

Self-Powered Multi-Modal Wearable Sensor Systems

*Veena Misra, Director, NSF ASSIST ERC Center
Distinguished Professor of ECE, NC State University*

*EnerHarv, 2022
assistcenter.org*



NC STATE UNIVERSITY



Justification for continuous monitoring and energy harvesting

- ▶ Need for vigilance due to risk
 - ▶ e.g., cardiac health, seizures, strokes Alzheimer's and dementia, falls, and more
- ▶ When impact of sensor parameters are not immediately known or appreciated
 - ▶ Role of environment
 - ▶ New correlations
- ▶ Understanding mental stress and context
- ▶ User constraints
- ▶ Battery weight
- ▶ Large deployment of Sensors
 - ▶ Agriculture, bridges, oceans, etc.
- ▶ Abundant wasted or available energy
 - ▶ Industrial settings, outdoor solar





From Valencell

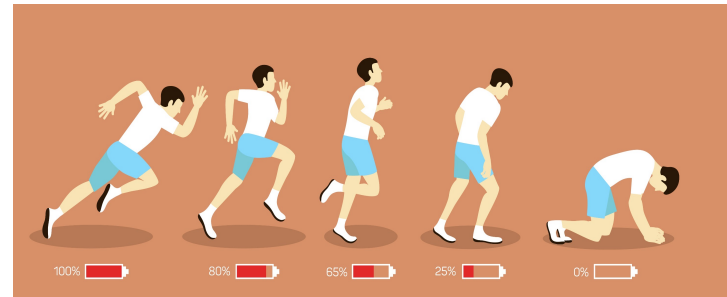
4 SSIST Long term monitoring requires disruptive powering

Ultra low power electronics/sensors

Directed energy



Self-powered operation for **vigilance**



Self-powered operation for **vigilance**

Power
Generation



Power
Consumption

Harvested and
Stored Power

Low Power
Electronics and
Sensors

Wearability and Data

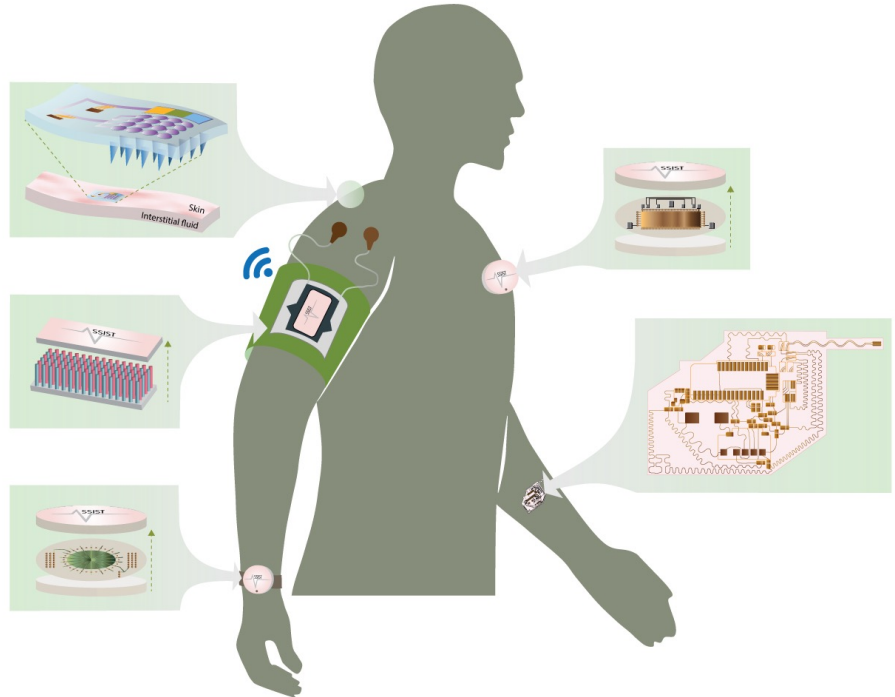


Advanced Self-Powered Systems of Integrated Sensors and Technologies

ASSIST's Always-on Wearable Platforms

Longitudinal, personalized and enabling new digital biomarkers

- **Self-powered**
- **Wearable, wireless and comfortable**
- **Physiological, biochemical and environmental sensor**
- **Informative and continuous data**



ASSIST's Engineered System

Body Heat
Body Motion
Solar
RF
Magnetic
Biochemical

Gases, VOCs,
PM

Vitals,
biochemical

Supercaps
Batteries

Flexible
High efficiency

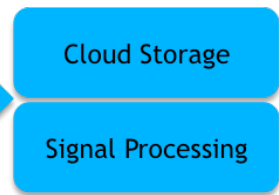
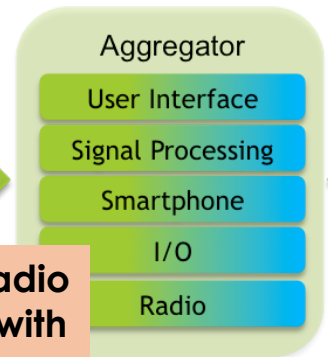
Low power radio
compatible with
phones

Low power SoC
and AFE

Wearable form
factors
Human factors



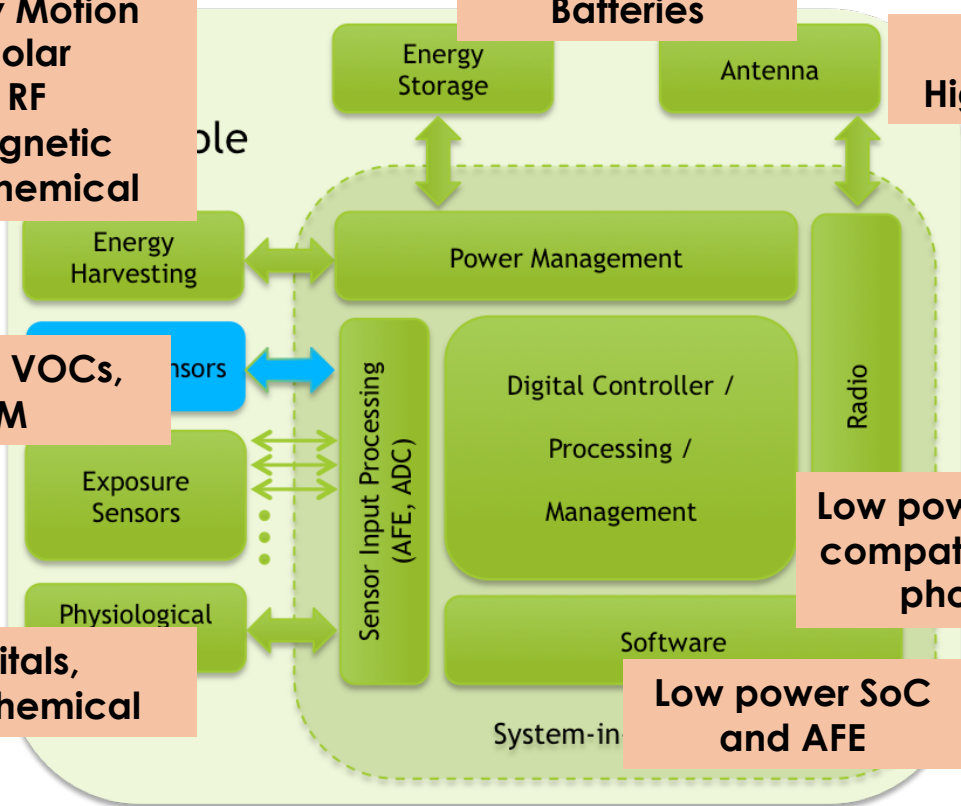
Medical / Off Body



On node/off-
node Data
analysis

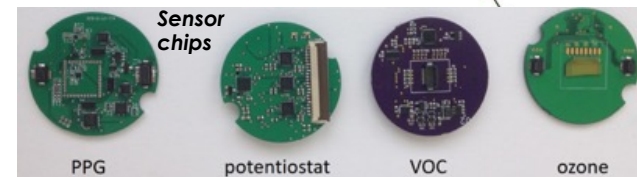
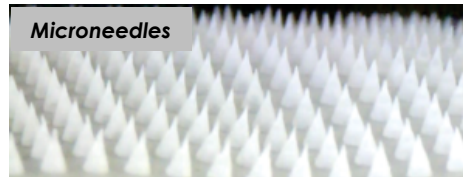
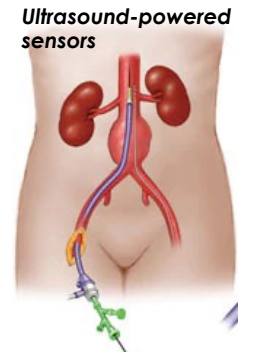
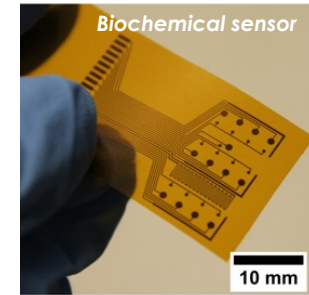
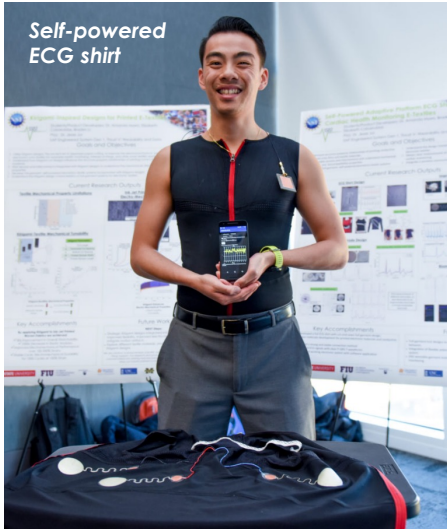
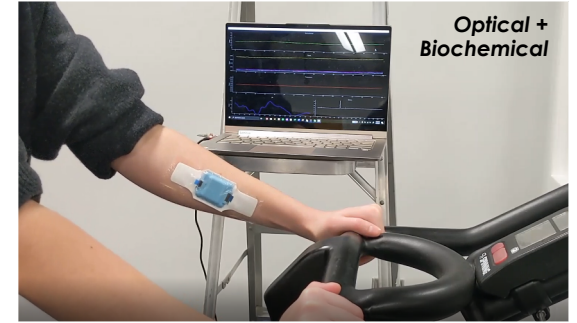
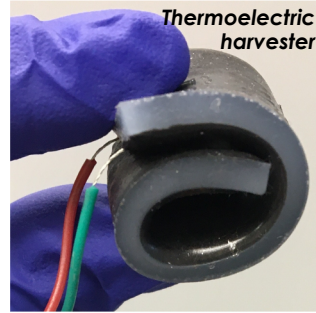
ASSIST Developed

Modified Consumer
Devices



ASSIST Research Areas

1. Energy Harvesting & Storage
2. Low Power Sensing
3. Low Power Electronics
4. E-textiles
5. System Integration & Data



Energy Harvesting Technology

Body Heat

- Flexible thermoelectrics

Body Motion

- Piezoelectrics
- Flexoelectrics
- Liquid metal

Ambient RF

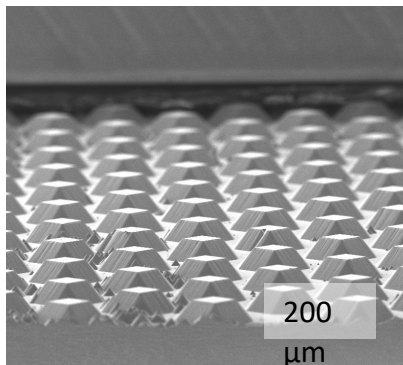
- Ambient Wi-Fi
- Novel antennas on textiles

Biofuels

- Passive sweat collection
- Novel enzymes for lactate and glucose conversion

Energy Storage

- Li ion capacitors
- High Energy Density
- Low leakage



Low Power Multi-Modal Sensors



Bioelectric

- Low power ECG
- Low power EDA
- Dry electrodes

Biophotonic

- Low power PPG
- Multi-wavelength LEDs
- Heart rate, respiratory rate, blood oxygen, sleep, blood pressure

Inertial

- Activity
- Coughing

Biochemical

- New enzymes for lactate, glucose, and uric acid
- Passive sweat/interstitial fluid collection

Environmental

- Gases for air quality and breath
- VOCs for air quality and breath
- Particulate matter

Multimodal sensors and their correlation



HEART DISEASE



CANCER



CHRONIC LUNG DISEASE



STROKE



ALZHEIMER'S DISEASE

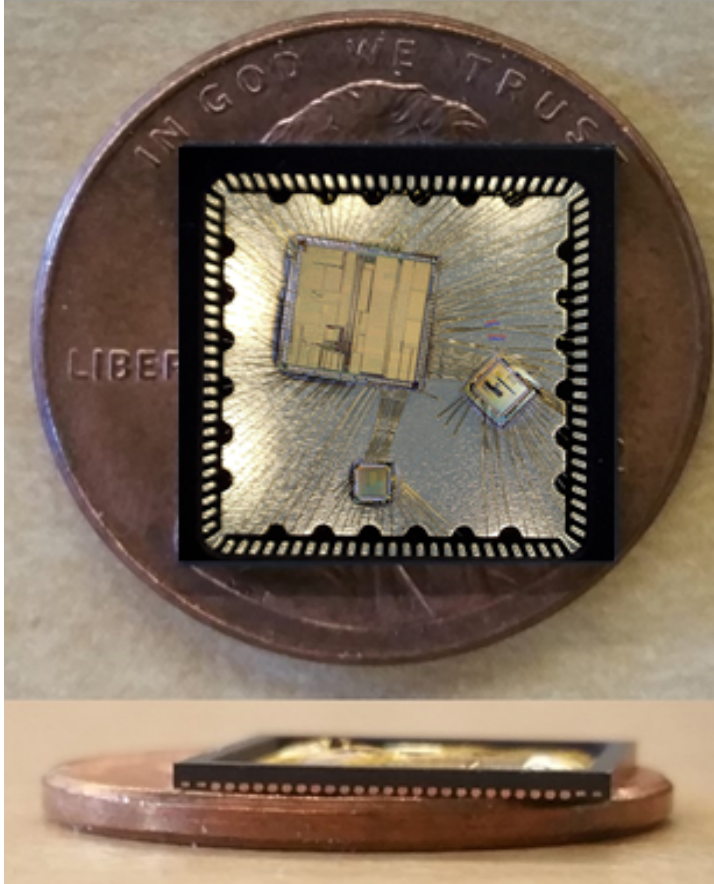


DIABETES



CHRONIC KIDNEY DISEASE

Low-Power Electronics: Multi-Chip Solution



System on Chip

- 566 nW total power
- RISC-V

Analog Front End Chip

- ECG, PPG, RR, Ozone
- Respiration and ECG always on
- RR triggers PPG/Ozone

Energy Management Chip

- Multi-modal: TEG/PV/Piezo
- Four custom voltages outputs

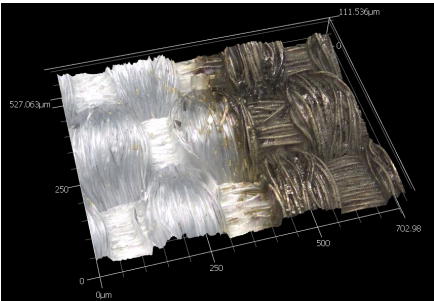
Custom Radio Chip

- BLE 4.0 Compliant
- 300 uW total power
- -69dBm sensitivity and 500Kb/s

Flexible and Wearable Technologies

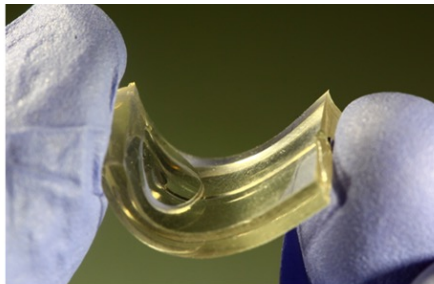
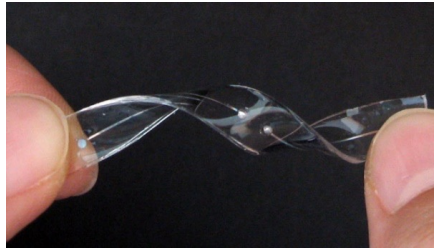
Smart textiles

- Printed electrodes
- Smart textile designs



Liquid metals

- Stretchable conductors
- TEGs, antenna, and energy harvesting



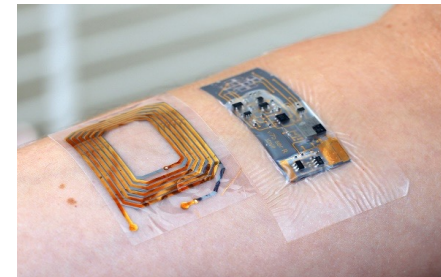
Fabric antennas

- Wearable and high efficiency



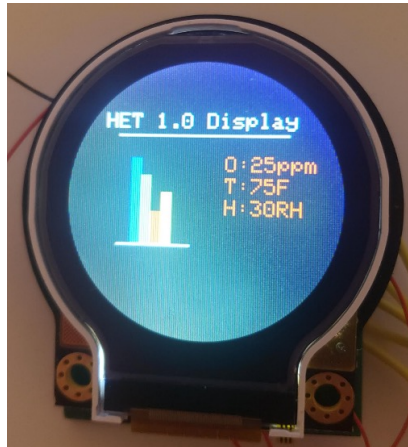
Flexible PCBs

- Thin profile providing comfort and flexibility



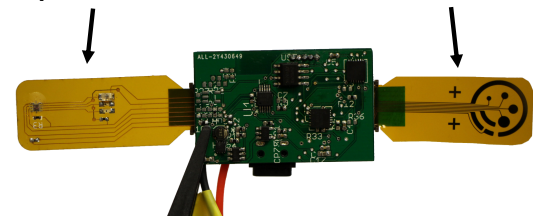
2-layer circuit board (< 25 μ m)

System Integration and Validation



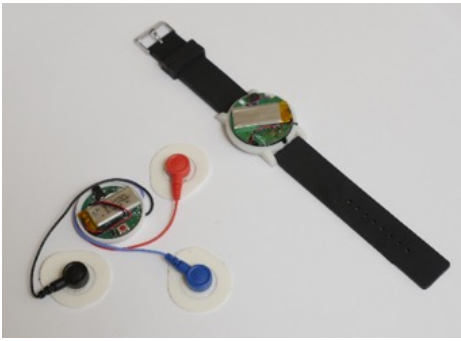
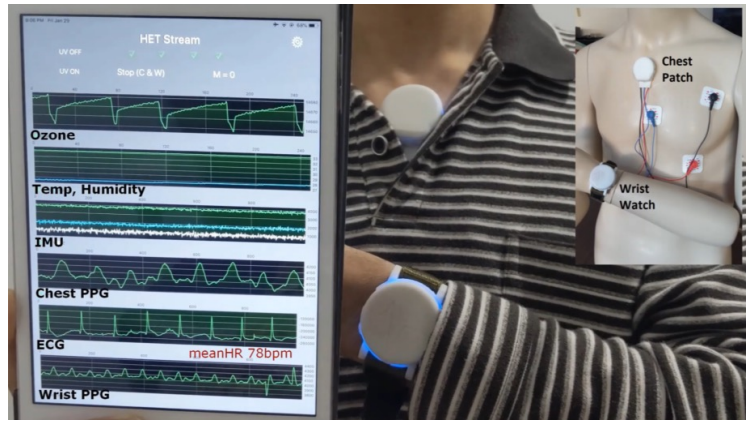
Optical Patch

Electrochemical Patch



ASSIST Use Cases

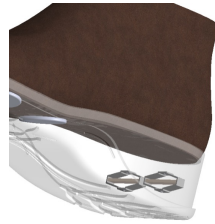
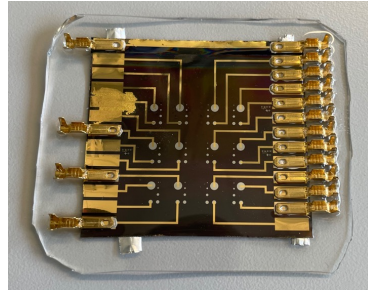
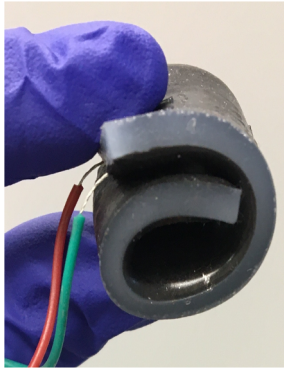
- Asthma
- Cardiac Disease
- Metabolic State
- Wound Monitoring
- Medication Adherence



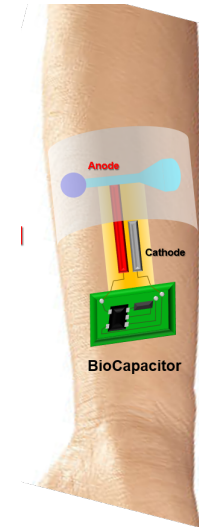
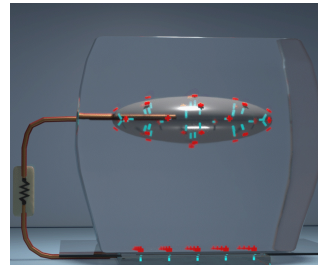
Pre-Clinical Studies

Multimodal Energy Harvesting Highlights

- ▶ Thermoelectrics
- ▶ Piezoelectrics
- ▶ Soft variable area harvesters
- ▶ Ambient RF Harvesting
- ▶ Biocapacitors



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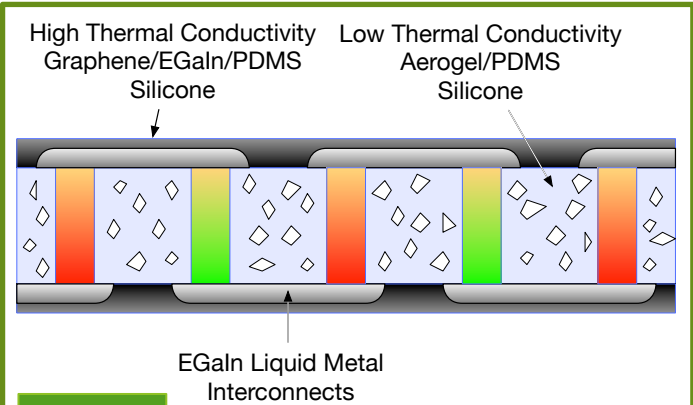
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INTERNATIONAL
UNIVERSITY



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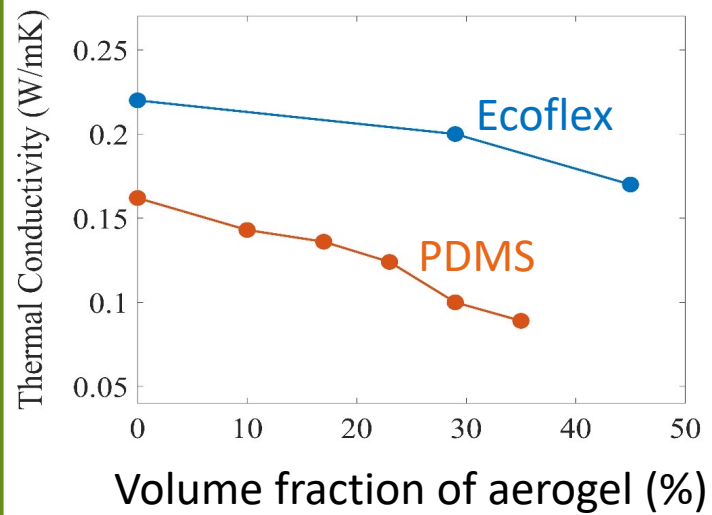
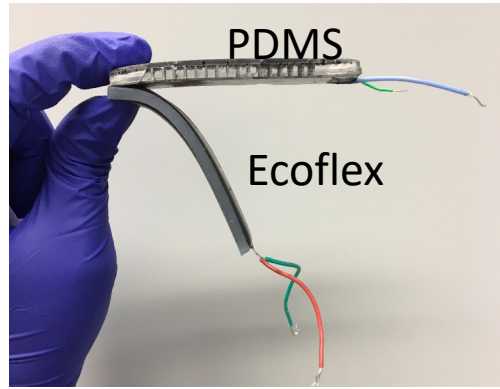
Wearable TEGs with Enhanced Flexibility



2019



NPJ Flexible Electronics 2021



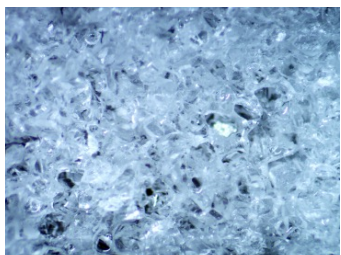
- Challenge:
- Ecoflex Thermal Conductivity higher
 - Aerogel Inclusion proved ineffective
 - Reduced Device Performance

Ozturk/Dickey

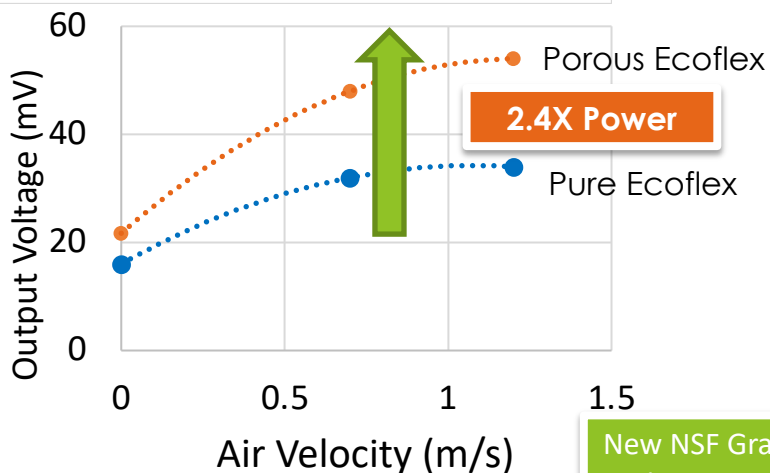
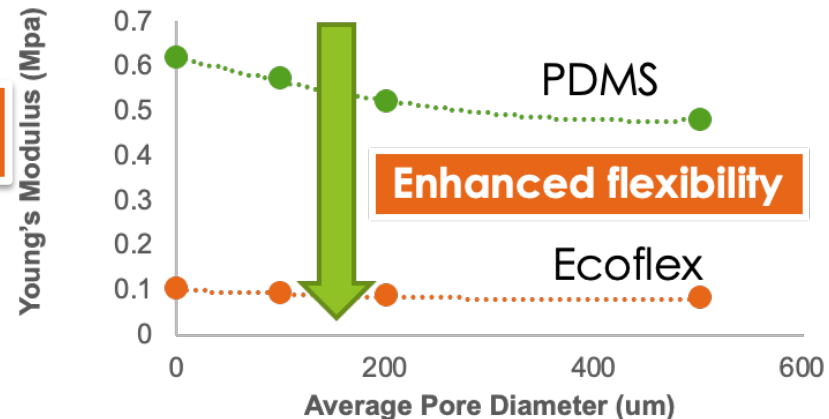
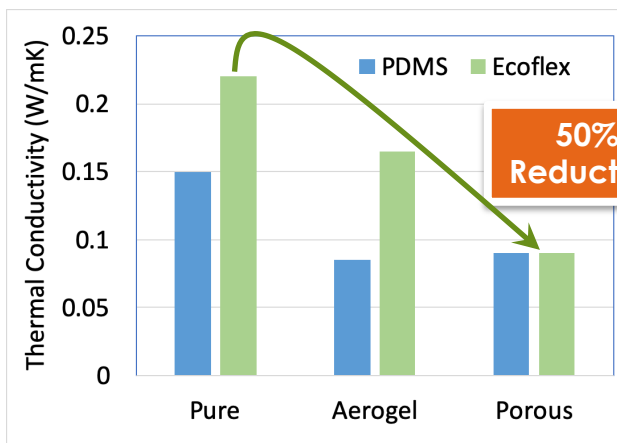
Low Thermal Conductivity Porous Ecoflex



Sugar granules mixed in silicone dissolved in H₂O

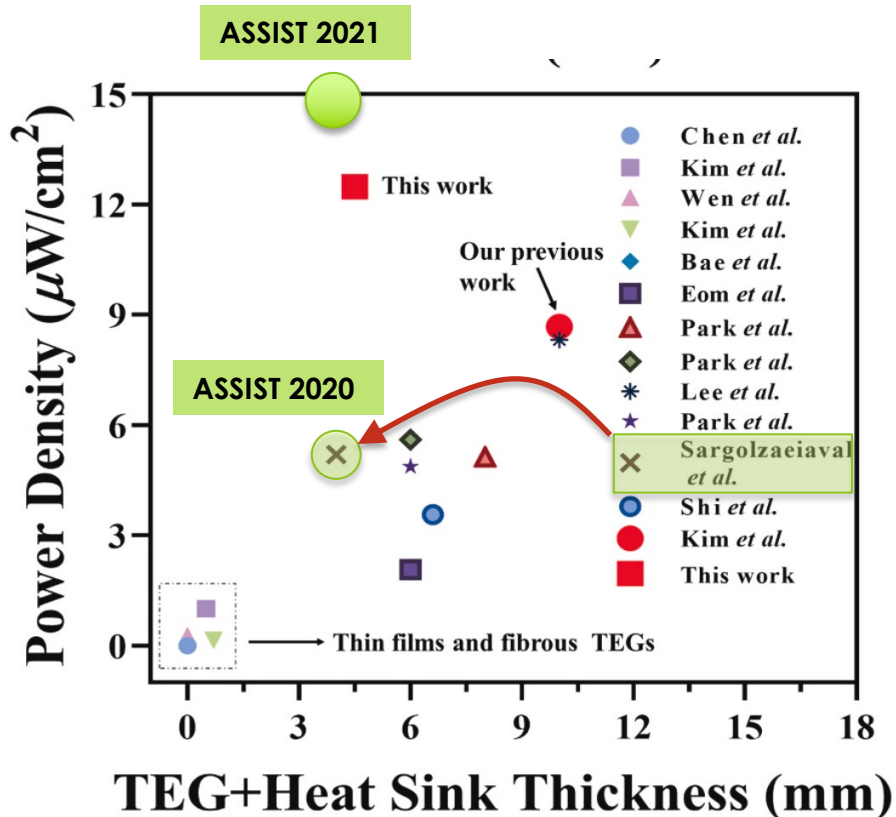


Porous Ecoflex



- Porous Ecoflex provides significantly enhanced flexibility without sacrificing device performance
- Porous Ecoflex TEGs are comparable to our best Aerogel/PDMS TEGs

Benchmarking (Natural Convection)



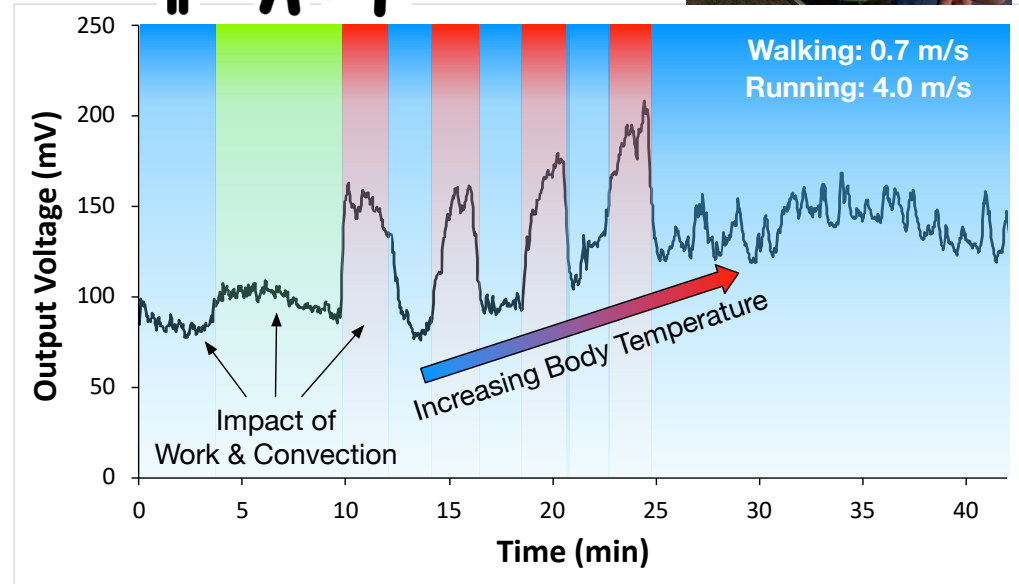
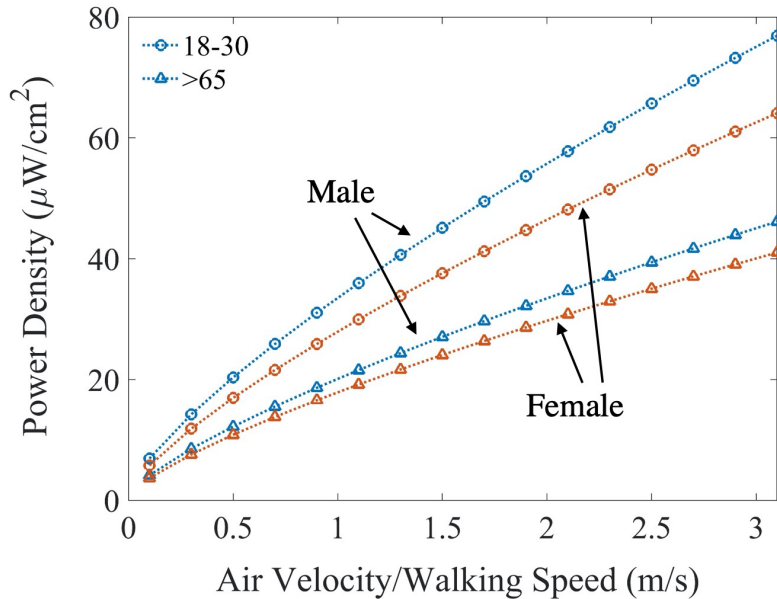
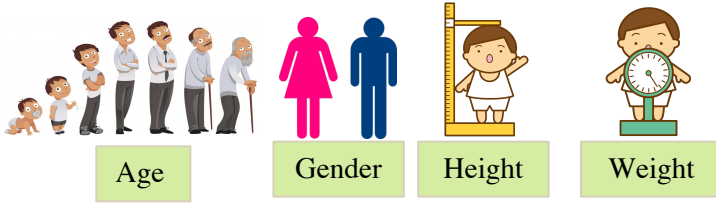
ASSIST TEGs offer higher performance due to

- Negligible resistance of liquid metal interconnects
- New silicone composites designed for optimal heat transfer
- Modeling

Khan et.al., "High power density of radiative-cooled compact thermoelectric generator based on body heat harvesting", Nano Energy, 2021

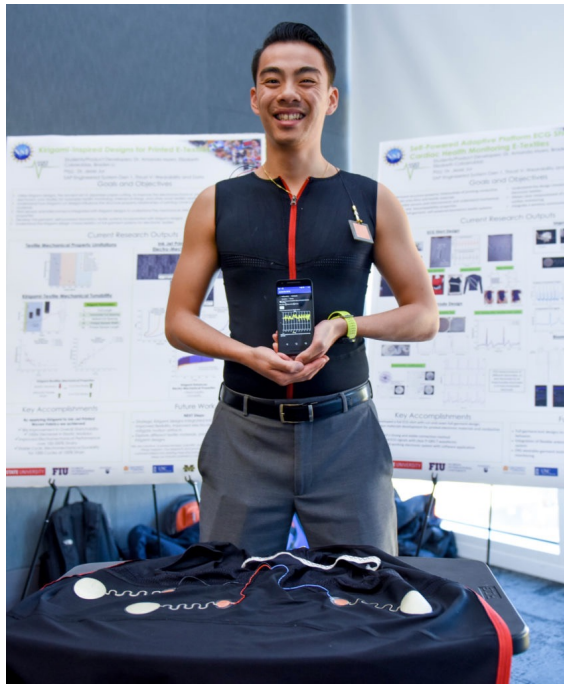


TEG Model and On-Body Characterization



Vigilant Cardiac Monitoring

Self-powered ECG shirt



ECG armband



ECG chest patch



Vigilant ECG Shirt



End-to-end functional



Wearable

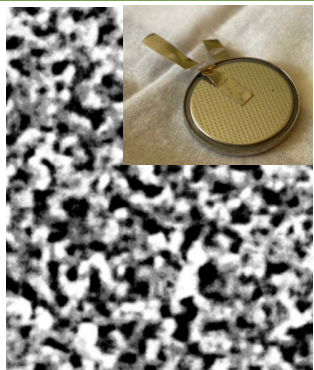


Self-powered

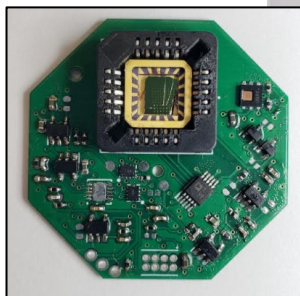




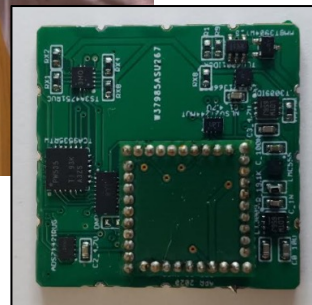
Flexible TEGs with
integrated solar cell



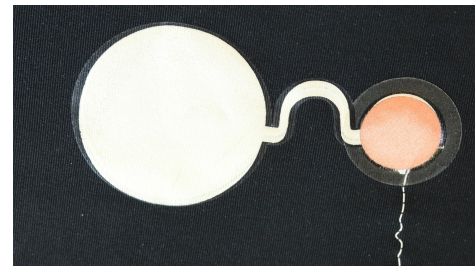
Supercapacitor with
high capacitance
retention



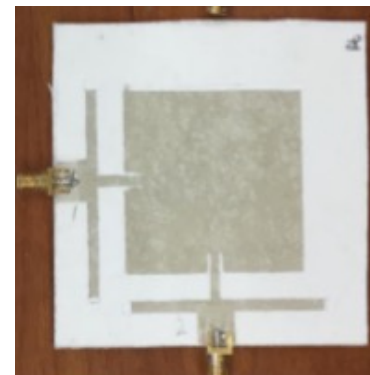
Custom AFE with
Ozone & ECG



Compressed
Sensing PPG



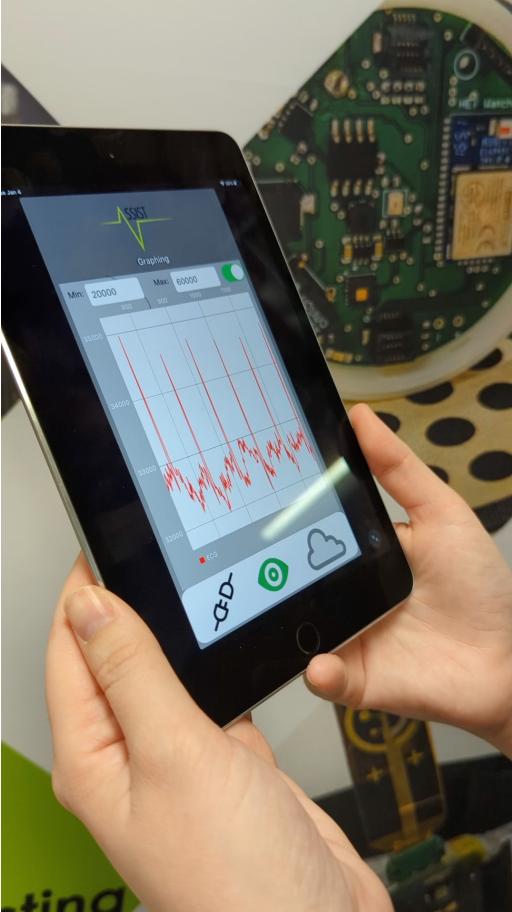
Washable ECG
electrodes and cabling



Screen-Printed Full
Duplex antenna

Self Powered Adaptive Platform 1.9 Demo

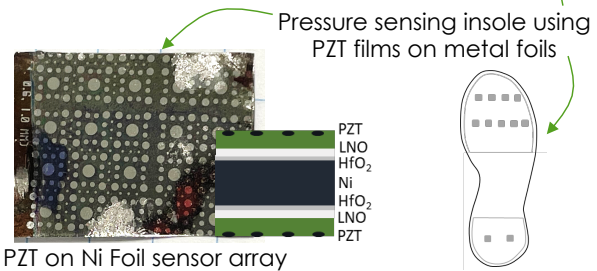
ECG Monitoring Armband



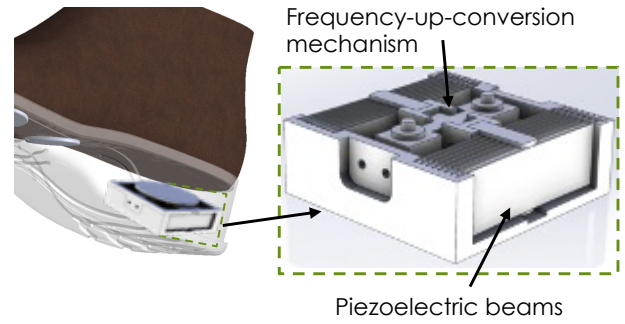
- Textile-integrated dry electrodes
- Wireless transmission of ECG Signal
- Comfortable, arm-based system

SSIST Self-Powered Smart Insole

- ▶ Falls result in > 3,000,000 trips to the emergency room, 28,000 deaths, and \$50B in costs, annually
- ▶ Falls in the elderly often end the ability to live independently



Heel-inserted Energy Harvester



Design goal: > 10 mW
 Current Design:
 60 mW simulated
 ~10 mW measured



Figure from Brightstar Care

Florence et al., *J. Am. Geriat. Soc.* 66 693 (2018)
 Bergen, Stevens, and Burns, *Morb. Mortal. Wkly. Rep.* 65 938 (2016).

Energy Harvester Design

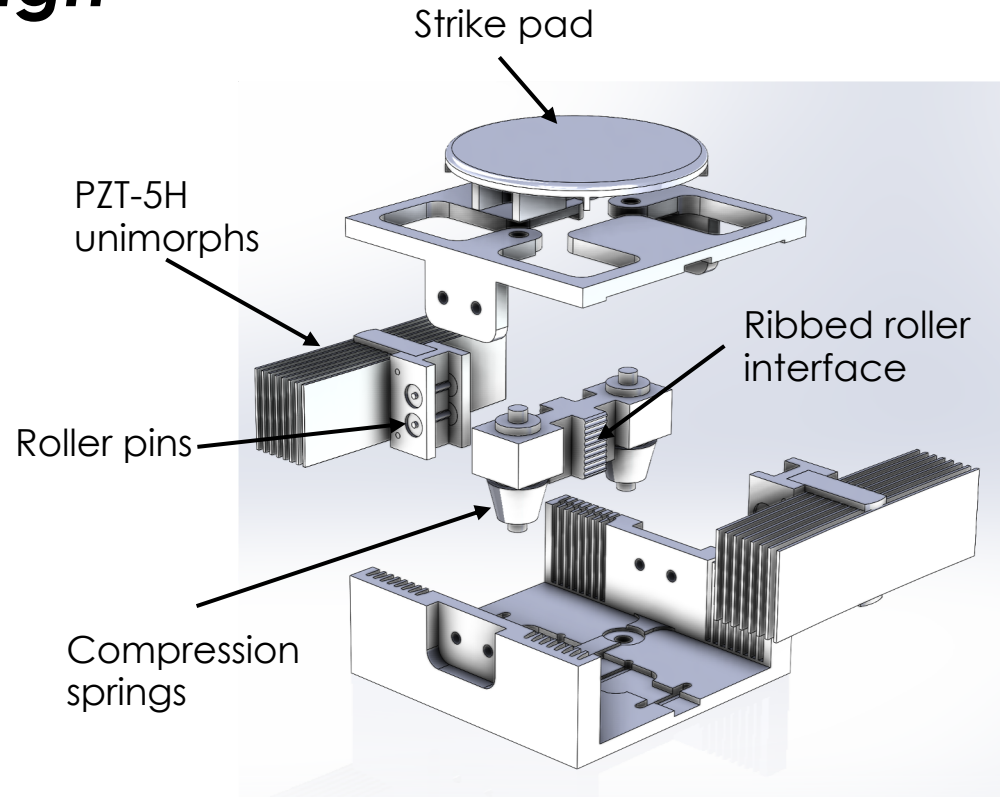
Piezo material FOM 0-pk mech. strain

$$P_{rms} = \frac{1}{4} \omega \left(\frac{d^2 c E^2}{\epsilon^T} \right) (vol) S^2$$

Frequency Volume of PZT

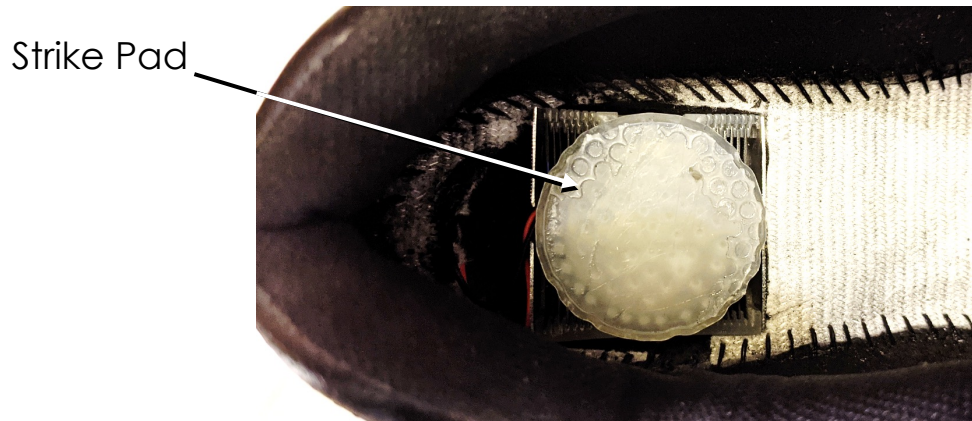
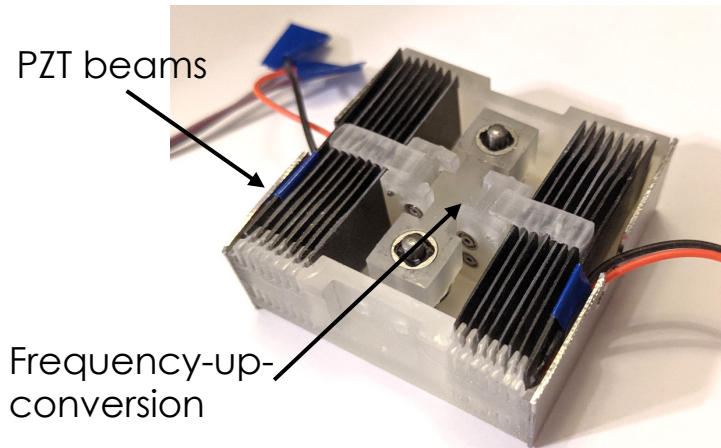
Expected User:
70 kg
1 Hz walking pace

Predicted Performance:
64 mW projected output
6x frequency up-conversion
1.02 mW/cm³



Roundy/Trolier-McKinstry

Energy Harvester Status



Current Measured Performance:

~ 10 mW output

6x frequency up-conversion

~ 0.25 mW/cm³

Current Status:

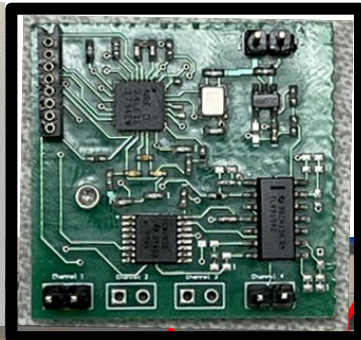
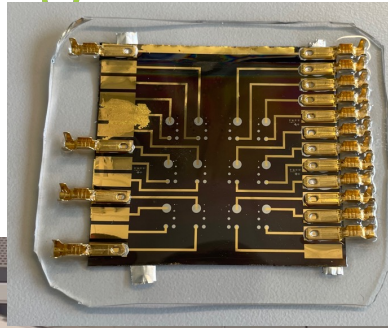
Strain levels are below design targets due to housing structure compliance



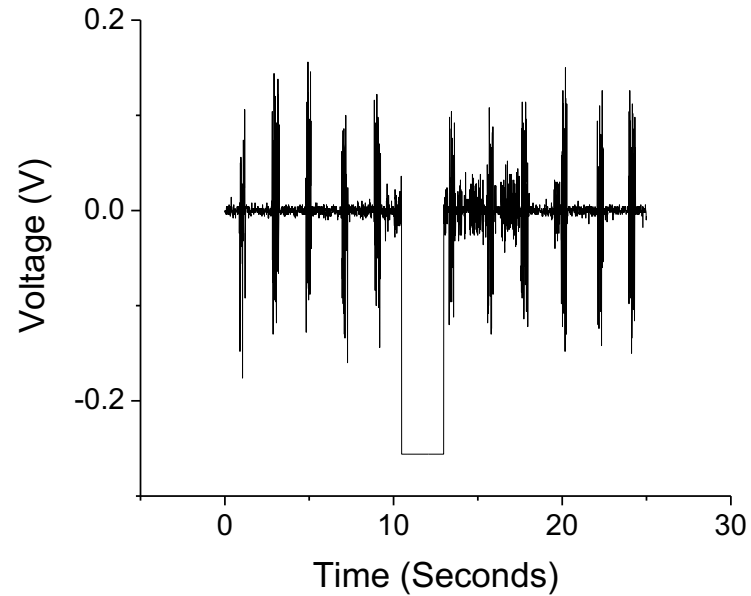
Design goal: > 10 mW

Current Design:
60 mW simulated

~10 mW measured



4 channel wireless sensing
circuit PCB



- Pressure response of single sensor with oscilloscope output data (confirmed in Instron tests)
- PZT film deposited using an ASSIST-developed dip coating system
- All system components demonstrated

Soft Materials for Energy Harvesting

► Problem

Energy sources that can convert mechanical energy to electrical energy can enable self-powered, tetherless, and sustainable wearable electronics, implantables, e-skins, sensors.

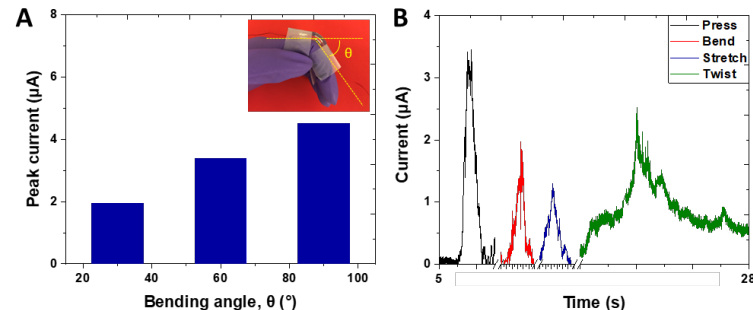
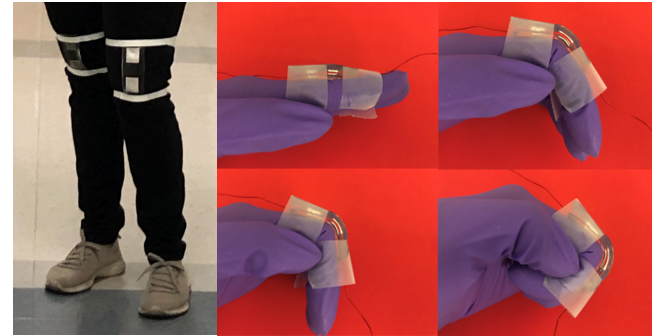
- Inadequacy of existing solutions - e.g., compliance with human skin, deformability, need for additional power source, moisture intolerant etc.

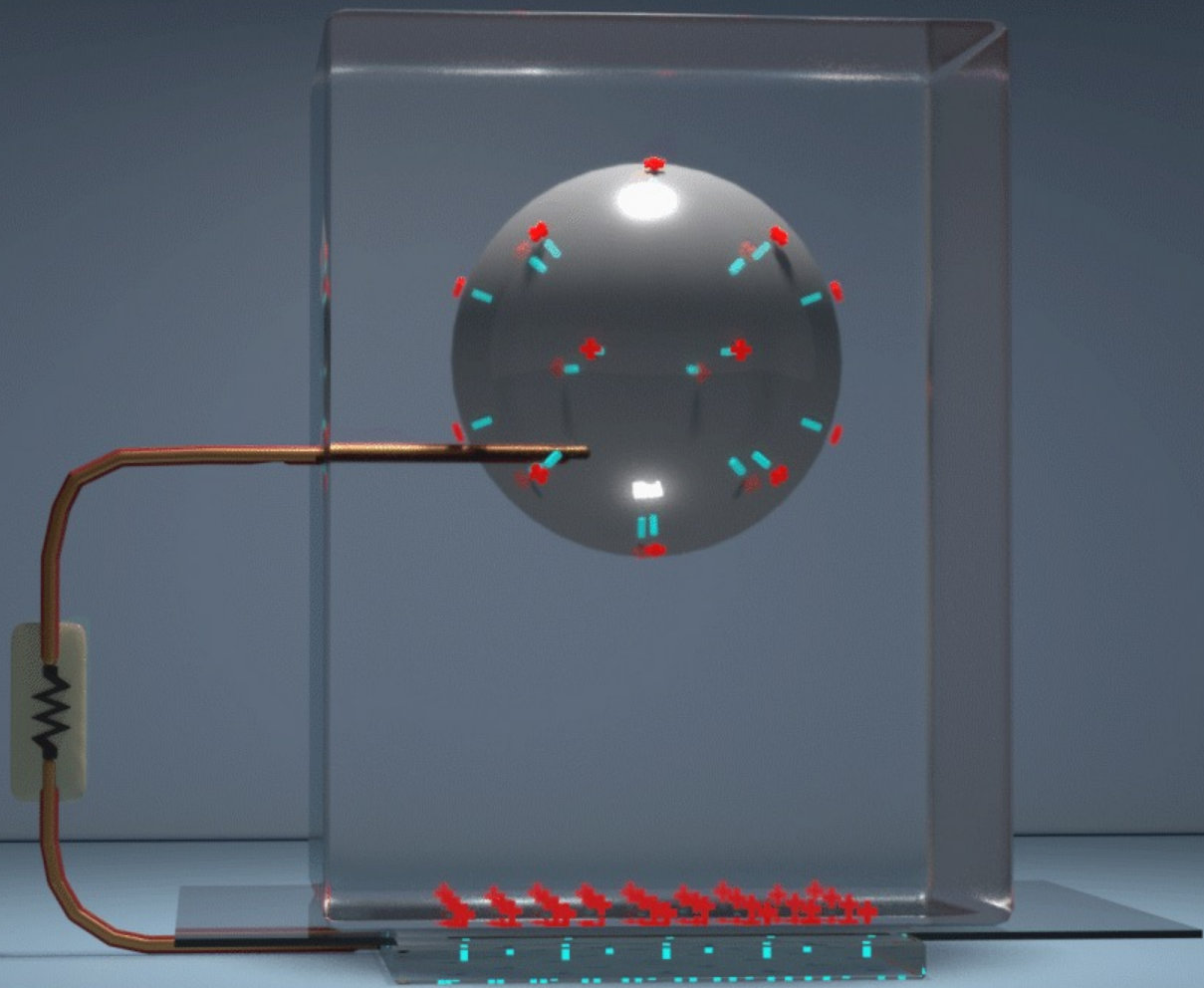
► Proposed solution

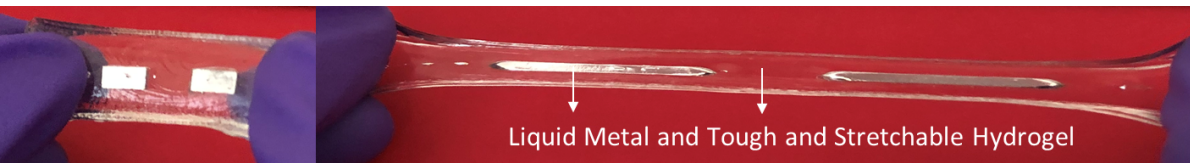
- Fabricate variable area liquid metal capacitors
- Develop high surface area electrodes to enhance power output

► Relevant applications

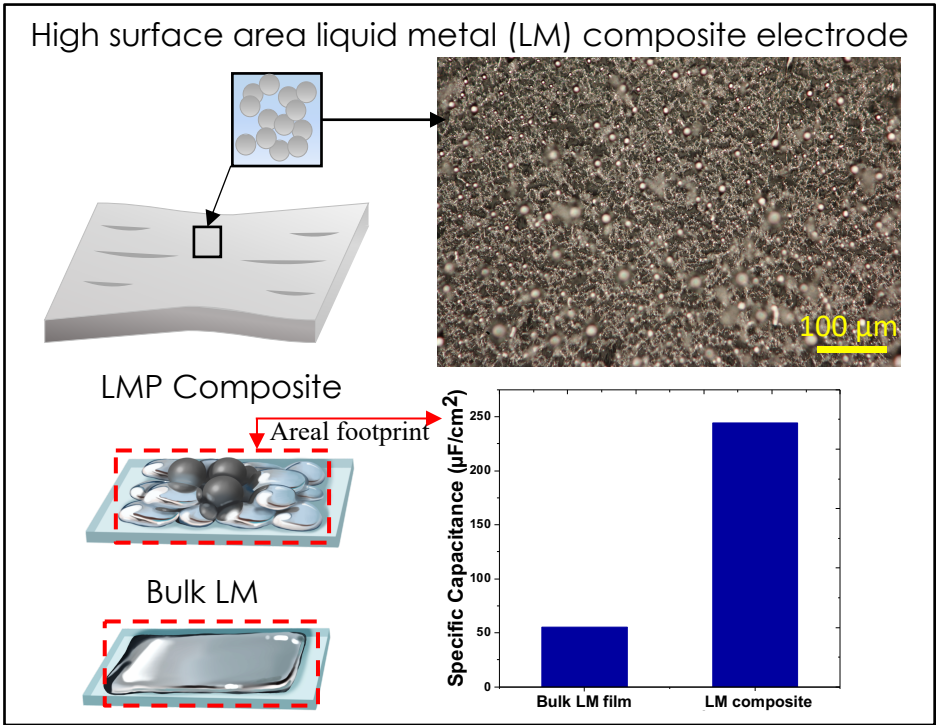
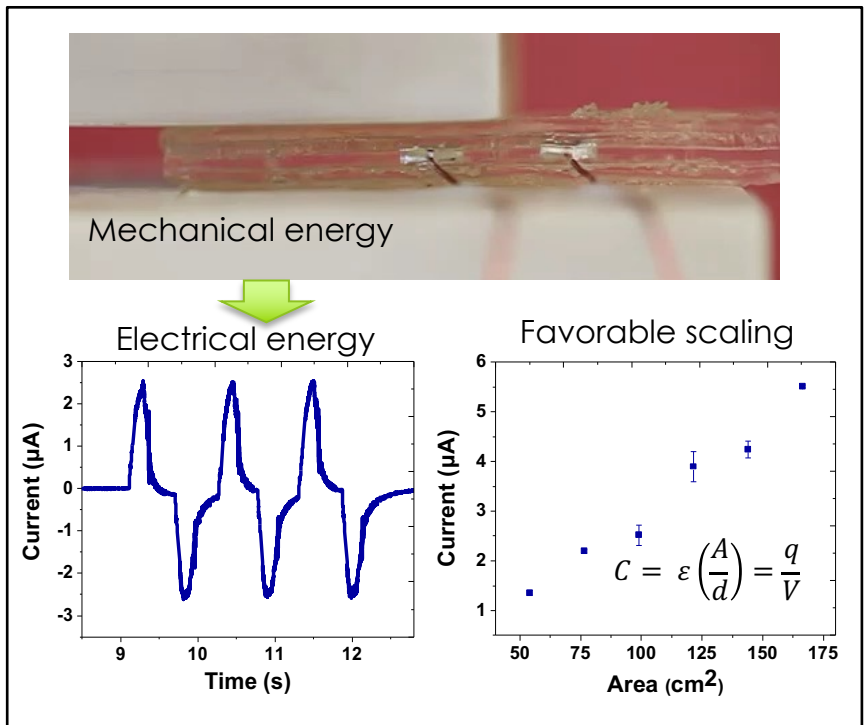
Energy harvester and self-powered sensors

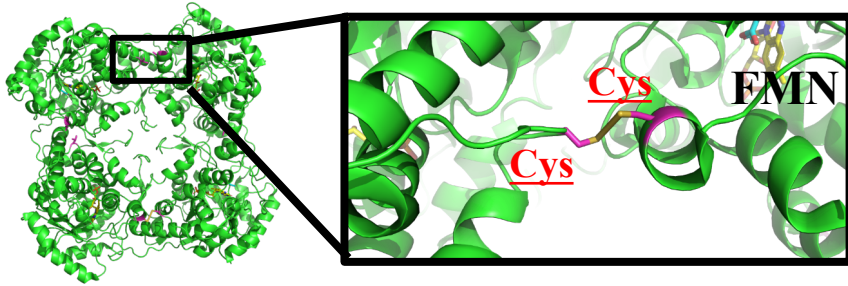




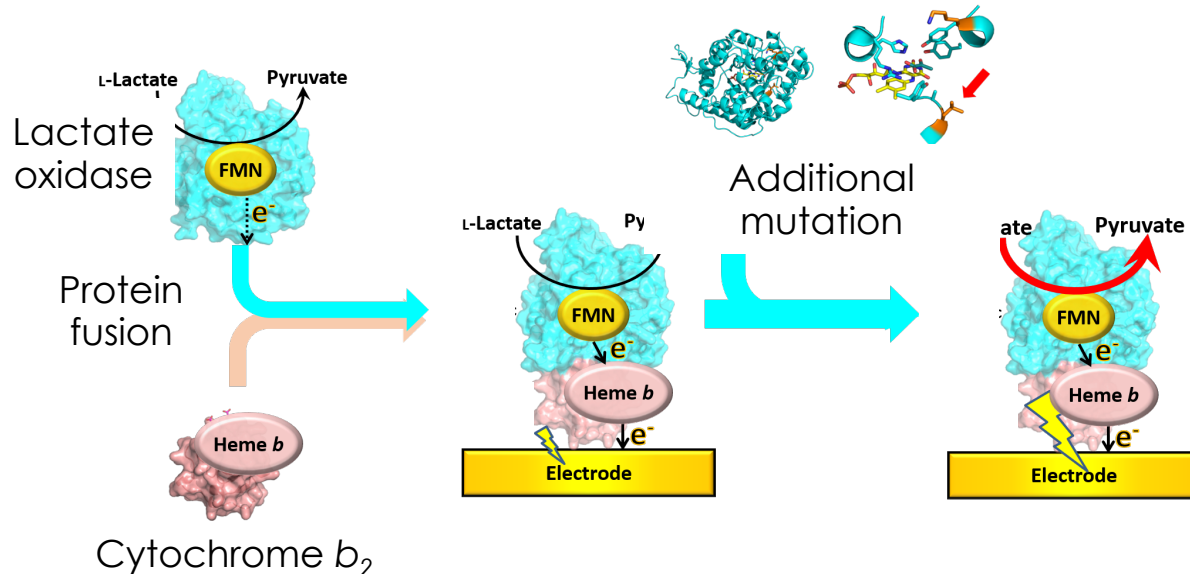


- Soft variable area electrical double layer capacitors
- Converts mechanical energy → electrical energy
- Works in air and underwater
- Offers favorable scaling



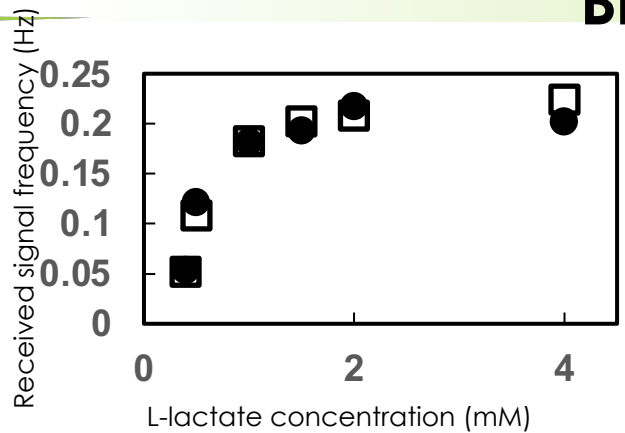


Engineered lactate oxidase (LOx) will be used for anodic catalyst for oxidation of lactate to harvest energy and sensing lactate concentration from sweat.



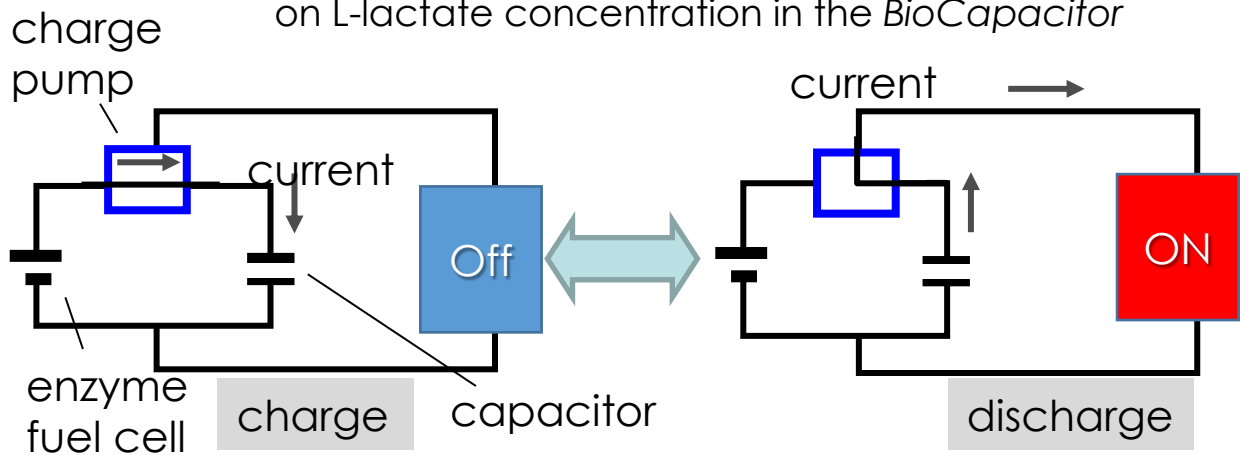
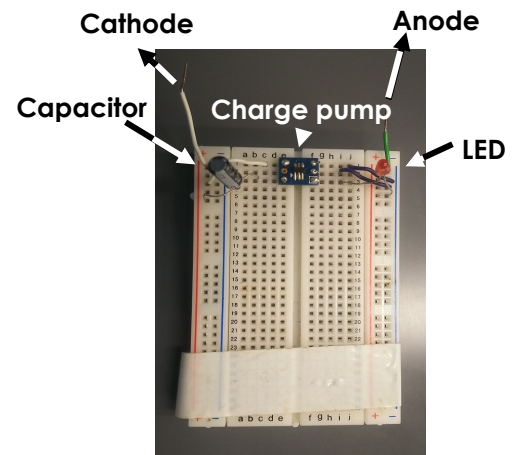
1. The enzyme is stable ($<70^{\circ}\text{C}$)
2. No impact of oxygen (virtually “dehydrogenase”)
3. Capable of direct electron transfer
4. Can catalyze the oxidation of lactate in high ($<10\text{mM}$) lactate concentration.

Goal: Power source that will enable transition from HET 2.0 to self-powered SAP 3.0.



- Engineered LOx immobilized electrode **(Physical adsorption)**
- Engineered LOx Nafion immobilized electrode **(Nafion coating)**

Dependence of charged and discharged frequency on L-lactate concentration in the *BioCapacitor*

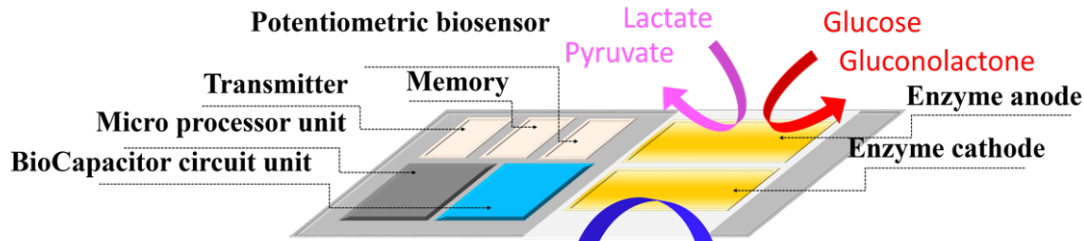


A *BioCapacitor* is an enzyme fuel cell connected with a capacitor via a charge pump circuit, which steps up the voltage, and the electricity generated from the biofuel cell is charged in a capacitor. A high voltage with sufficient current can be intermittently generated by the *BioCapacitor*.

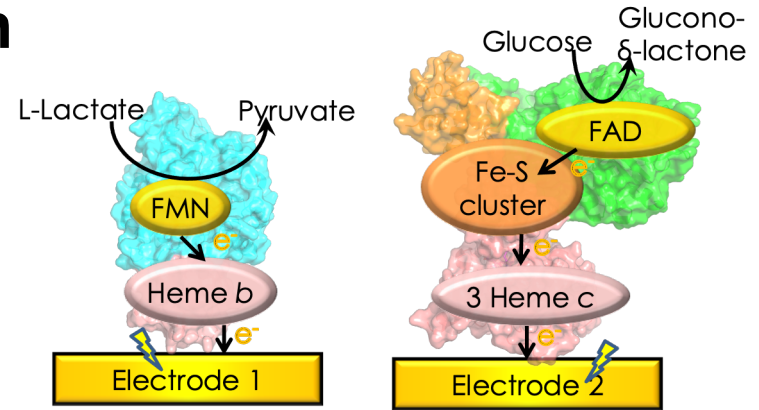
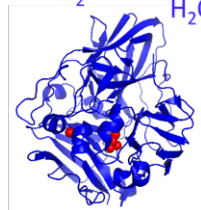
Self-Powered Multimodal Metabolite Sensing System



Reader
BLE
Communication



Engineered extremophile derived DET-type multi copper oxidase; the cathodic enzyme

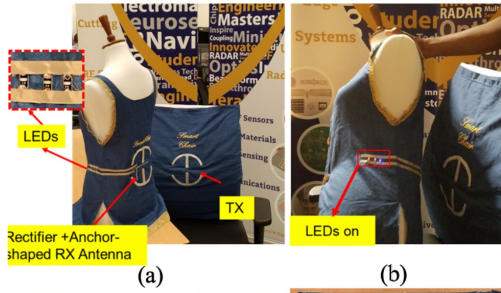


- Direct electron transfer (DET) type glucose/lactate sensors
- **Dual-BioCapacitor harvests energy from glucose and lactate** to power sensors and wireless signal transmission system towards SAP 3.0.
- Engineered stabilized enzymes should enable continuous operation for > 2 weeks. Sode

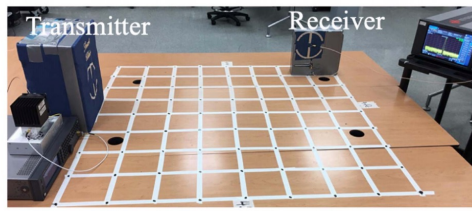
Extending the Range of RF Powering

- The range of powering the wound monitoring platform was extended to 2 ft. using combination innovative anchor shape which provides fringing field, which increases distance and misalignment resiliency.
- Antenna were embedded in fabric surfaces for ergonomic use, where transmission can occur from beds and other fabric surfaces.

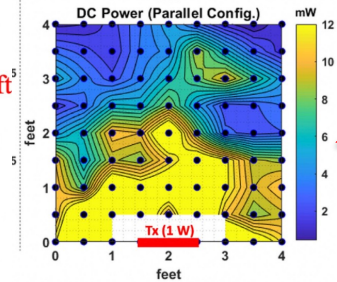
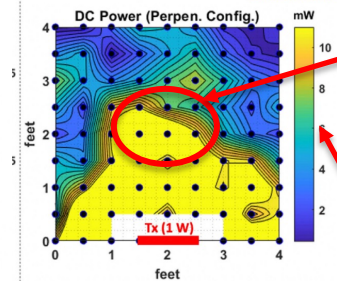
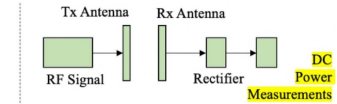
Implementation vision



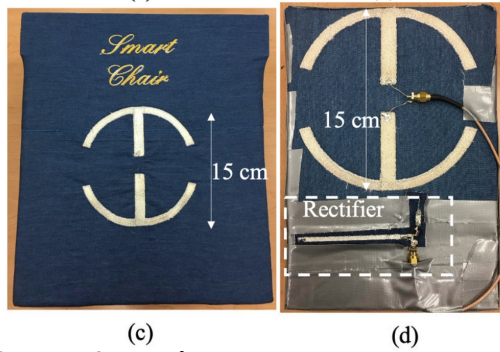
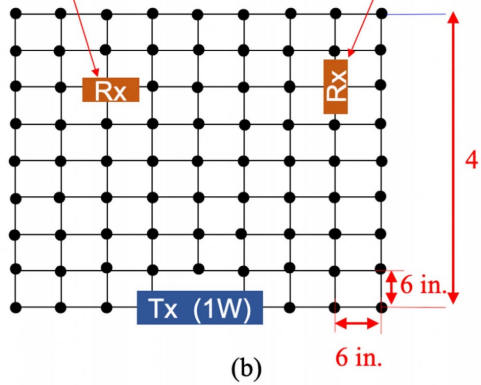
Measurement Set-up



Power collection results



Parallel Configuration (a) Perpendicular Configuration (b)

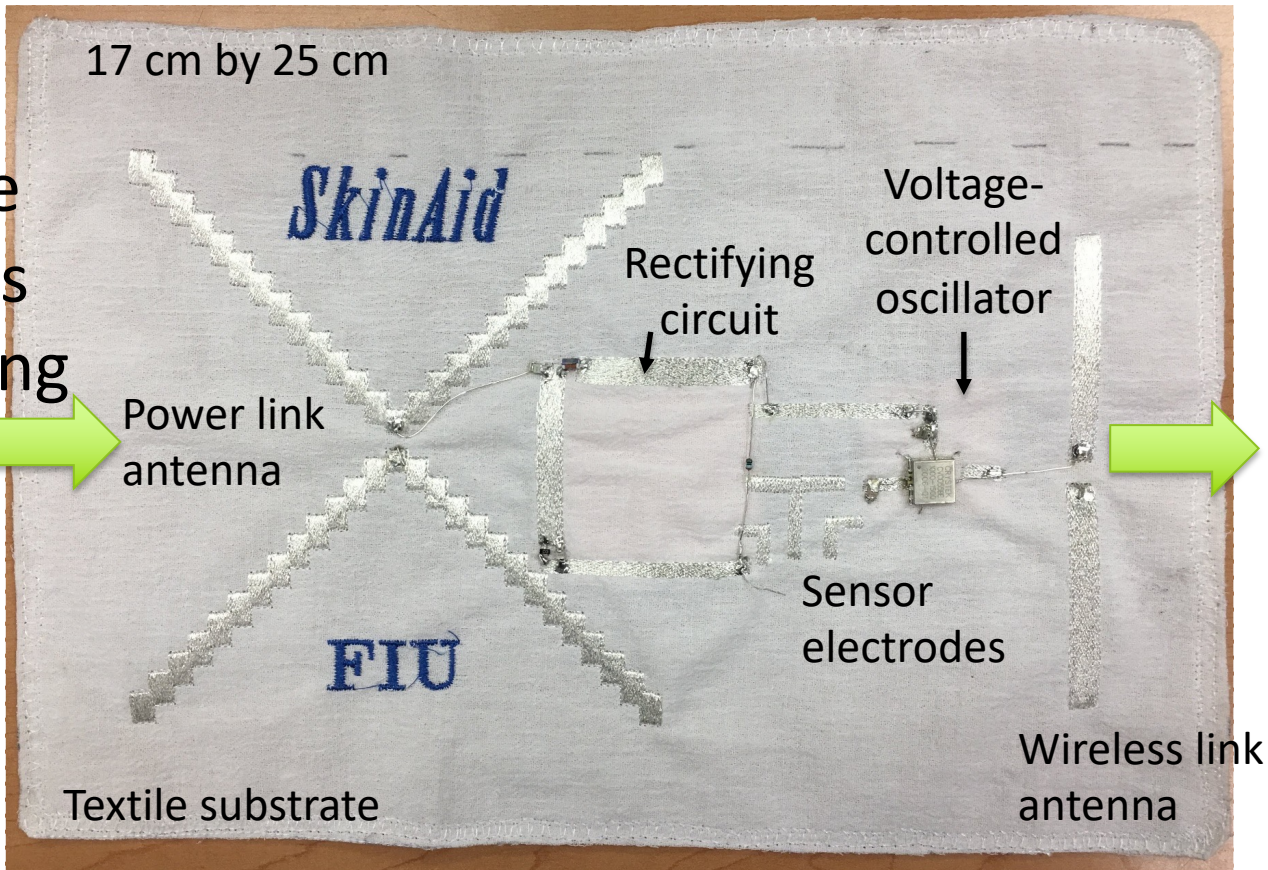


10 mW+ power collected at 2 feet from the Transmit, and 2 ft lateral area.

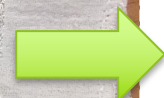
Power transfer resilient to antenna orientation

S. Bhardwaj and J. L. Volakis, "An Ergonomic Wireless for Integration With Daily Life Activities," in *IEEE Transactions on Microwave Theory and Techniques*, doi: 10.1109/TMTT.2020.3029530.

Remote wireless powering



Modulated signal with pH/Uric Acid sensor data (to external Kiosk)



17 cm by 25 cm

Power link antenna

Rectifying circuit

Voltage-controlled oscillator

Sensor electrodes

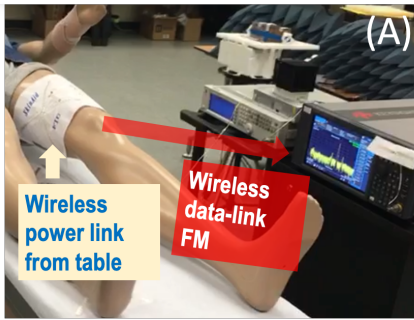
Wireless link antenna

Textile substrate

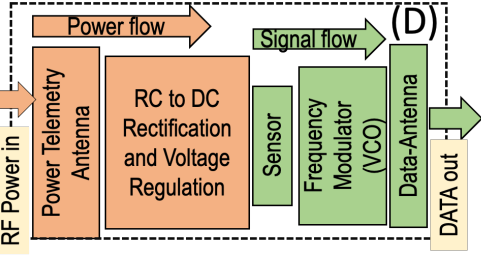
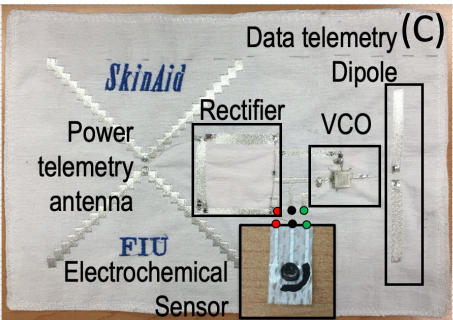
Uric Acid and pH Monitoring using VCO based Patch ³⁷

1. The bandage was measured by connecting with samples of different uric acid concentration and samples of different pH concentration.
2. The RFID unit transmitted the sensor data as frequency modulation. The signal was recorded 7 ft from the patch.
3. RFID used a VCO based modulation approach, using remote powering.

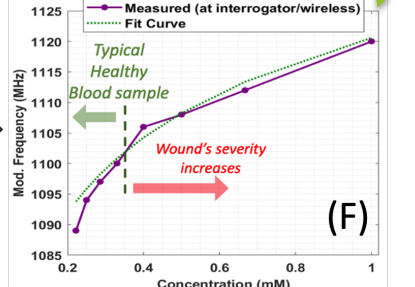
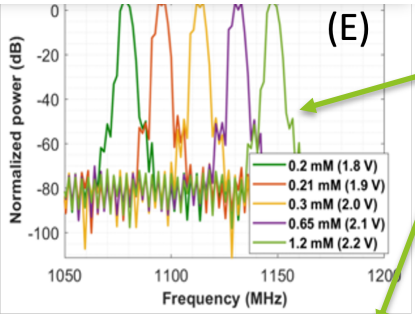
Measurement Set-up



Fabric Patch Implementation

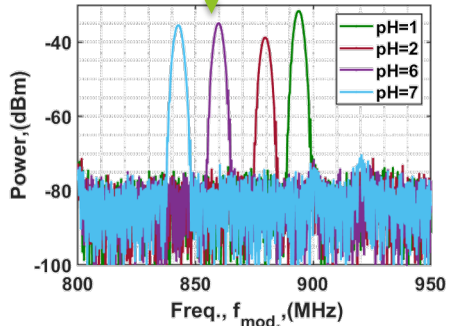


Frequency modulated return data



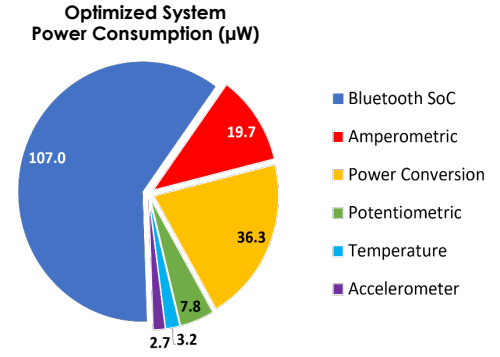
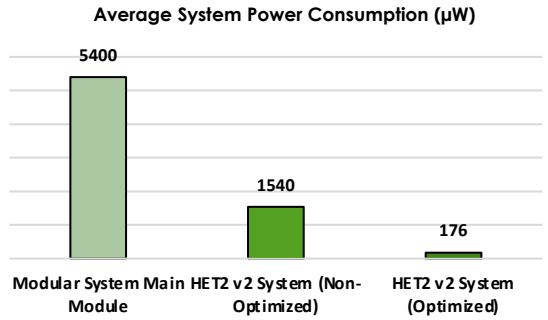
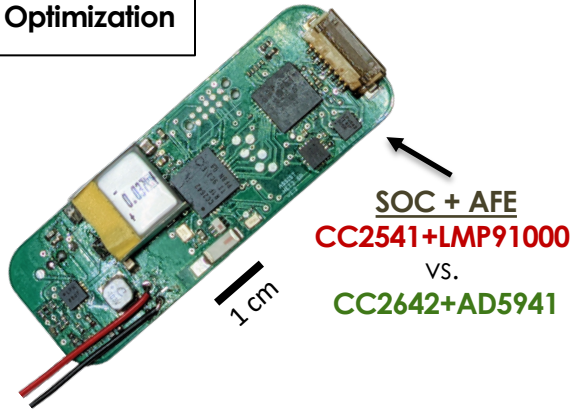
Uric Acid sensing

pH Sensing

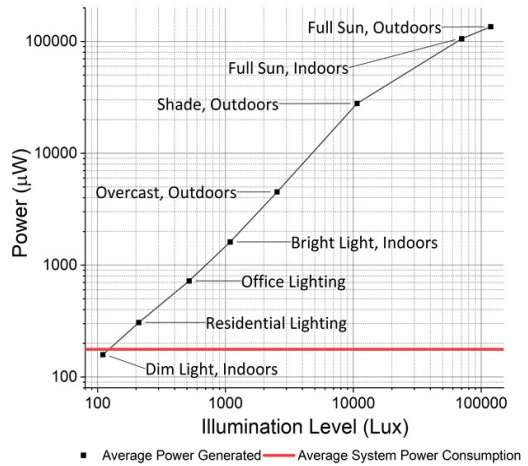
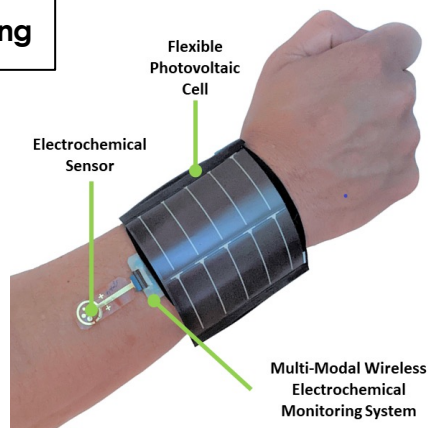


Progress towards self powered Biochemical Platform

Power Optimization



Energy Harvesting





ASSIST Power Generation

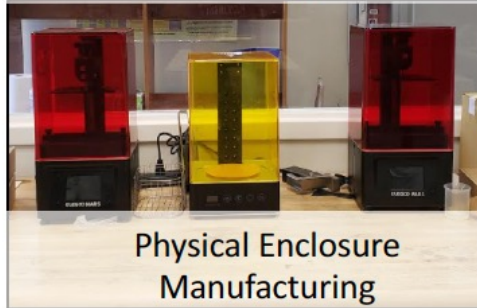
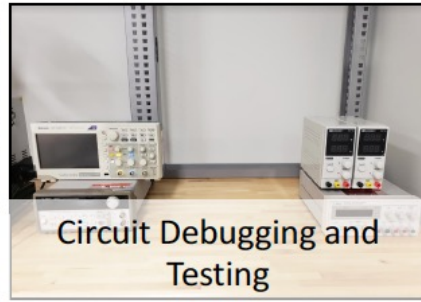
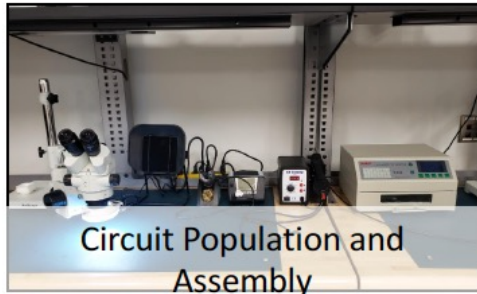
Modality	Use Case	What Makes ASSIST systems unique	Power Levels
Flexible Thermoelectric	Vigilant ECG	Use of state-of-the-art bulk thermoelectric legs in a highly flexible matrix optimized for low thermal conductivity and liquid metal interconnects. Superior performance and manufacturability	20 $\mu\text{W}/\text{cm}^2$ (no air flow - natural convection) - 80 $\mu\text{W}/\text{cm}^2$ (1.2 m/s air flow, walking)
Mechanical Harvesting	Self-powered Gait Monitoring	Integrated system for self-powering gait monitoring co-designed for comfort and power output; potential to be high sensitivity and more robust than state of the art; Flexoelectric harvesters using silicon are unique.	10 mW
RF Harvesting	Wound Healing	Flexible and fabric based wound monitoring patch, with RF power harvesting and data com links on the same patch. The sensing modality is compatible with different electrochemical sensors, e.g. Uric Acid, pH.	10 mW at 2 ft distance from a 1W RF source
Biochemical Harvesting	Sweat Sensing	Harvesting energy from lactate based innovative bioelectrochemical device, BioCapacitor, using direct electron transfer type engineered super stable lactate dehydrogenase covering dynamic range of sweat lactate concentration.	1 mW (lactate/glucose enzyme fuel cell)

ASSIST Application Areas

ASSIST Technologies	Health & Wellness	Animal Health	Agriculture	Smart Cities, Offices, Homes	Self-powered IoT nodes
Thermal, Mechanical, RF Harvesting	✓	✓	✓	✓	✓
Physiological Sensors	✓	✓			
Body fluid based Sensors	✓	✓			
Environmental Sensors	✓	✓	✓	✓	
Ultra low power SoC and Radios	✓	✓	✓	✓	✓
Smart Flexible Materials	✓	✓	✓	✓	✓
Supercapacitor	✓	✓	✓	✓	✓

Rapid Prototyping Group

Increasing the TRL level of our technologies and systems to drive engagement with industry and clinical partners



RPG aims to deliver the lowest power biometric hardware platforms for research & commercial benchmarking

- ▶ Open-source development
- ▶ RPG Capabilities
 - ▶ PCB Layout
 - ▶ Arduino firmware
 - ▶ Sensor dashboarding



Dr. Dieffenderfer



Industry Membership Program

Full



Medtronic

Associate

HANES
Brands Inc

muRata
INNOVATOR IN ELECTRONICS



AstraZeneca

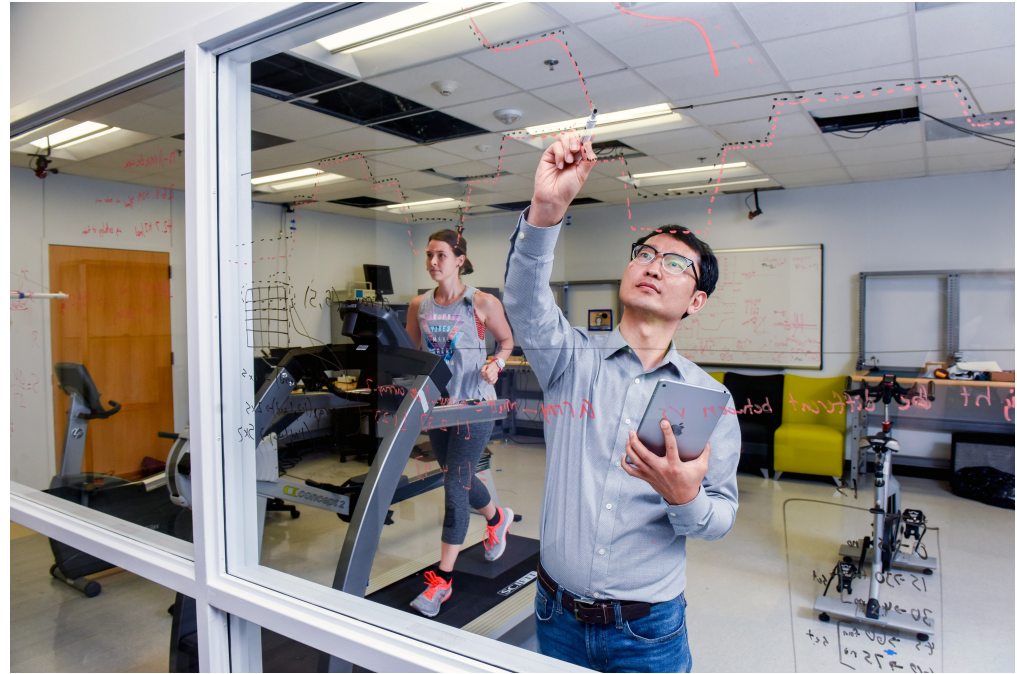


Affiliate



ASSIST Industry Membership Program

- ▶ Industry Advisory Board
 - ▶ Project request and selection
- ▶ Directed Research
 - ▶ “Enhancement” - 10% overhead
 - ▶ Sponsored - University overhead
- ▶ Facilities and Equipment Use
 - ▶ Human Performance Lab
 - ▶ Prototyping
- ▶ Industry Mentorship
- ▶ Student Internships (INTERN)
- ▶ Spin-outs and Commercialization



Acknowledgements

assistcenter.org

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 - ▶ Orlin Velev
 - ▶ Michael Dickey
 - ▶ Shekhar Bhansali
 - ▶ Shubhendu Bhardwaj
-

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THANK YOU