application to Smart Shoes

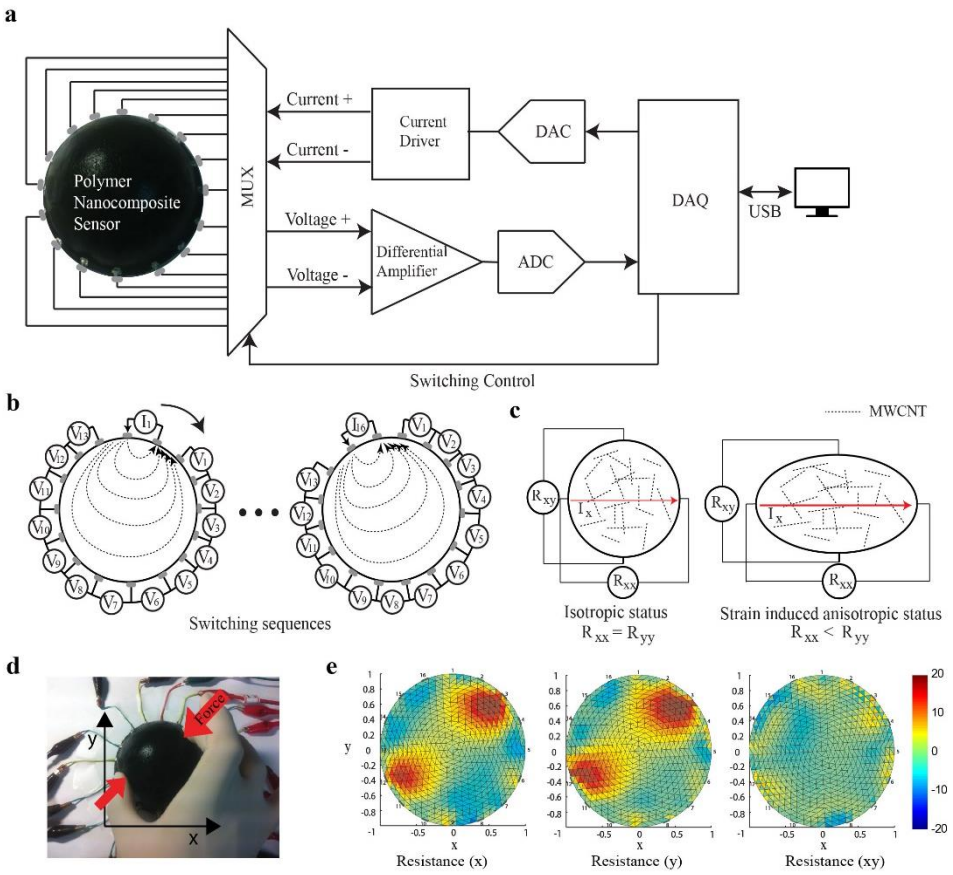


# Electrical Impedance Tomography + Flexible 3D Strain Sensor

H. Lee, I. Park, J. Kim, et al., Scientific Reports 7, 39837 (2017)

# Electrical Impedance Tomography + Flexible 3D Strain Sensor



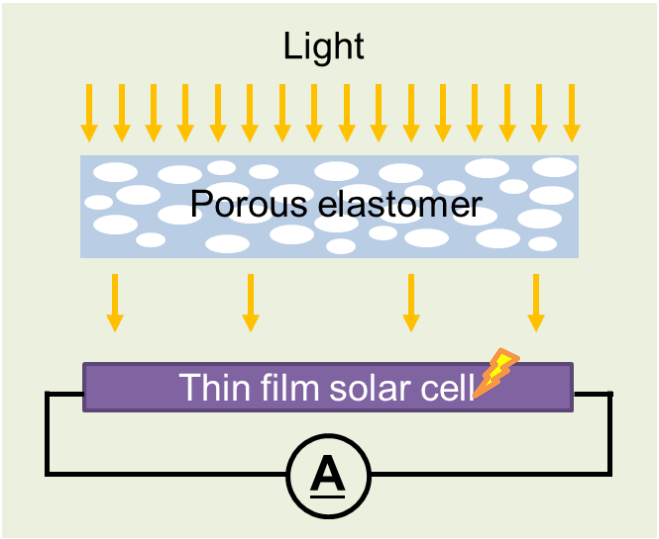

*Scientific Reports (2017),* Collaboration with Prof. Jung Kim @ KAIST

# Electrical Impedance Tomography + Flexible 3D Strain Sensor

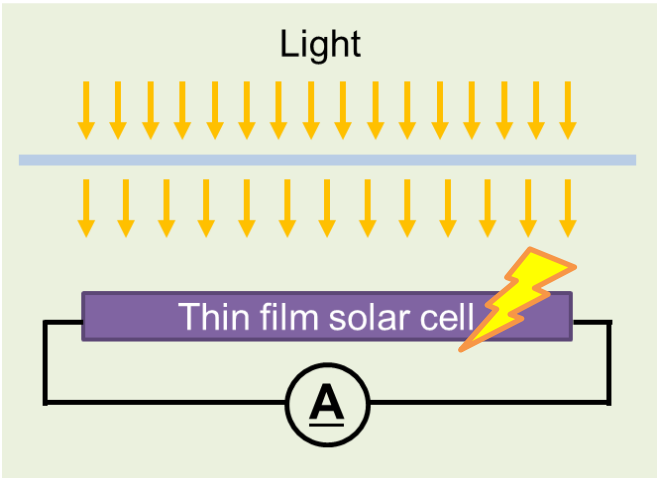
# Self-Powered Pressure & Human Motion Sensor

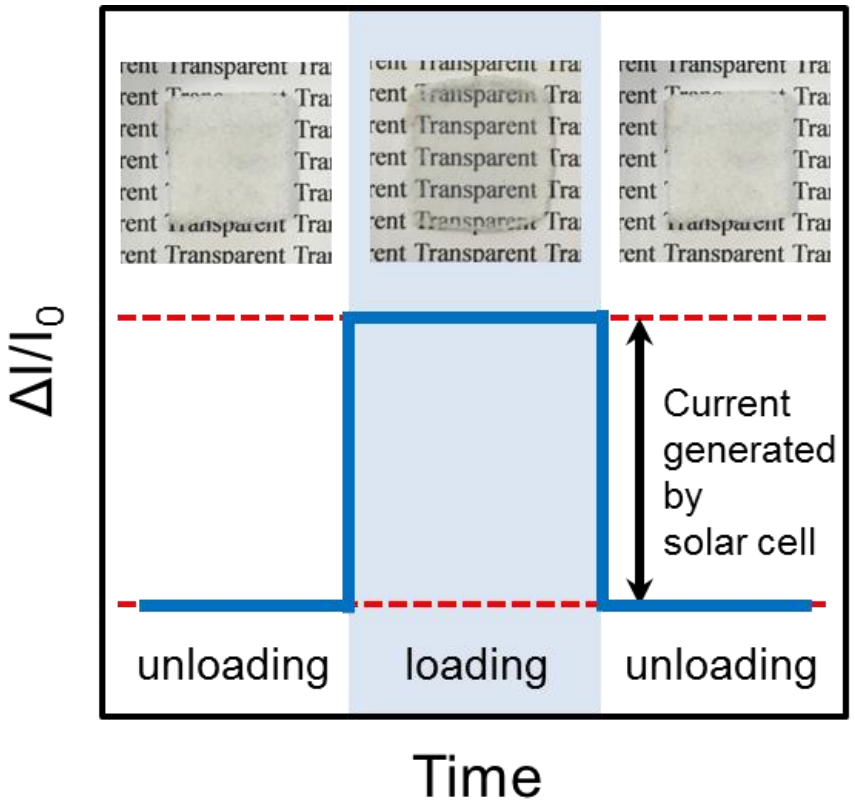
D. Kwon, I. Park, et al., in review (2018)

# Sensing Mechanism




Pressure Release



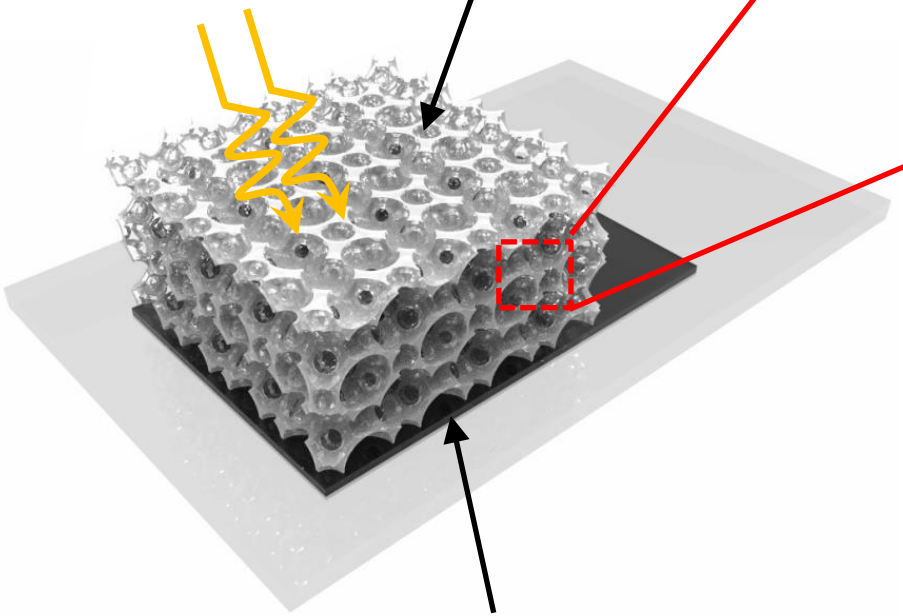




➔ Porous elastomer is used as a pressure-responsive light transmission medium.

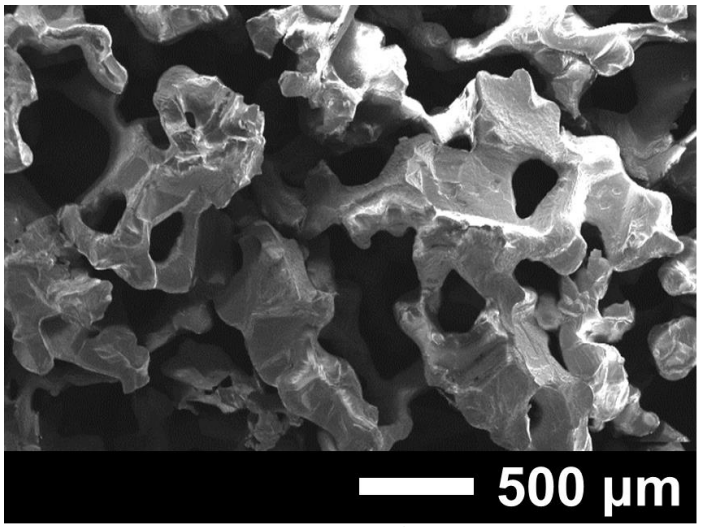
# Self-powered Pressure Sensor

Light source

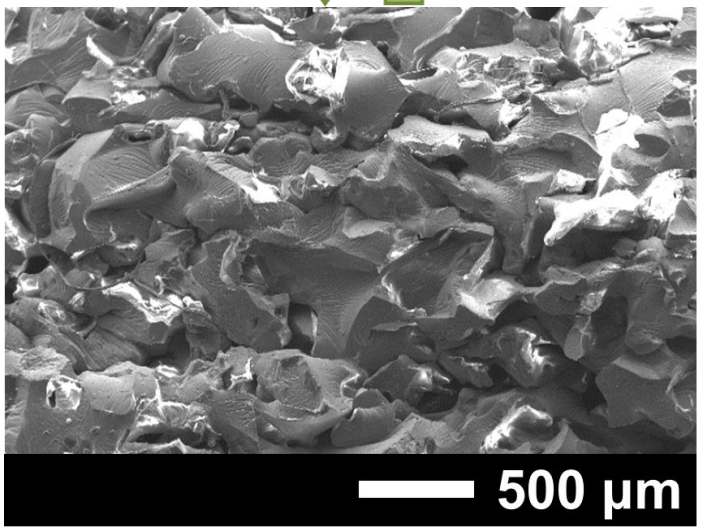
Pressure-responsive
porous Ecoflex film



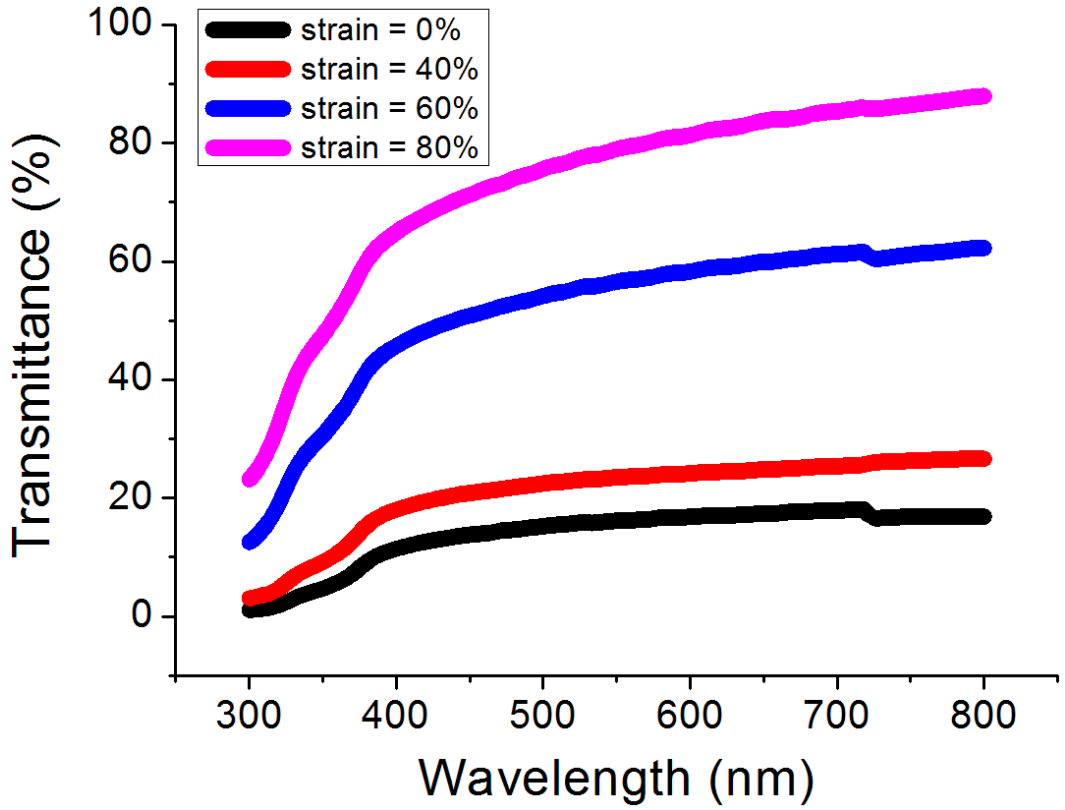
Thin film solar cell

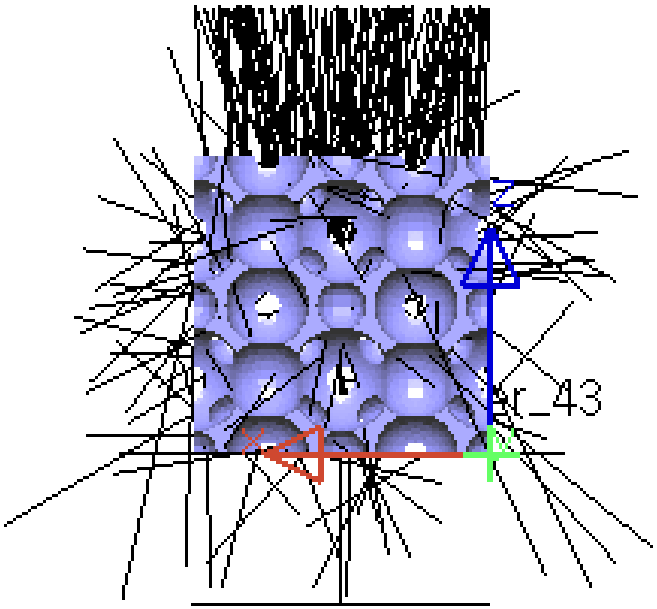



Pressure Release

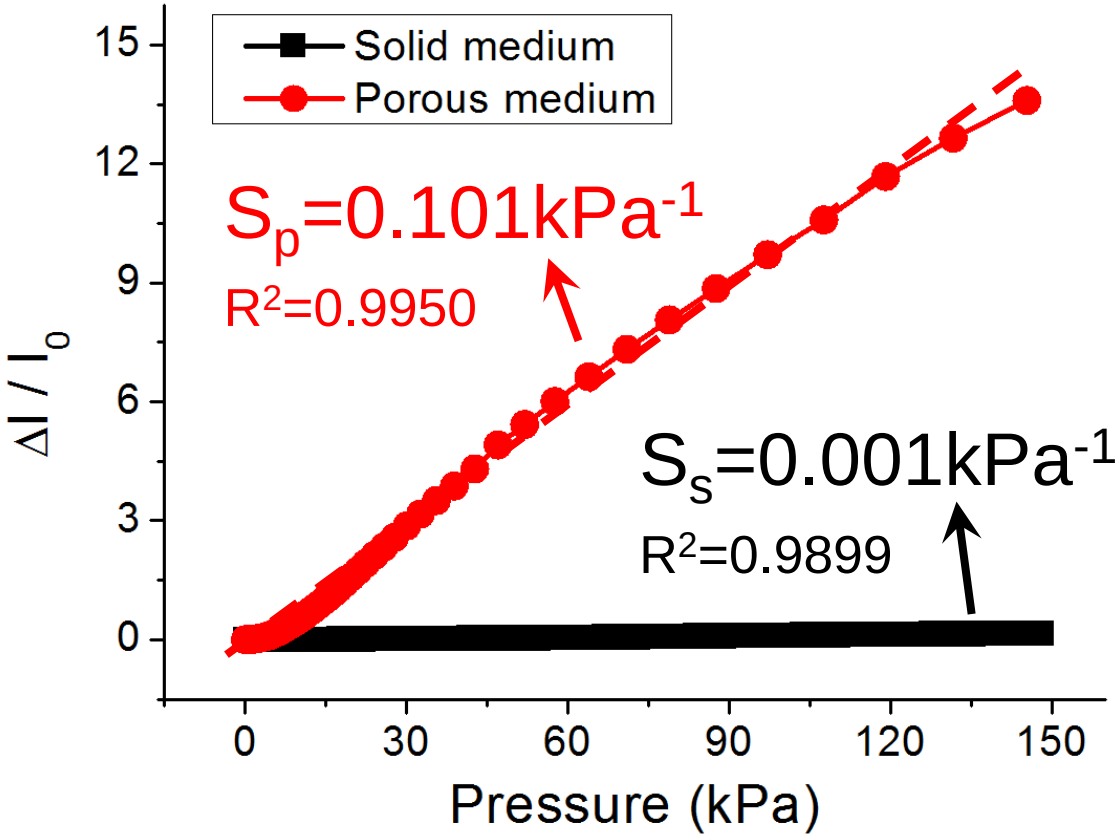


# Transmittance of Porous Ecoflex Film



# Pressure-Response Curve




➢ Sensitivity (S)

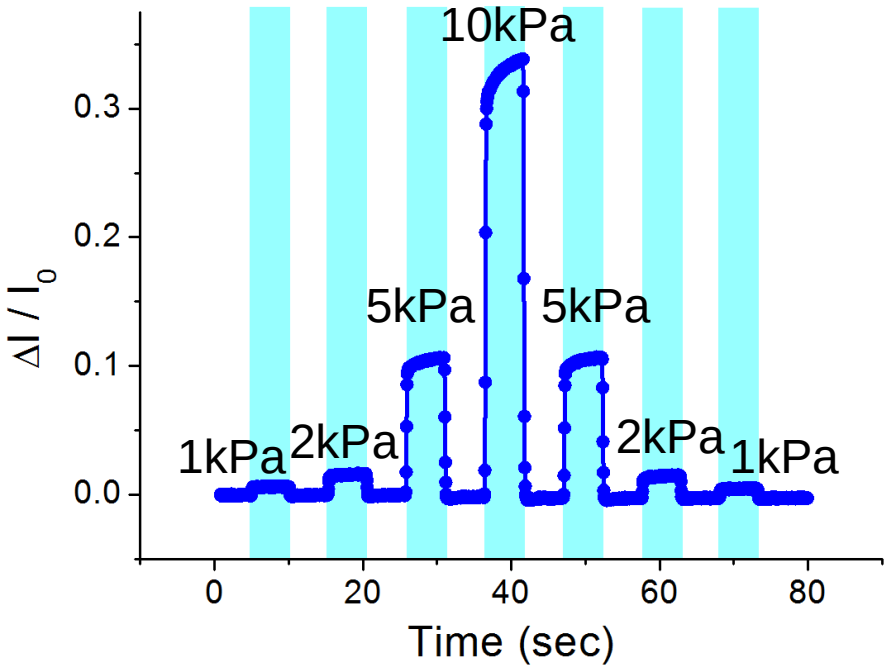
$$S = \frac{\delta(\Delta I / I_0)}{\delta P}$$

$S_p / S_s \fallingdotseq 100$

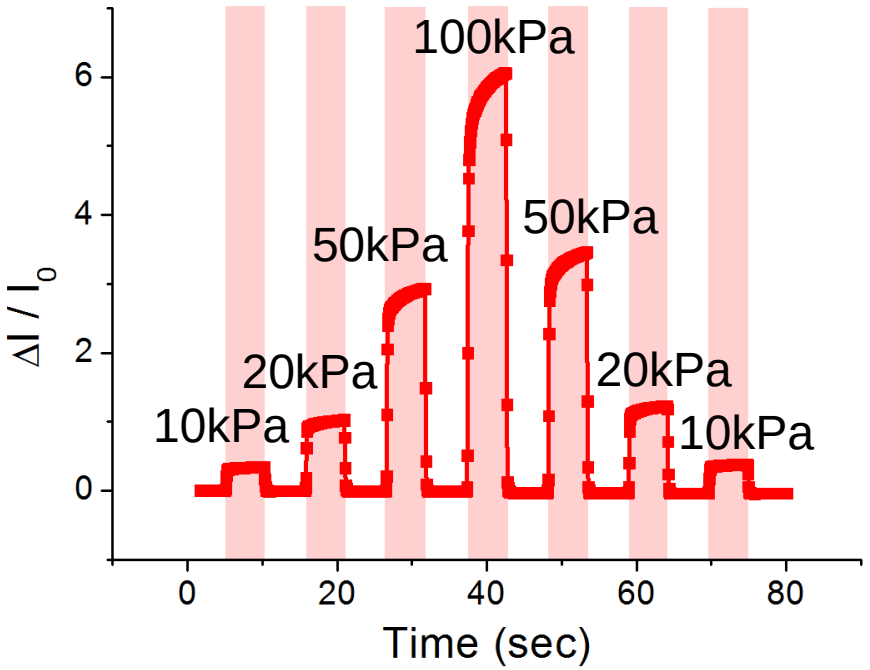
➔ High sensitivity: $S_p$=0.101kPa$^{-1}$ (~100 times higher than solid)
➔ Great linearity: $R^2$ = 0.9950
➔ Wide span: whole tactile pressure range (>100kPa)

# Dynamic Pressure Response

Regime: 1-10kPa



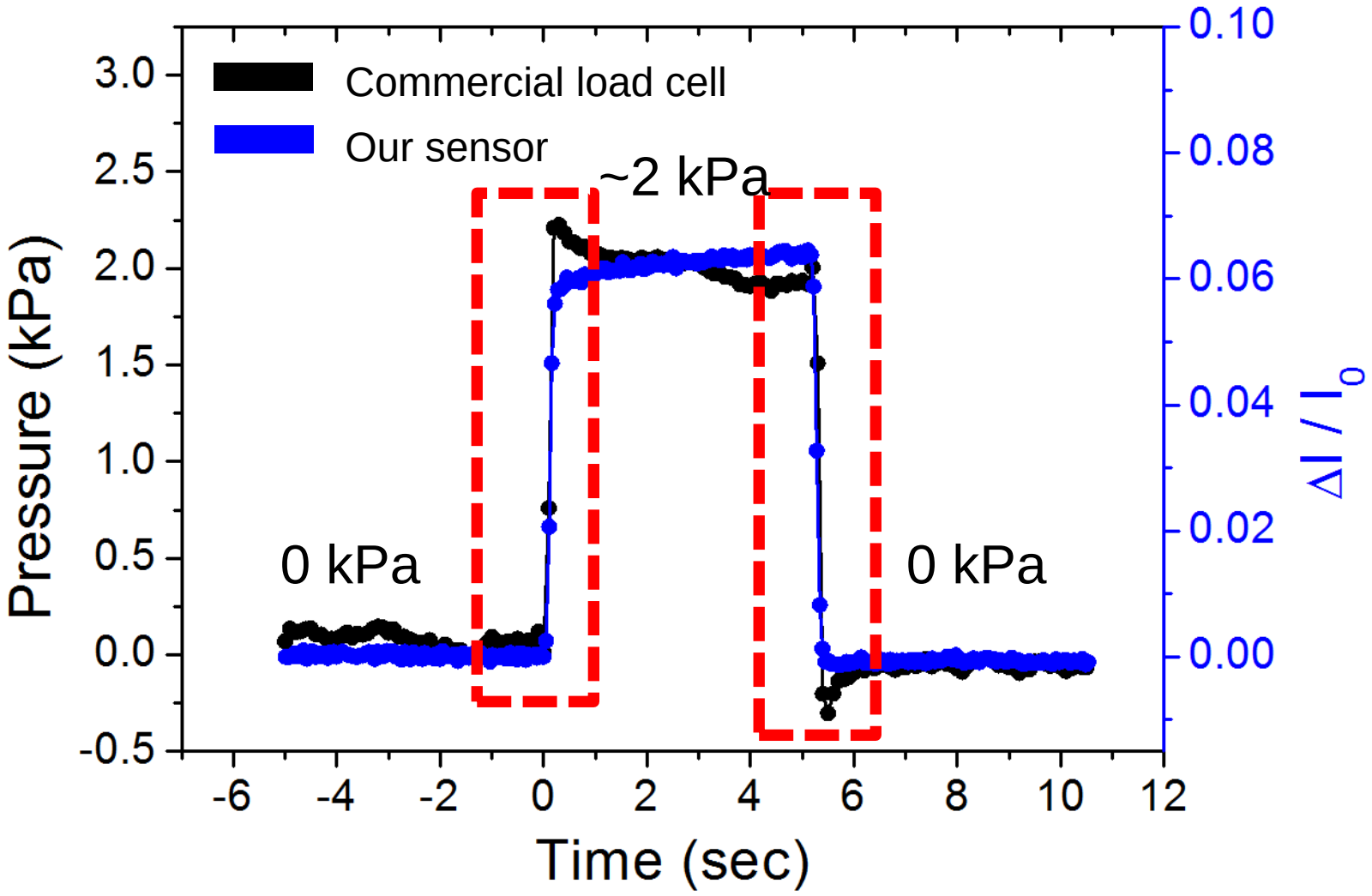

Regime: 10-100kPa



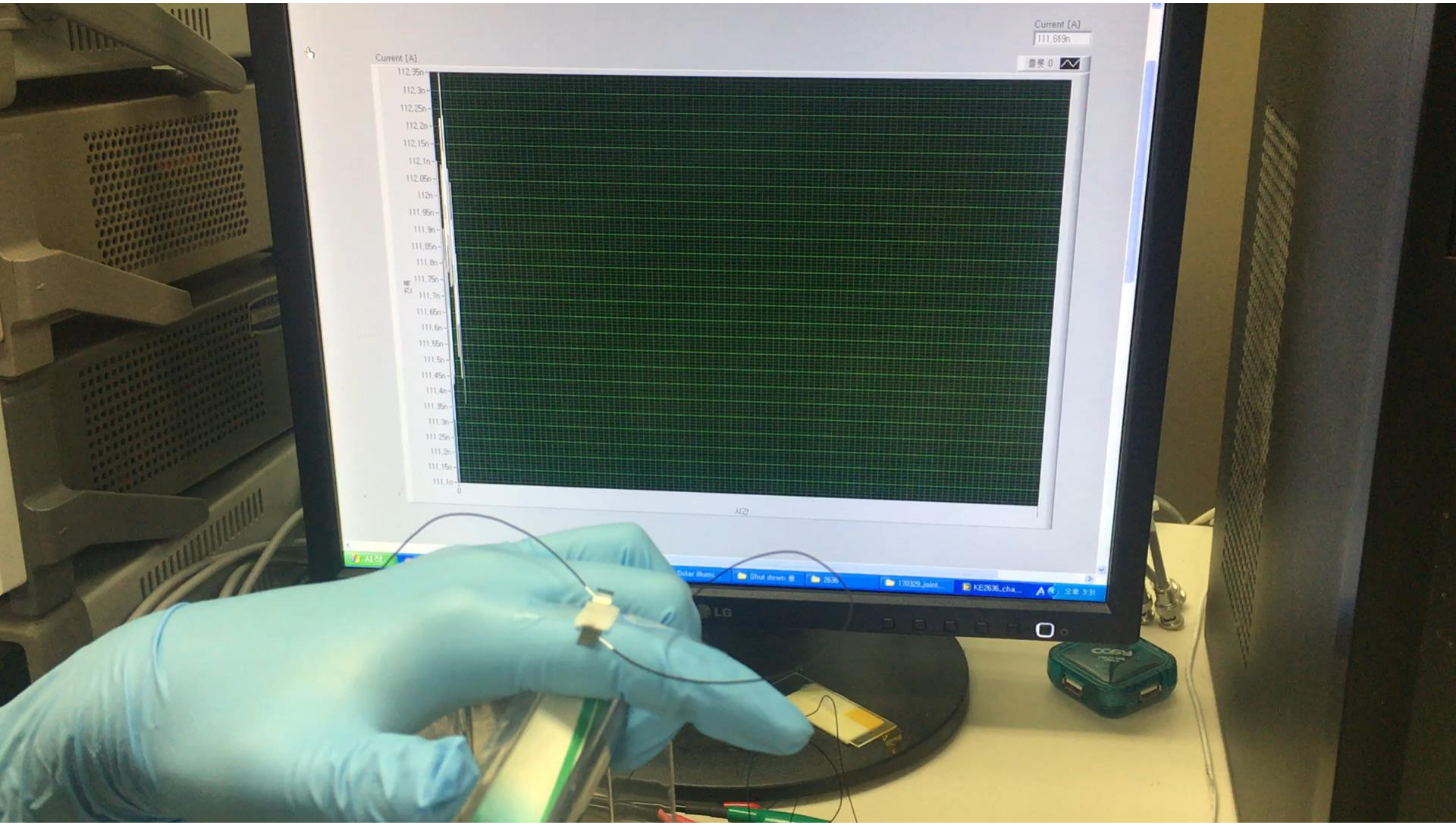

✓ Dynamic pressure response in different pressure scale

➔ Great match between input & output profile

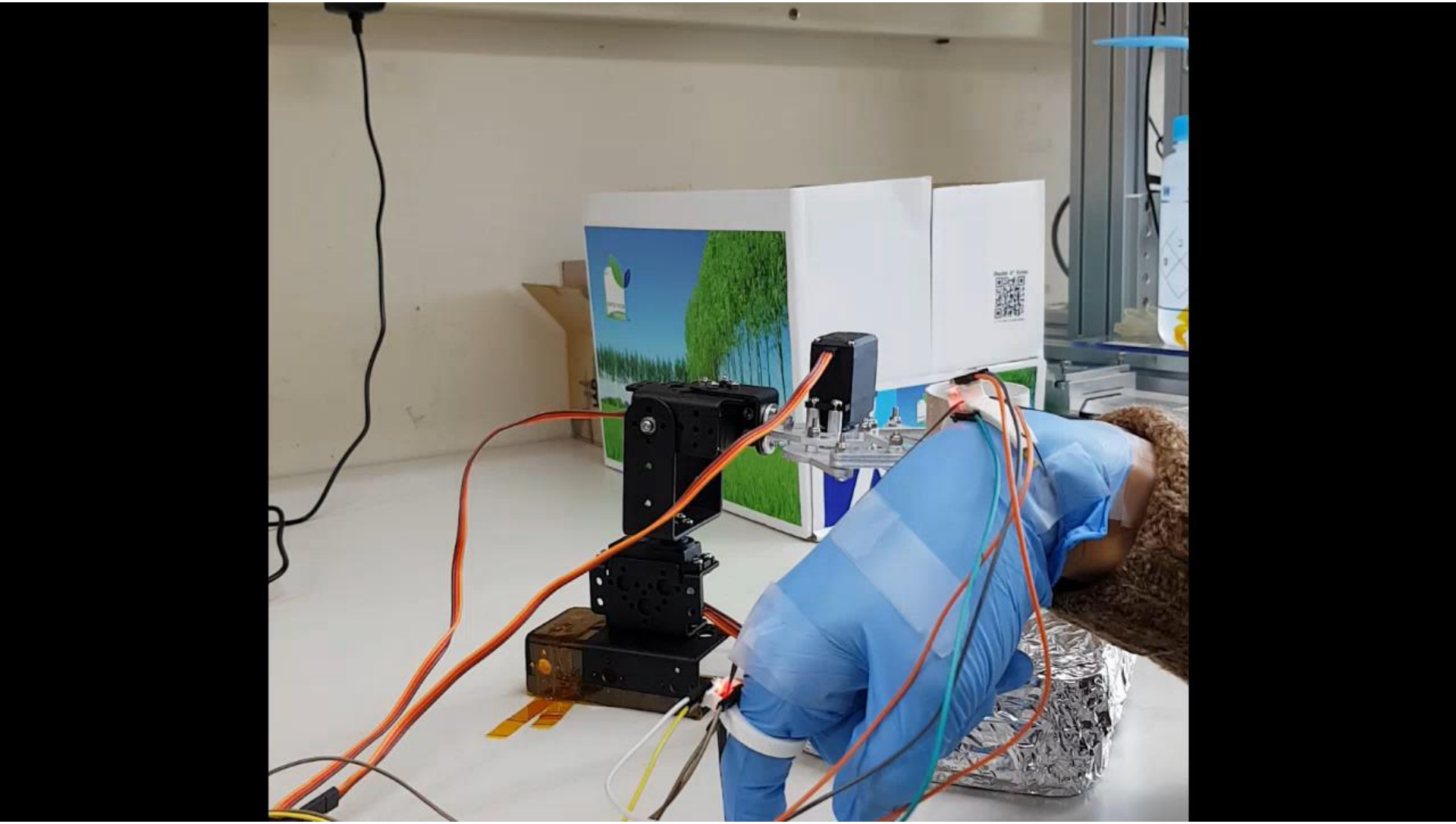
# Response Time and Recovery Time



# Detection of Joint Motion in Real-Time



# Detection of Joint Motion in Real-Time



# Summary & Outlook

- **Flexible and stretchable sensors will play a crucial role in the wearable human detection and user interface applications.**

- **Today, I have introduced the following technologies on soft-micro/nanostructure based flexible and stretchable sensors:**
  1. Stretchable strain sensors based on metal nanoparticle thin films with numerous micro-cracks
  2. Stretchable strain sensors based on metal nanowire percolation networks
  3. Stretchable strain sensor array based on carbon-nanotube network
  4. Soft pressure sensors based on high piezocapacitive properties of porous elastomer materials
  5. Soft pressure sensors based on high piezoresistive properties of porous elastomer – CNT nanocomposite
  6. Multi-contact 3D strain mapping sensor based on nanocomposite and electrical impedance tomography

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## MINT LAB members

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NRF National Research Foundation of Korea
SAMSUNG
hp
서울아산병원 Asan Medical Center
KRISO 선박해양플랜트연구소
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- Prof. Jongmin Shim (Univ. Buffalo)
- Prof. Metin Sitti (Max Planck Inst.)
- Prof. Keun Han Park (Univ. of Utah)

# Thank you!

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