Sensor Devices for Mobile and Wearable Applications

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Personalized smart healthcare technology

- Bio-potentials
- Neuro-chemicals
- Biomarkers
- Pulse
- Temp.
- $pO_2$
- Respiration
- Motion
- Pulse
- $pO_2$
- Bio-potentials
- Neuro-chemicals
- Biomarkers
- Motion
- Respiration

Sensor-integrated mobile and wearable systems which can monitor physiological and clinical parameters at point-of-care or home are promising for personalized smart healthcare technology.
Mobile and wearable POCT (point-care-testing) systems for personalized healthcare

Standalone IOT

Smartphone-integrated

dressable

accessory

skin-attachable

implantable
Mobile point-of-care testing (mPOCT) systems

**Portable PoCTs**: limits in connectivity and personalization

- iSTAT
  - Abbott Labs
- Blood analyzer
  - Alere
- Accu-Check
  - Roche
- Coaguchek
  - Roche
- Stratus troponin analyzer
  - Siemens

**mPOCTs**: advantage in connectivity (spatiotemporal mapping, epidemic demography, preventive healthcare) but limit of low accuracy and no standardization

- Glucometer
  - iHealth
- LFA reader
  - CELLMIC
- SAW biosensor
  - OJbio
- Heart monitor (ECG)
  - Alivecor
Fluorescence imaging-based high accuracy biosensing for mPOCT

ELISA is a gold standard in immunoassays

- Spectrophotometer
- PMT
- Smartphone
- CMOS Image Sensor (CIS)

Rough exposure time control / low SNR

Issue: Low Accuracy
Smartphone-based “seesawed” fluorescence imaging for high accuracy apta-assay

False-negatives (FN) ↓  
Sensitivity (TP/(FN+TP)) ↑

W. Lee et al., Biosensors and Bioelectronics 94(2017), 643
Smartphone-based “seesawed” fluorescence imaging for high accuracy apta-assay

\[ r^2 = 0.9888 \]
\[ r^2 = 0.9842 \]

Sensitivity
1 - Specificity

ELISA
Portable device

\( M \ E \ F( A g) \rightarrow S N R \uparrow \)

Prototyping of using 3D printing
Calibration curve for 17\( \beta \)-estradiol with smartphone fluorescence microscope

Statistical accuracy test of target analyte spiked wastewater

<table>
<thead>
<tr>
<th></th>
<th>Area under ROC curve</th>
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<tbody>
<tr>
<td>ELISA</td>
<td>0.956</td>
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<tr>
<td>Mobile biosensor</td>
<td>0.922</td>
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</tbody>
</table>
Smartphone-based fluorescence imaging of pathogenic bacteria for on-the-spot detection

Sample volume: 100 μL

10 CFU/mL (single bacterial cell in 100 μL) detectable

But, typical target concentration in blood (sepsis) and food safety: 1~10 CFU/mL

S. Shrivastava et al., Biosensors and Bioelectronics, 95 (2018)
Fluorescence imaging-based IOT-enabled on-the-spot POCT system

- Fluorescence imaging based biosensing
- Bacteria separator/concentrator
- Probes for bacteria and toxin
- Cartridge integrated with MEF substrate

IOT-enabled system
Skin-attachable sensor patches for wearable electronics

**Accessory:** non-invasive but limit in **unobtrusive** monitoring

**Patch:** non-invasive and **unobtrusive** monitoring, high SNR due to conformal contact with skin

Biostamp MC10

S-patch Samsung
What can be measured by skin-attachable sensor patches?

Engineering of skin-attachable sensor patches

**Stretchable materials**
- Sensing materials, electrodes, electrochemical electrodes, dry biopotential electrodes

**Devices**
- Stretchable sensors, energy harvesters, energy storage devices

**Packaging**
- Substrate, dry adhesives, interconnect, encapsulation

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**Stretchable materials & devices**

- **Substrate**
- **Chemical sensor**
- **Biosensor**
- **Physical sensor**
- **Dry adhesive**
- **Selective membrane**
- **Stretchable interconnect**
- **Encapsulation**

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**Sensor-integrated systems**

**Circuits**
- Signal acquisition, power management, data handling

**S/W**
- Applications, big data, AI

**Clinical**
- New applications, clinical evaluation, services
Stretchable physical sensors for skin-attachable patches

- **Pressure sensor**

- **Strain sensor**

- **Temperature sensor**

- **Self-powered stretchable piezoelectric sensor**

- **Self-powered strain sensor**
  - ACS Nano 9, 8801 (2015)

- **UV sensor**
  - ACS Appl. Mater. Interfaces. 9, 3598 (2017)

- **Tem. & Strain sensor**

- **Supercapacitor**

- **Magnetometer**
# Approaches for stretchability

<table>
<thead>
<tr>
<th>Materials</th>
<th>Strategies</th>
<th>Designs</th>
<th>Process methods</th>
<th>Stretchable direction</th>
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</thead>
<tbody>
<tr>
<td><strong>Intrinsically stretchable components</strong></td>
<td>Using intrinsically stretchable materials</td>
<td><strong>Elastomeric nanocomposites</strong></td>
<td>Spin-coating, printing, spraying, electropinning</td>
<td>Omni-direction</td>
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<tr>
<td><strong>Geometric engineering of compliant materials</strong></td>
<td>In-plane, geometric engineering</td>
<td>Serpentine routing</td>
<td>Patterning</td>
<td>Uniaxial</td>
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<tr>
<td></td>
<td>Out-of-plane, geometric engineering</td>
<td>Wavy structure</td>
<td>Pre-stretching and release</td>
<td>Uniaxial, Biaxial</td>
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<tr>
<td></td>
<td>Island-bridge</td>
<td>Transfer printing</td>
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<td>Biaxial</td>
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<tr>
<td></td>
<td>Imperceptible</td>
<td>Transfer on pre-strained ultrathin substrate</td>
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<td>Uniaxial</td>
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<tr>
<td></td>
<td>Out-of-plane, 3D structuring</td>
<td><strong>Microstructured pattern</strong></td>
<td>Soft lithography spin coating, printing, spraying</td>
<td>Multi-direction, but not fully stretchable</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td>Omni-direction</td>
</tr>
</tbody>
</table>

*References*:
- *ACS Nano* 2015, 9, 6252
- *Adv. Sci.* 2015, 2, n/a
Approach 1: Intrinsically stretchable elastomeric nanocomposites

Nanomaterials

- Thin films
- Sheets
- Nanofibers
- Microfibers

Elastomer

- Transparent
- Stretchable

Piezoelectric
Pyroelectric
Piezoresistive
Chemoresistive
Thermoresistive
Photoresponsive
Electroactive
Stretchable, transparent and ultrasensitive strain sensor for emotion detection

PU-PEDOT:PSS (top)
SWCNT
PU-PEDOT:PSS (bottom)
PDMS

Transmittance (%)
Wavelength (nm)

Resistance change, \( \Delta R/R_0 \) (%)
Time (sec)

Before cyclic stretching
After cyclic stretching
1000 cycles, up to 20%

Gauge Factor (GF)
Strain (%)

Roh et al., ACS Nano 11 (2015) 6252
Stretchable, transparent and ultrasensitive strain sensor for emotion detection

(a) forehead
(b) near the mouth

Laughing

Resistance change, $\Delta R/R_0$ (%)

<table>
<thead>
<tr>
<th>Time (sec)</th>
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<th>5</th>
<th>10</th>
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<tbody>
<tr>
<td>Laughing</td>
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Crying

Resistance change, $\Delta R/R_0$ (%)

<table>
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<th>Time (sec)</th>
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<th>5</th>
<th>10</th>
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<tbody>
<tr>
<td>Crying</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Stretchable, transparent, ultrasensitive, self-powered strain sensor for activity monitoring

Evaluation

Strain: 0%

Strain: 100%

Hwang et al., ACS Nano 9 (2015) 8801, collaboration w/ prof. S.W. Kim
Stretchable, transparent, ultrasensitive, self-powered strain sensor for activity monitoring

Electrical performance of integrated devices during stretching as 10% of strain

TENG

SC

Triboelectric nanogenerator

Supercapacitor

Strain sensor
Stretchable, transparent, ultrasensitive, self-powered strain sensor for activity monitoring.
All-elastomeric transparent and stretchable multi-sensors for activity monitoring


Reduced graphene oxide-PU channel, PU gate dielectric and PEDOT:PSS-PU electrode
All-elastomeric transparent and stretchable multi-sensors for activity monitoring

Monitoring thermal distribution by FET temperature sensor array

TS-FET array

Normalized current ($I_{DS}/I_{DS0}$)

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<thead>
<tr>
<th>Row</th>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
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<td>4</td>
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</tbody>
</table>
All-elastomeric transparent and stretchable multi-sensors for activity monitoring

Simultaneous monitoring skin temperature and muscle movement during drinking hot water
All-elastomeric transparent and stretchable multi-sensors for activity monitoring

Simultaneous monitoring skin temperature and muscle movement during workout
Approach 2: Mogul-patterned elastomeric substrate for stress-relieving

A versatile substrate for stretchable electronics

Approach 2: Mogul-patterned elastomeric substrate for stress-relieving

- Omniaxially stretchable and stress of the layers are readily relived.
- Conventional processing (CVD, PVD, ALD, spin coating, spray coating, printing etc) can be used to form the layers directly on the substrate
- Multi-layer stacking is possible by forming layers directly on the 3D micro-pattern
Omniaxially stretchable R-GO gas sensor on mogul-patterned elastomeric substrate

**Structure**

- Active Layer (R-GO)
- Electrode (Au)

**Stability of Au electrode (70nm)**

After 1,000 cycles of stretching in x- and y-directions at 50% strain
Omniaxially stretchable R-GO gas sensor on mogul-patterned elastomeric substrate

Investigation of electrical stability

Electrical stability of Au electrode

[ Dynamic test ]

[ Cyclic test ]

Electrical stability of chemical sensor

[ Dynamic test ]

[ Cyclic test ]

NO₂ sensing

Under stretched condition

Response, \( \Delta I/I_0 \) (%)

Time (s)

No strain
30% strain

Gas OFF

2.5ppm
5ppm
10ppm
25ppm
Omniaxially stretchable piezoresistive pressure sensor on mogul-patterned substrate

Device Structure

- Mogul-patterned PDMS
- PEDOT:PSS-SWCNTs
- Ag paste

Pressure responsivity

- Unstretched state
- Under 30% stretching state

Stability under stretching

- Materials stability under stretching
- Device stability under stretching

Omniaxially stretchable piezoresistive pressure sensor on mogul-patterned substrate

Demonstration: Tremor detection

- Skin area
- Vibration detection using the device
- FFT (fast Fourier transform)

Demonstration setup

- Experimental mixer for vibration
- Vibration detection using the accelerometer in smartphone
Skin elasticity evaluation

Cutometer

Ballistometer

Measurement scheme

Omniaxially stretchable piezoresistive pressure sensor on mogul-patterned substrate

Relative skin elasticity

Skin elasticity evaluation

Cutometer

Ballistometer

Measurement scheme

Skin elasticity evaluation

Cutometer

Ballistometer

Measurement scheme

Skin elasticity evaluation

Cutometer

Ballistometer

Measurement scheme

Skin elasticity evaluation

Cutometer

Ballistometer

Measurement scheme
Omniaxially stretchable self-powered piezoelectric sensor

Key Issues for Stretchable Sensors
- Low stretchability
- Poor stability of electrode under stretching
- Complicated process
- High cost

Stacked mat of BT NPs-PU nanocomposite and P(VDF-TrFE) nanofibers on stress-relieving mogul-patterned elastomeric substrate

Omniaxially stretchable self-powered piezoelectric sensor

Stability at 30% stretching strain

Walking Pattern Detection

Charge Storage during walking

Open Circuit Voltage-Voc (V)

Fast Movement

Slow Movement

Fast Movement

Charge Storage during walking

Voltage (V)

Time (sec)

0 700 1400 2100 2800 3500
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

0 700 1400 2100 2800 3500
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

Short Circuit Current-Isc (nA)

Time (sec)

1000 Cycles 3000 Cycles 5000 Cycles 7000 Cycles 9000 Cycles

Short Circuit Current-Isc (nA)

Time (sec)
Disposable stretchable biosensor patches for \( \mu \text{POCT} \)

- Electrochemical enzyme biosensors
- Electrochemical and optical immunosensors

Sweat, ISF

Wound fluid
Disposable stretchable label-free electrochemical immunosensor for wound monitoring

- **Cyclic voltammograms** of a device under a) a non-stretched and 10, 20, and 30% stretched condition, b) without twisting and under twisting, and c) before cyclic stretching and after cyclic stretching 1000 times at 30% strain

- **Differential pulse voltammograms** of immunoreaction of TNF-α protein under 0 % (d) and 30 % (e) strain and calibration curve (f) in human serum
Perspectives

- Efforts toward the improvement of stability and reliability of the sensing nano-materials are required for real applications.
- Sensor-integrated systems need to be developed by considering the specific needs and service scenario.
- Collaborative research is essential for success.
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