Unconventional Hydrogel Scaffolds, Electronics and Machines

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MIT

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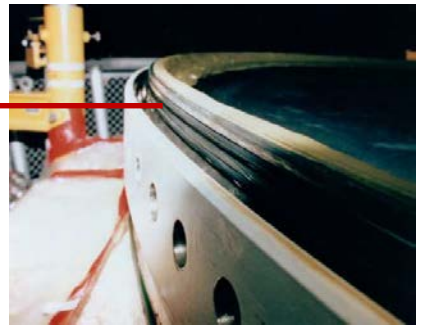
2017 MIT Conference

Jan 27 2017

Impact of Soft Materials: from engineering to health



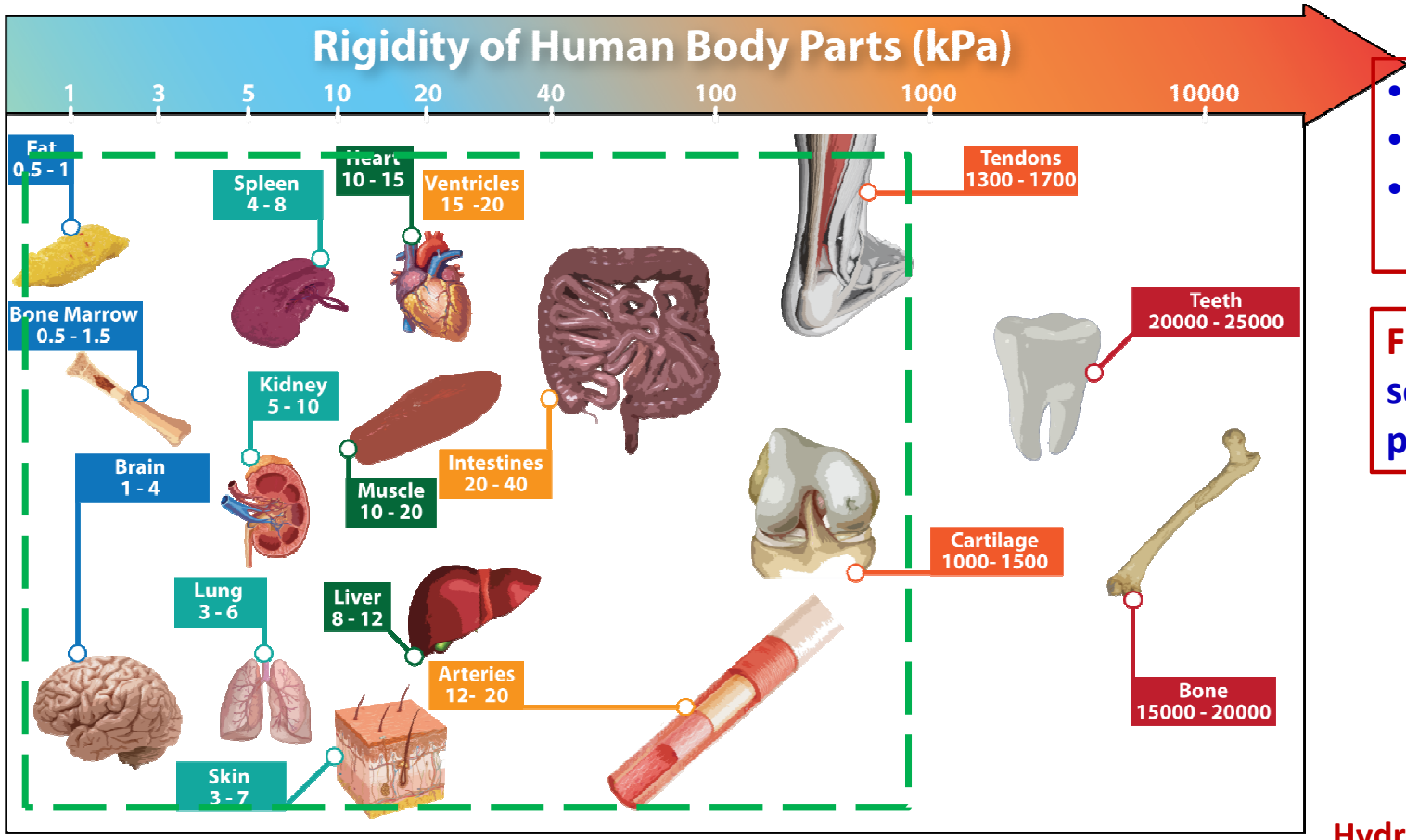
- Failure of O-ring seal caused the Space Shuttle Challenger disaster in 1986.
- Approximately 17 percent of Americans witnessed the launch and disaster.

Impact of Soft Materials: from engineering to health

In collaboration with Samsung Display

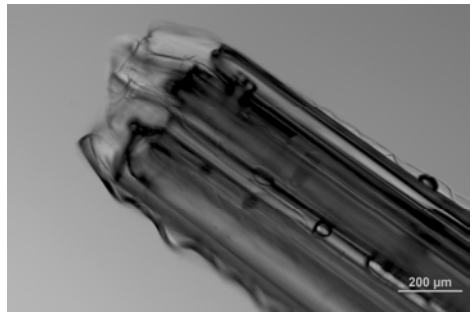
Replace traditional rigid components with polymers and gels to enable flexible electronics and wearable devices.

Impact of Soft Materials: from engineering to health



- Modulus: 1kPa~10MPa;
- Water concentration: 70%
- Robust: under millions of cycles of loads.

Future biomedicine relies on soft materials with similar properties as body.

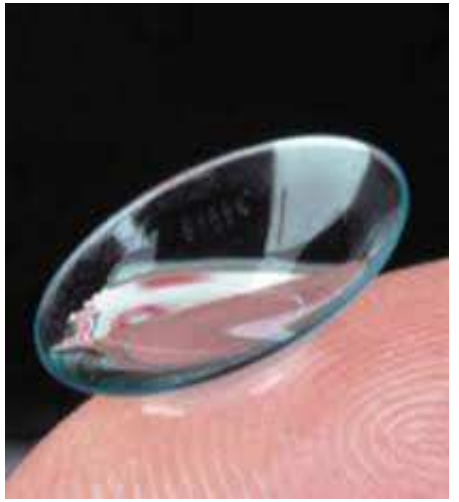


Hydrogel Neural Probe with Anikeeva

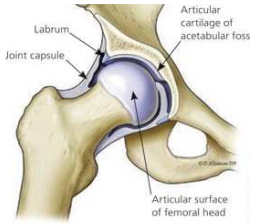
Hydrogels

Extremely Tough

Conventional hydrogels are weak and brittle



Conventional hydrogel
Fracture toughness ~1 Jm^{-2}

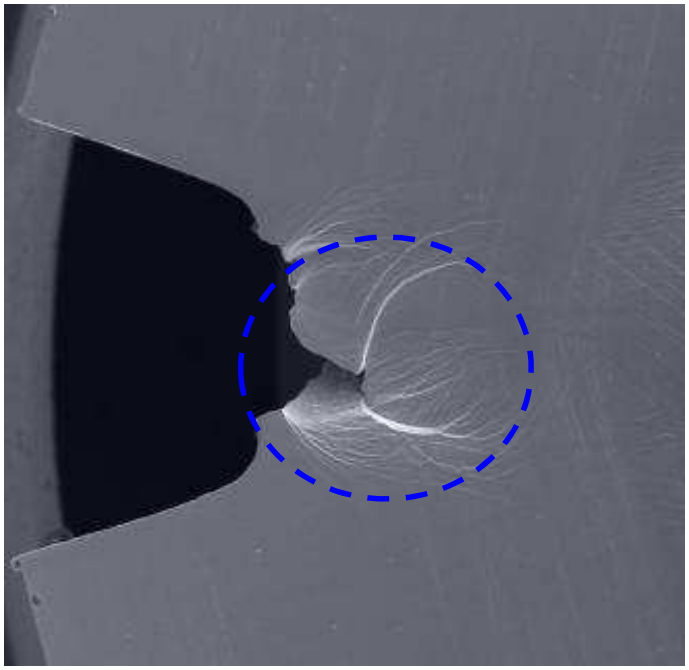


Cartilage
Fracture toughness
~1,000 Jm^{-2}

Glass

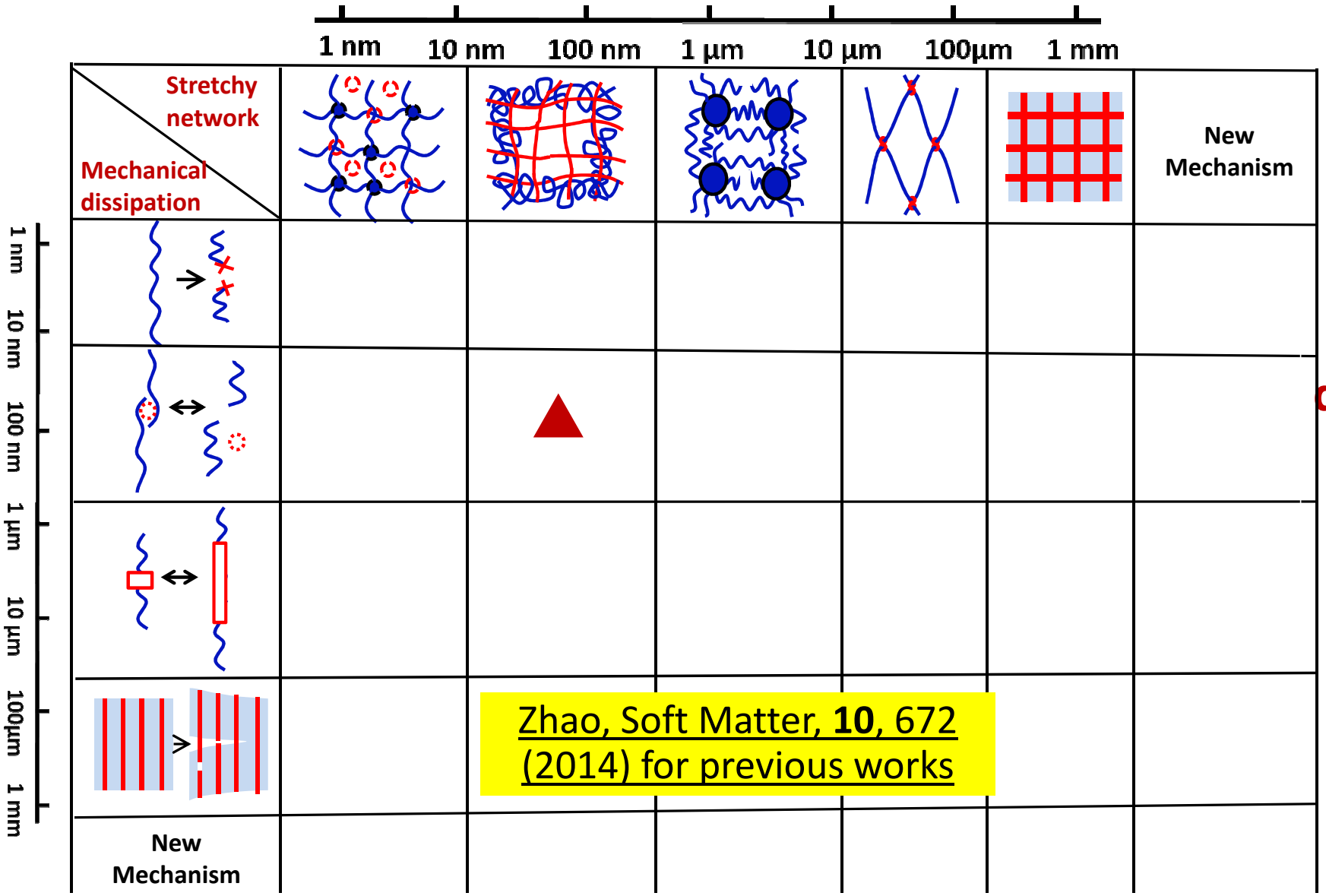
Fracture toughness
= Surface energy

Metal



Fracture toughness
= Surface energy +
Dissipation in a zone

Zhao, Soft Matter, 10, 672 (2014)



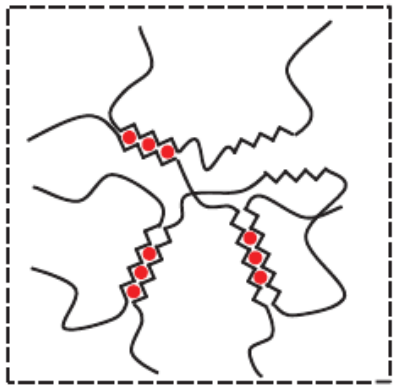
Zhao, Soft Matter, **10**, 672 (2014) for previous works

Build dissipation into stretchy networks

Tough hydrogels: build dissipation into stretchy network

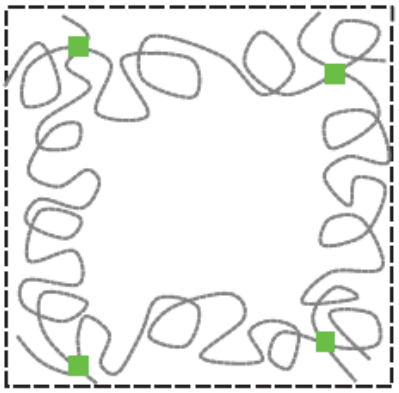
Individual Components are very Brittle!

Dissipation

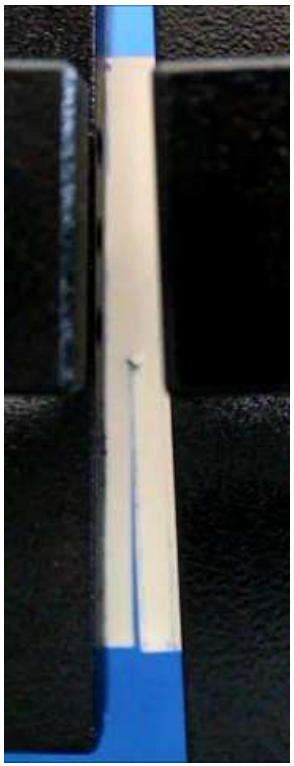


Reversible crosslink:
Alginate Ca^{2+}
dissipates energy

Stretchy network



Long-chain network:
PAAm maintains high elasticity



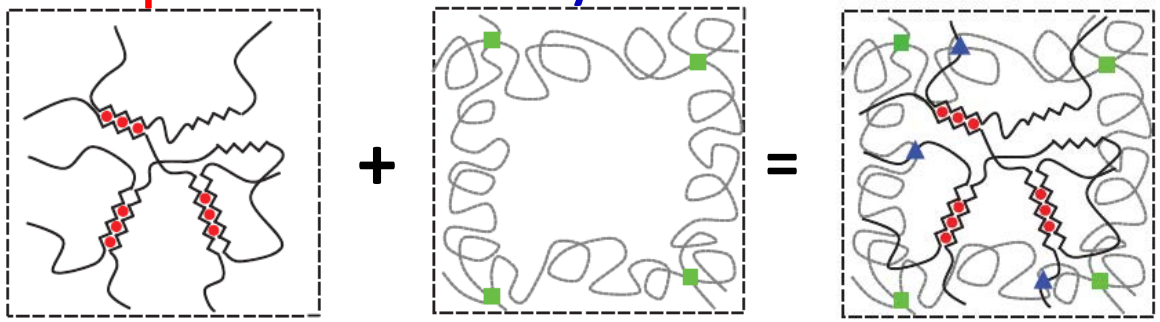
Alginate
~50 Jm^{-2};

PAAm
~50 Jm^{-2}

Tough hydrogels: Build dissipation into stretchy network

Nanoscale Interpenetration gives Extremely High Toughness

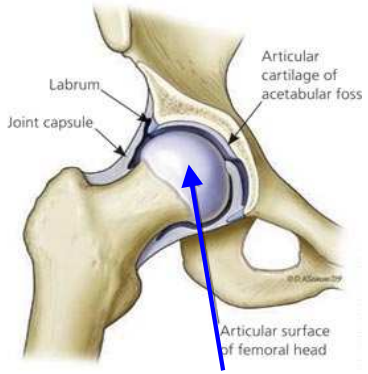
Dissipation + **Stretchy network** =



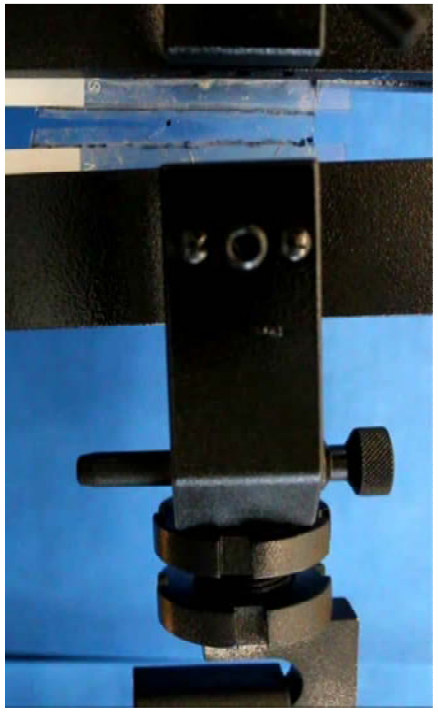
Reversible crosslink: Alginate+Ca^{2+}

Long-chain network: PAAm

- **~90% water**
- **Fracture energy 9000 Jm^{-2}**
- **Stretchability 21 times**



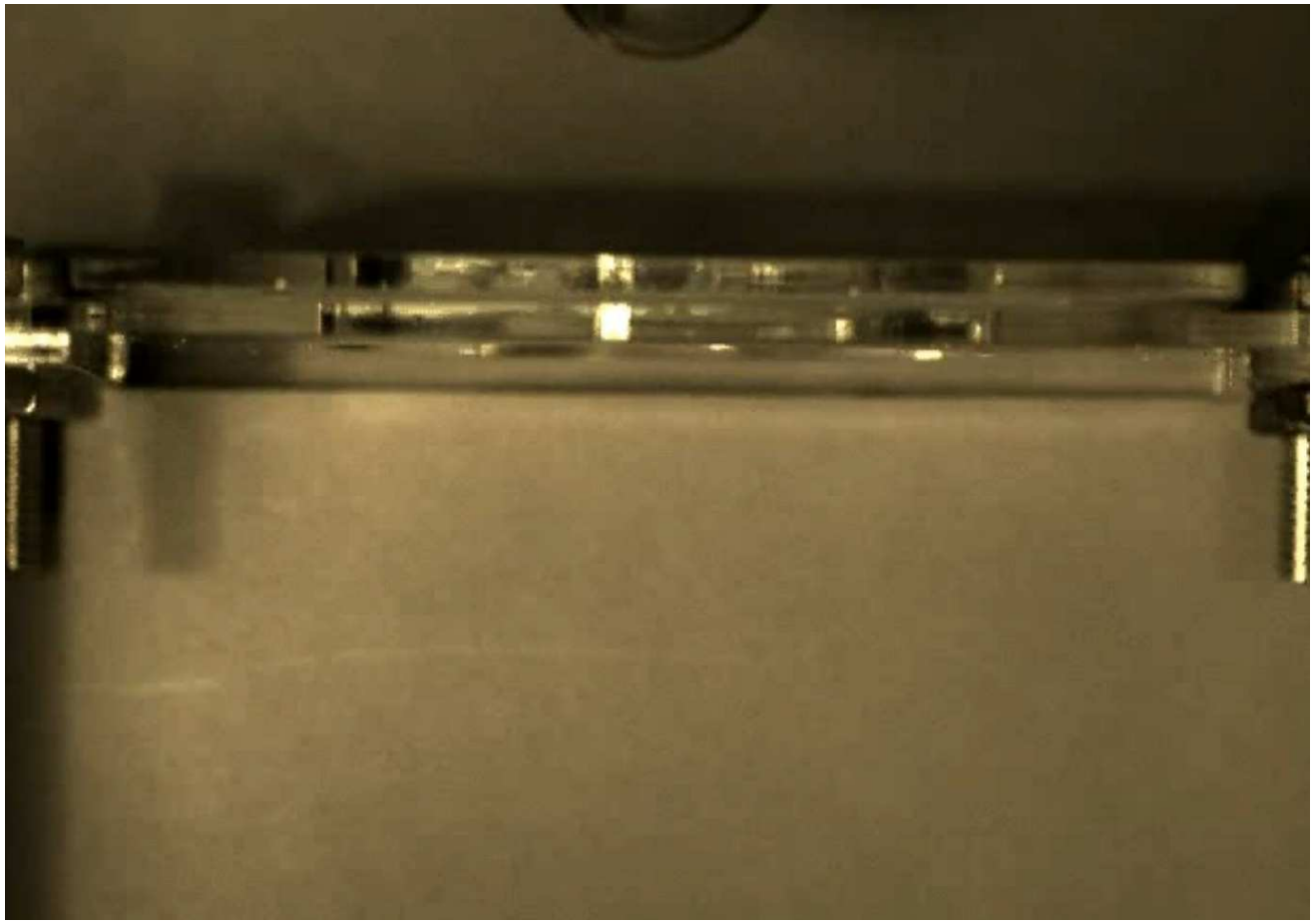
>1000Jm^{-2}



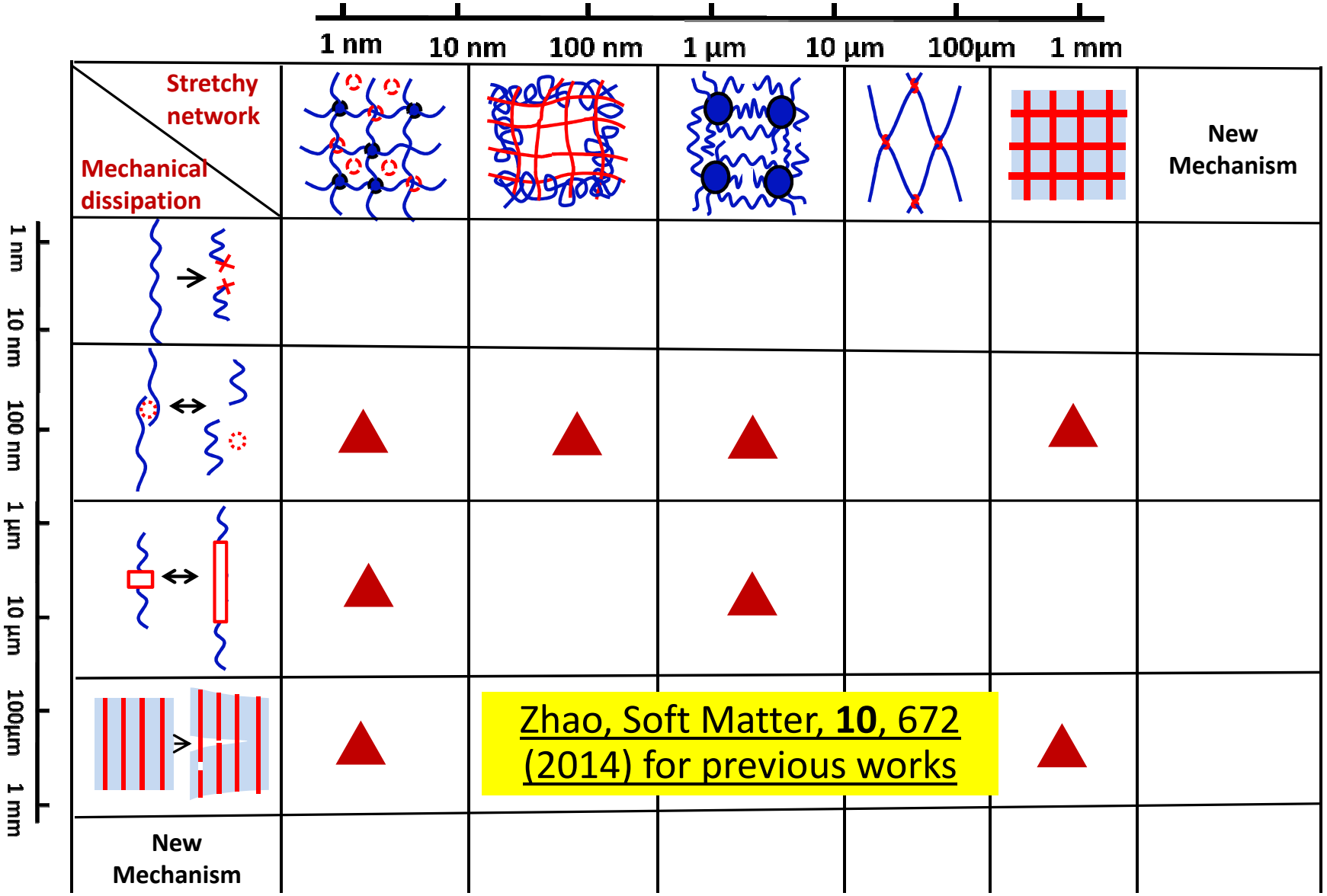
Sun et al, Nature, **489**, 133 (2012)

in collaboration with Prof. Suo, Vlassak and Mooney

Hydrogel film with 90% water and 1mm thickness



Impact of a ball of 64 g at 6m/s



Polymer Candidates:

- PAA
- PAAm
- PEG
- Alginate
- Chitosan
- ELP
- ….

Nano-filler Candidates:

- CNT
- Graphene
- Graphene oxide
- Nanoclay
- ….

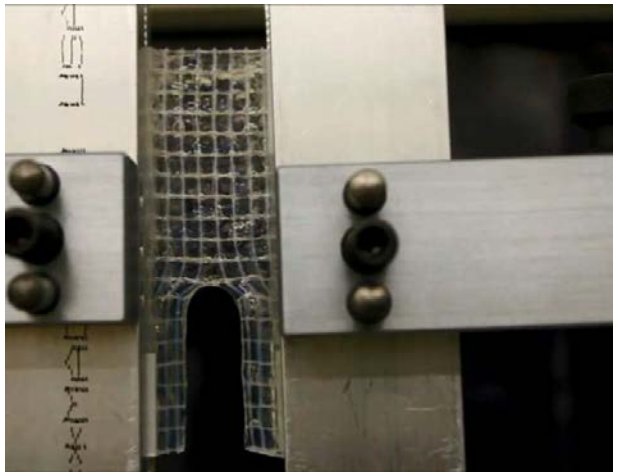
Macro-fiber Candidates:

- PLG
- PCL
- PGA
- …..

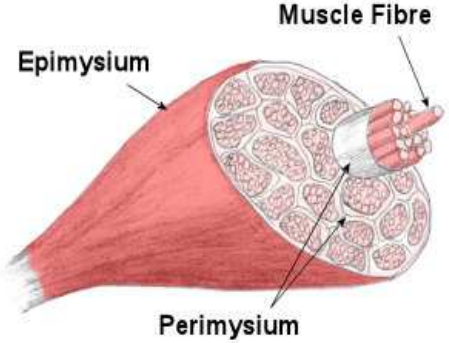
Tough Hydrogels -- A Wide Range of Rigidity with Diverse Polymers

1~5 kPa;
1,000 Jm^{-2}

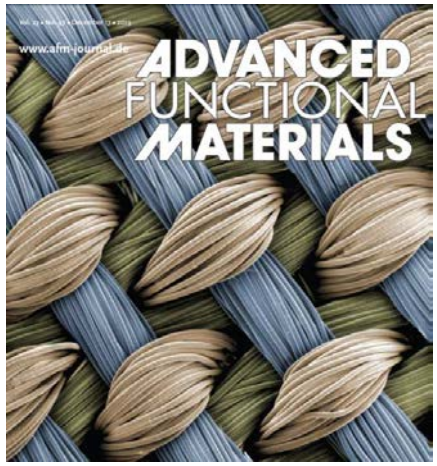
Lin et al, Extreme Mechanics Letters, 1, 70 (2014)



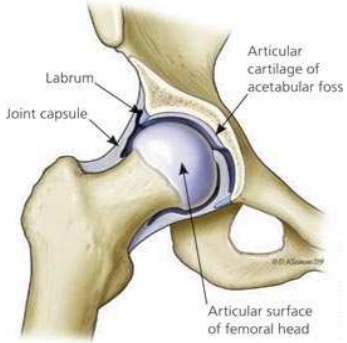
10~100 kPa;
1~10 kJm^{-2}



Sun et al, Nature, **489**, 133 (2012)
Lin et al Soft Matter, 10, 7519, (2014)

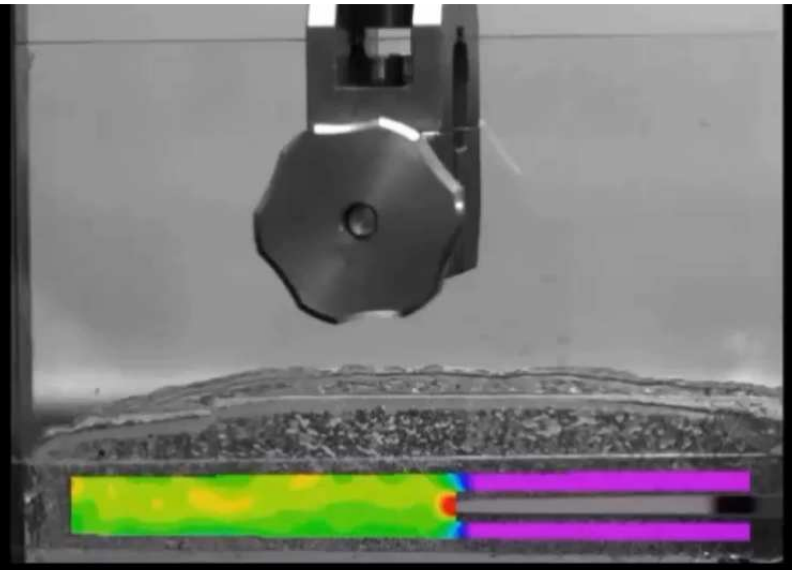


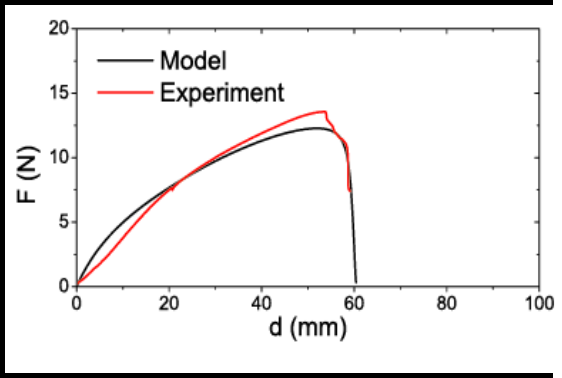
1~10 MPa
10~50 kJm^{-2}



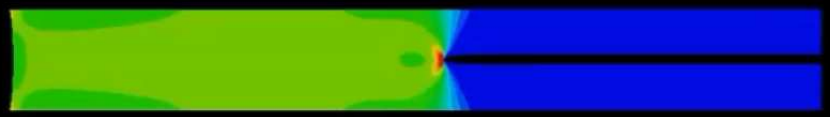
Liao et al, Advanced Functional Materials, **47**, 5833 (2013);

Experiment

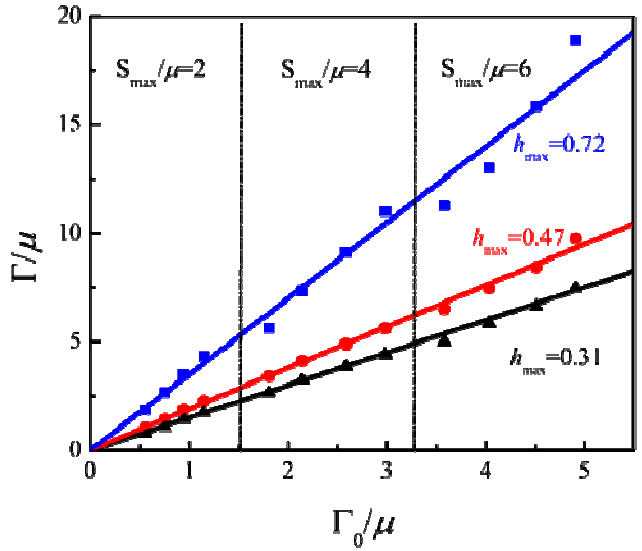


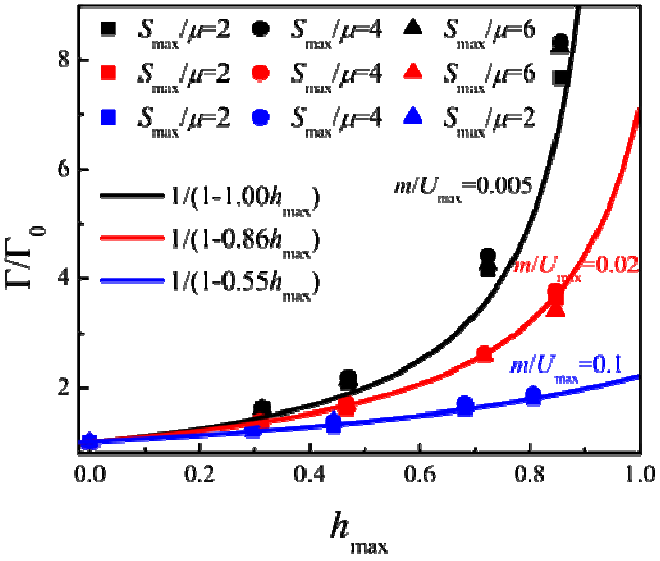


Model
(No fitting parameter)



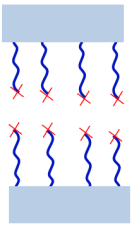
Governing Equation for fracture toughness



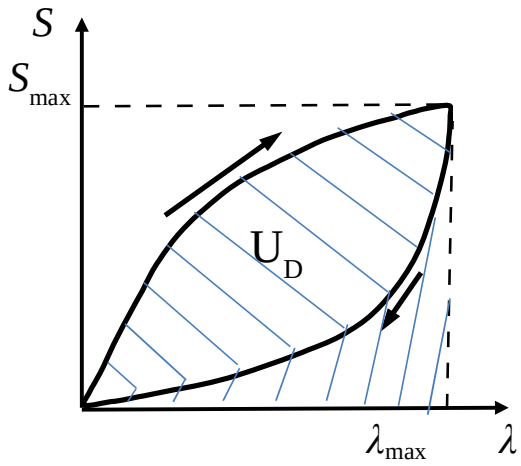


$$\Gamma = \frac{\Gamma_0}{1-\alpha \cdot h_{\max}}$$

Intrinsic Fracture Energy



Maximum hysteretic ratio



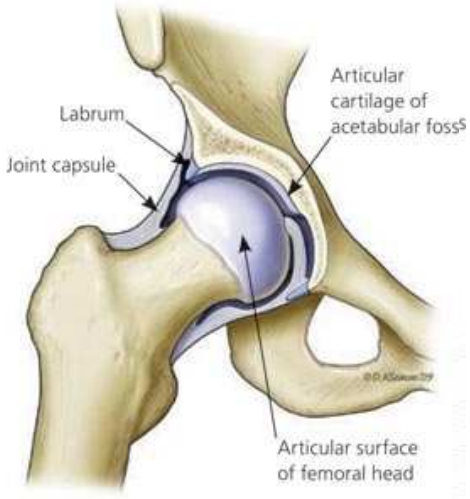
$\alpha \approx 1$ for stretchy materials

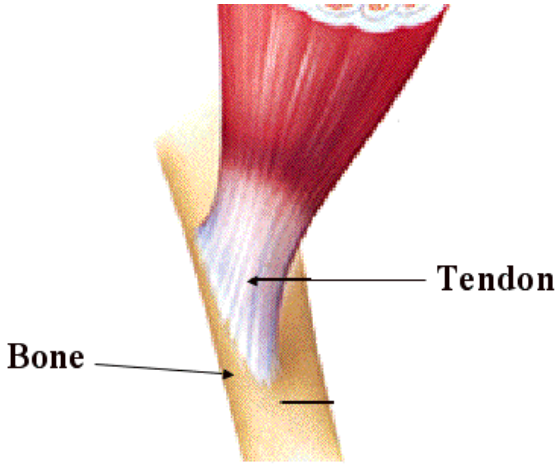
Zhang et al, EML, 4, 1 (2015)

Hydrogels

Extremely Adhesive

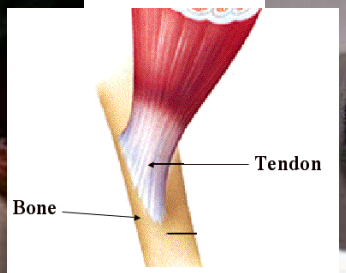
Adhesive Hydrogels in Nature

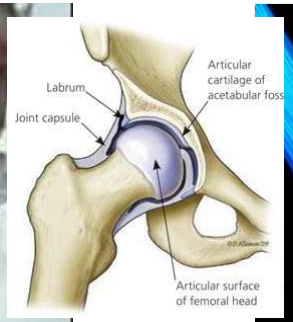


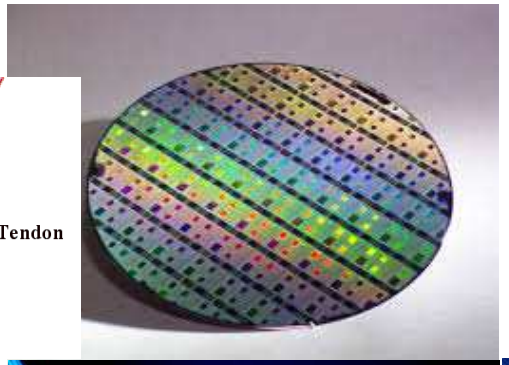


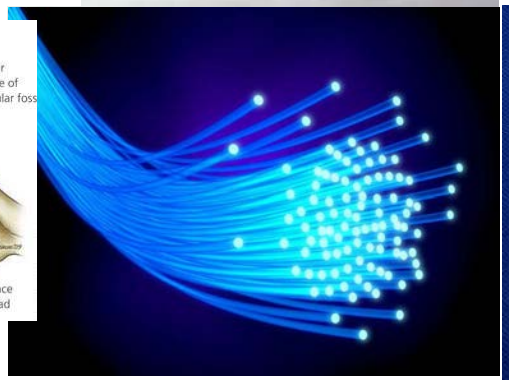
Interfacial toughness ~800Jm^{-2}

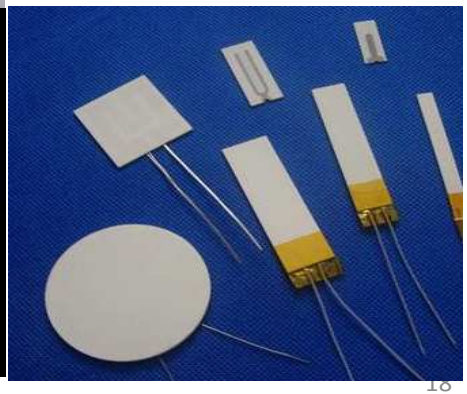
Design Adhesive Hydrogels









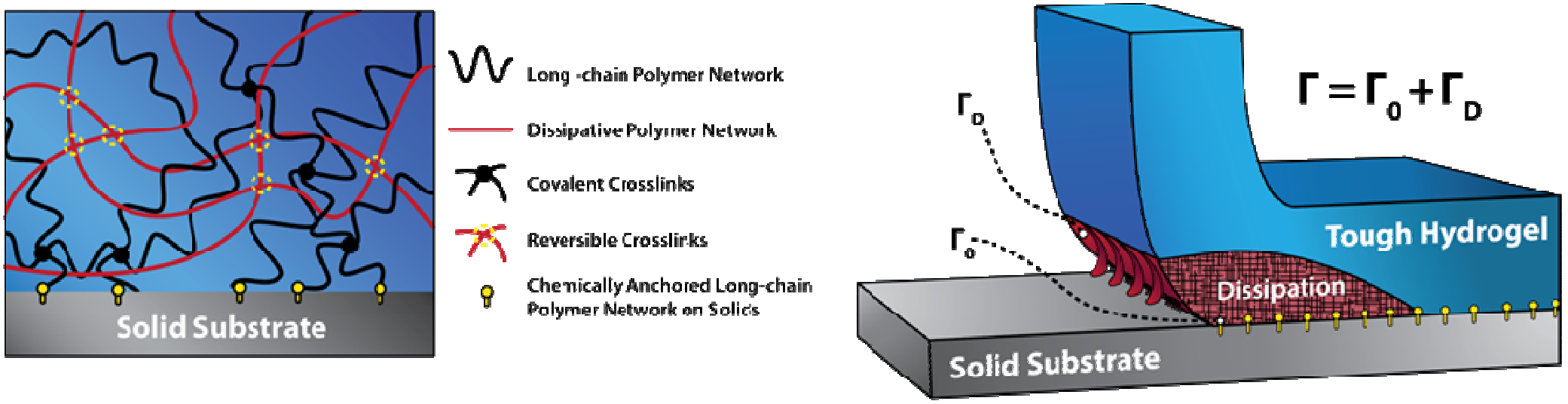


90% water; ~kPa

Diverse engineering solids; MPa~GPa

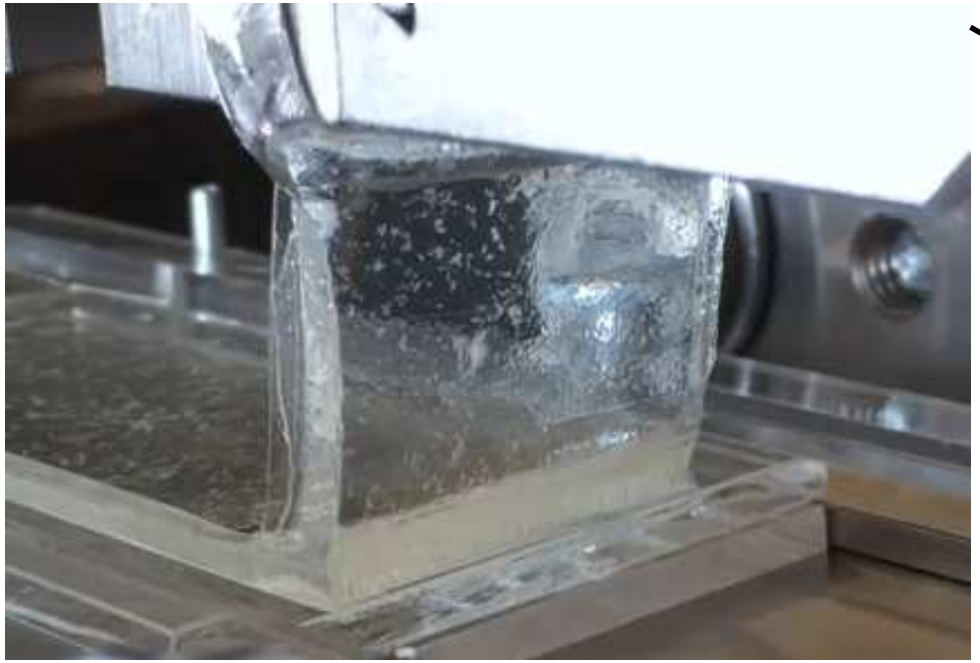
Tough Hydrogels: Build dissipation into stretchy network.

Adhesive Hydrogels: Anchor stretchy network on hard material.

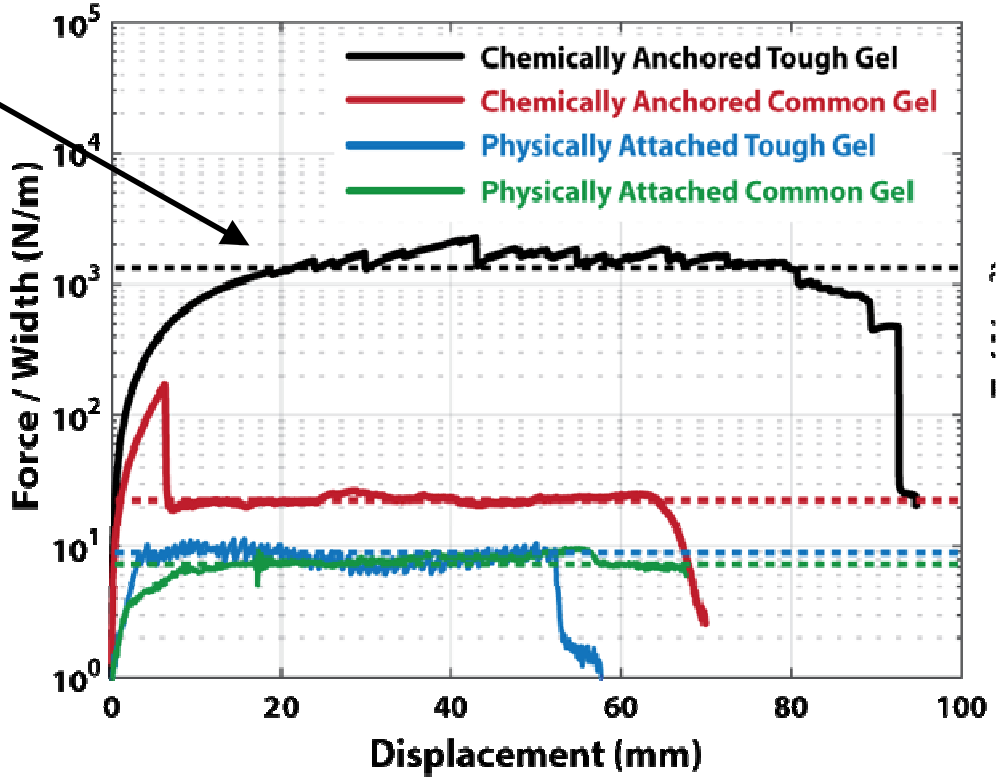


Yuk et al, Nature Materials, 15, 190-196 (2016);
Yuk et al, Nature Communications, 7, 12028 (2016)

Hydrogels with 90% water bonded on Si, SiO_2, glass, ceramics, Ti, Al, Fe et al

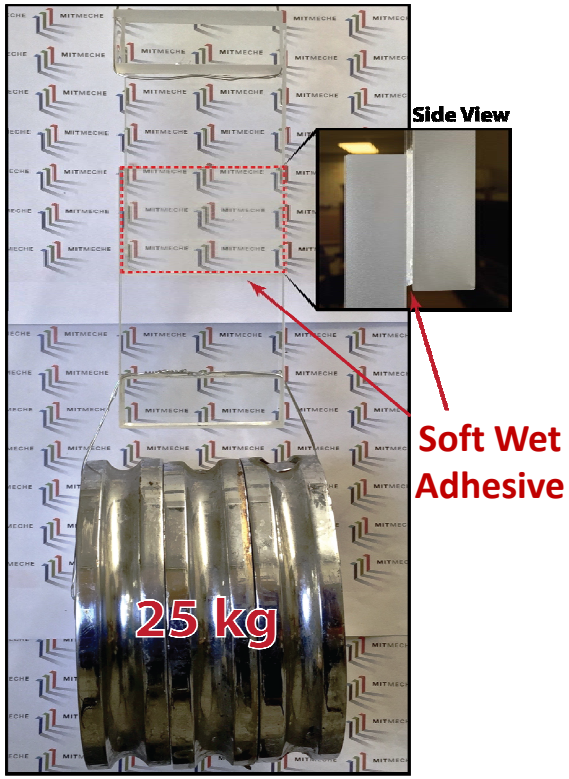


Detachment and Finger Instability



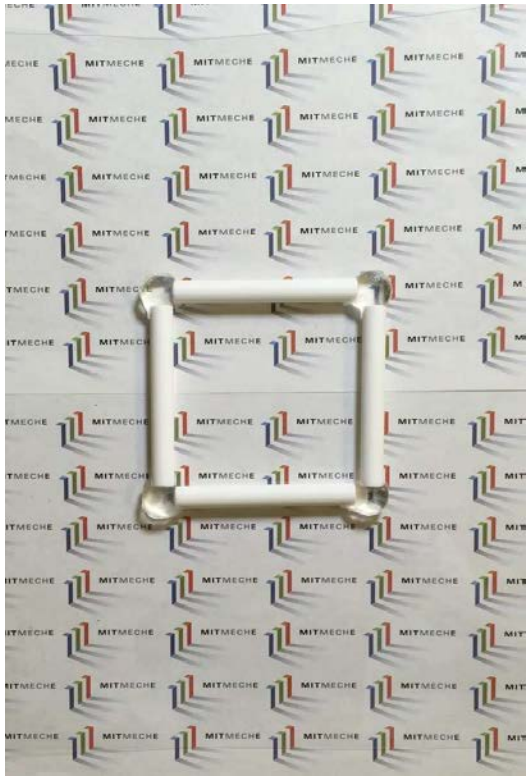
Yuk et al, Nature Materials, 15, 190-196 (2016);

Hydrogel-Engineering Material Hybrids

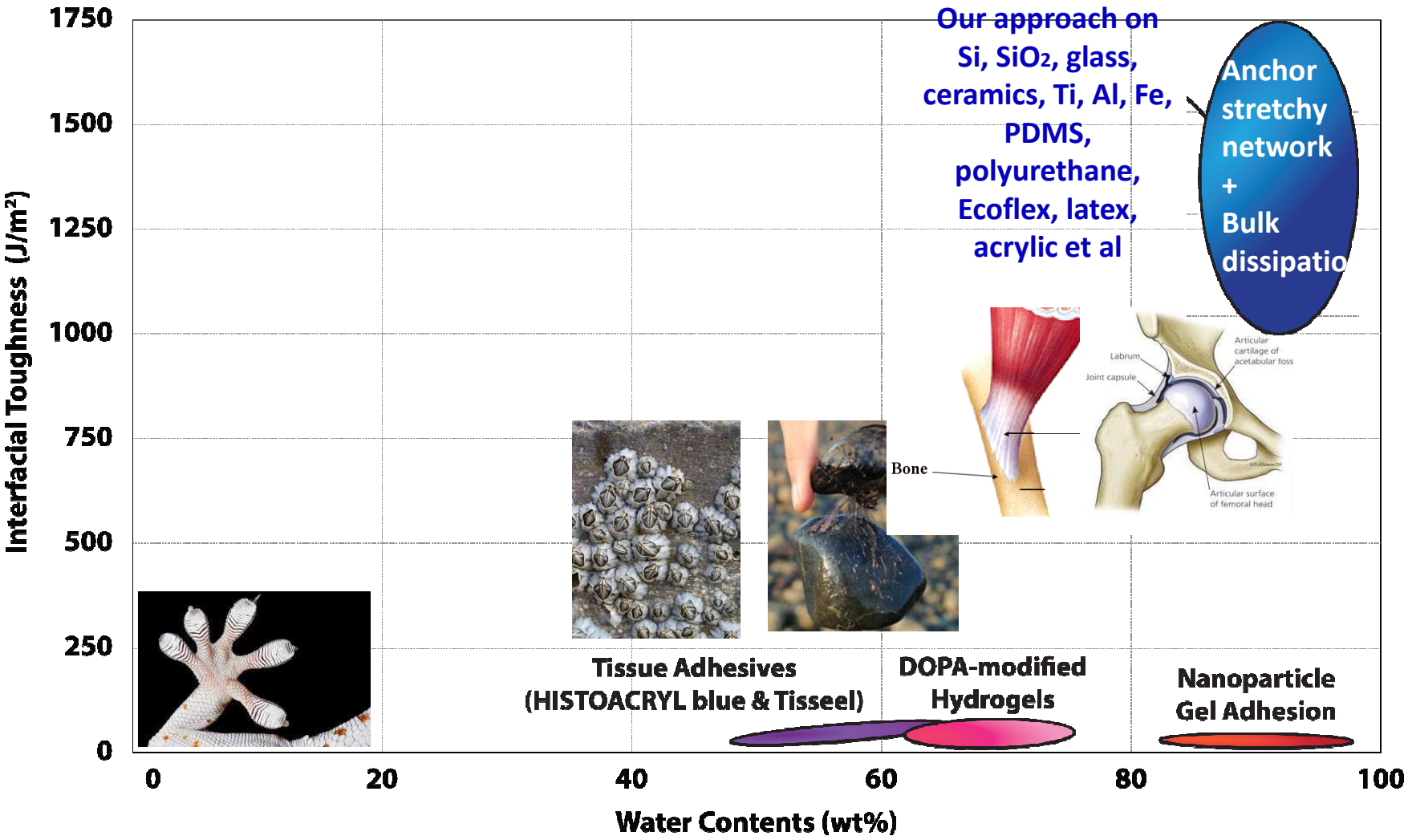


With glass

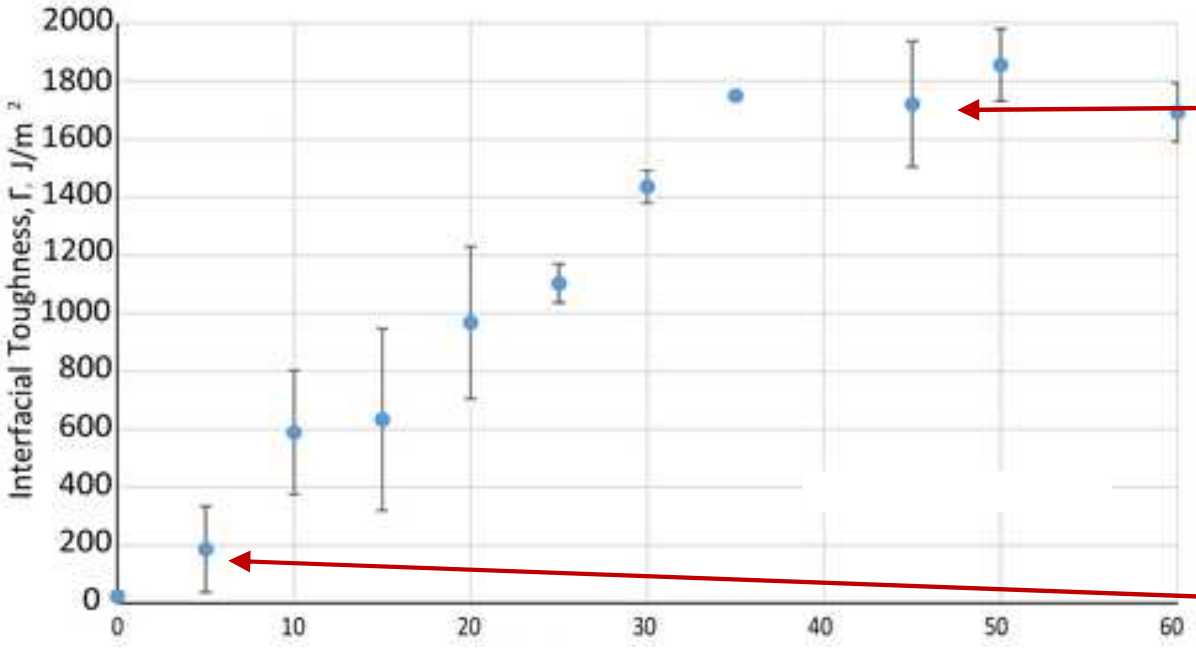
With silicon



With ceramics


Interfacial Toughness (J/m²)
1750
1500
1250
1000
750
500
250
0
0
20
40
60
80
100
Water Contents (wt%)
Our approach on
Si, SiO2, glass,
ceramics, Ti, Al, Fe,
PDMS,
polyurethane,
Ecoflex, latex,
acrylic et al
Anchor
stretchy
network
+
Bulk
dissipatio
Bone
Labrum
Joint capsule
Articular
cartilage of
acetabular foss
Articular surface
of femoral head
Tissue Adhesives
(HISTOACRYL blue & Tisseel)
DOPA-modified
Hydrogels
Nanoparticle
Gel Adhesion

Tunable Adhesion from 1 to 1000 Jm-2

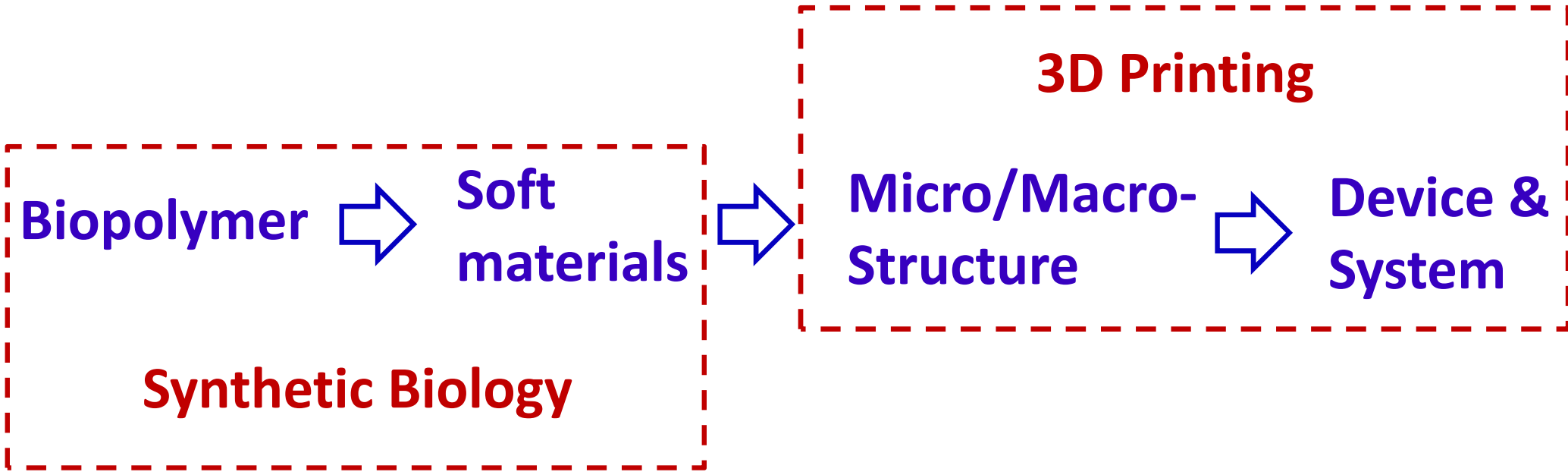


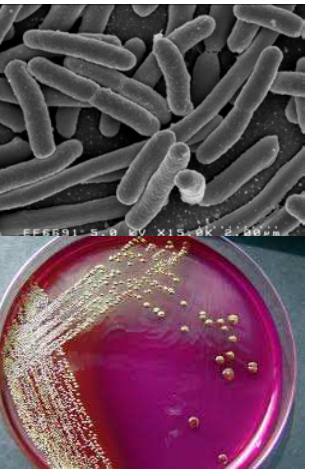
Functional group coverage (%)

Parada et al, In submission (2017)

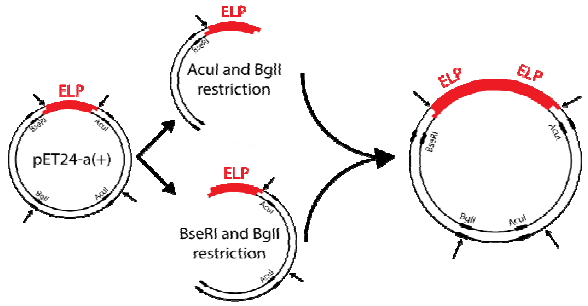
Hydrogels

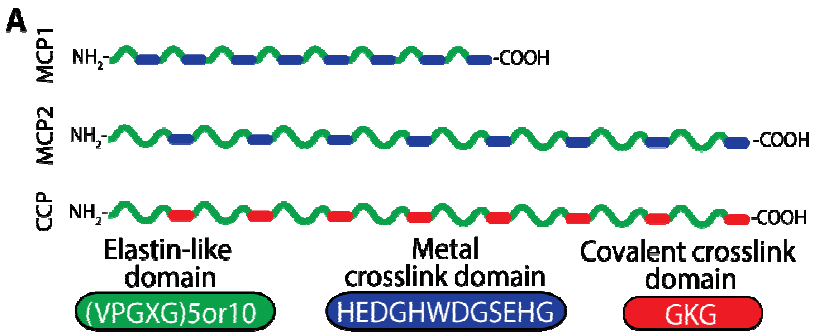
Manufacturing

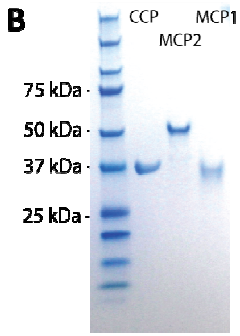


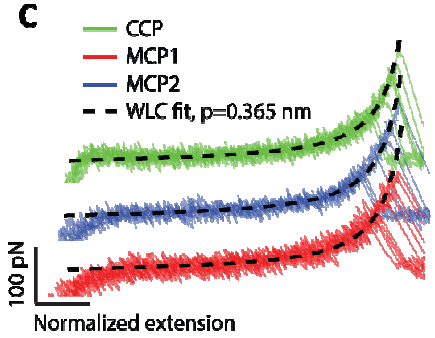


Biopolymers Designed by Synthetic Biology







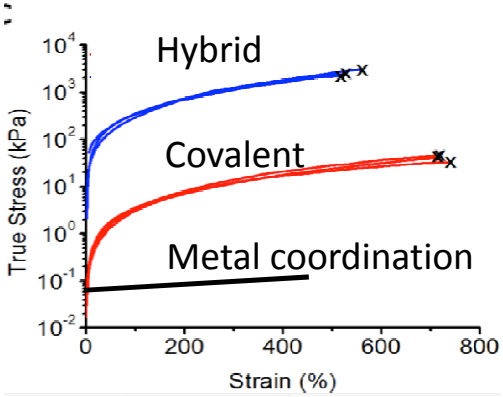


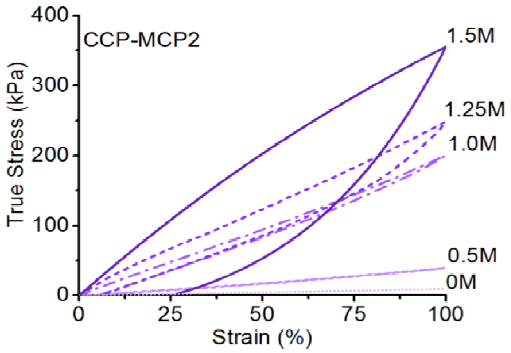
Ghoorchian et al
Adv. Funct. Mater.,
DOI:10.1002/adfm.
201500699 (2015)

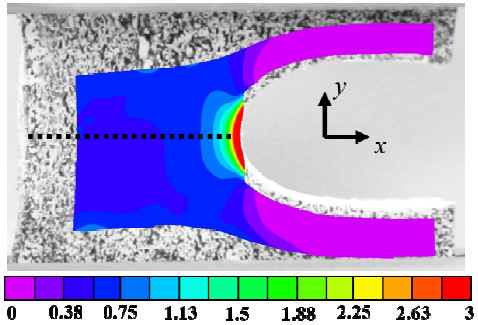
Gonzalez et al,
Unpublished (2015)

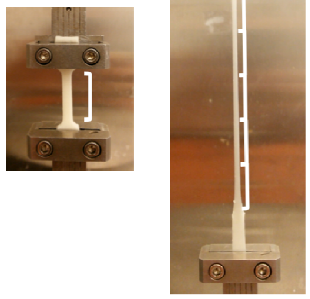
In collaboration with Gabriel Lopez and Tosh Chilkoti at Duke

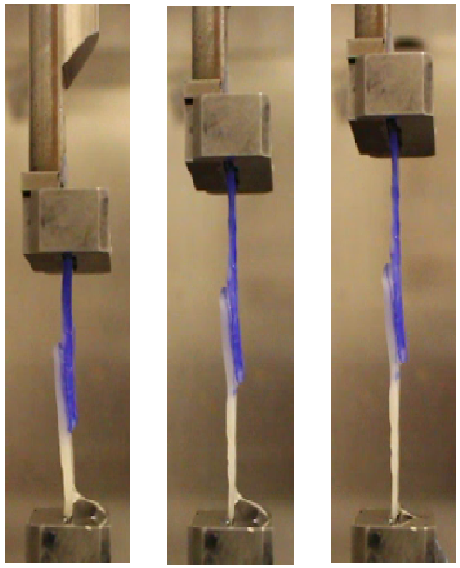
Biopolymers Designed by Synthetic Biology



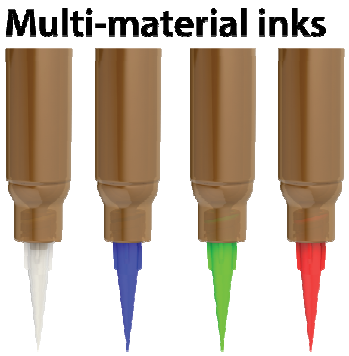


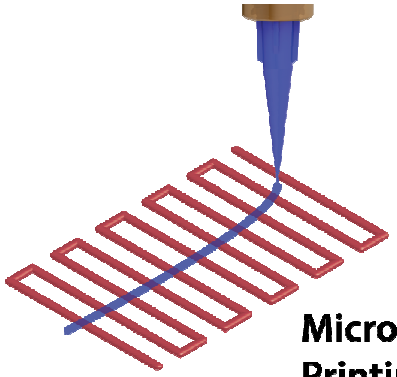




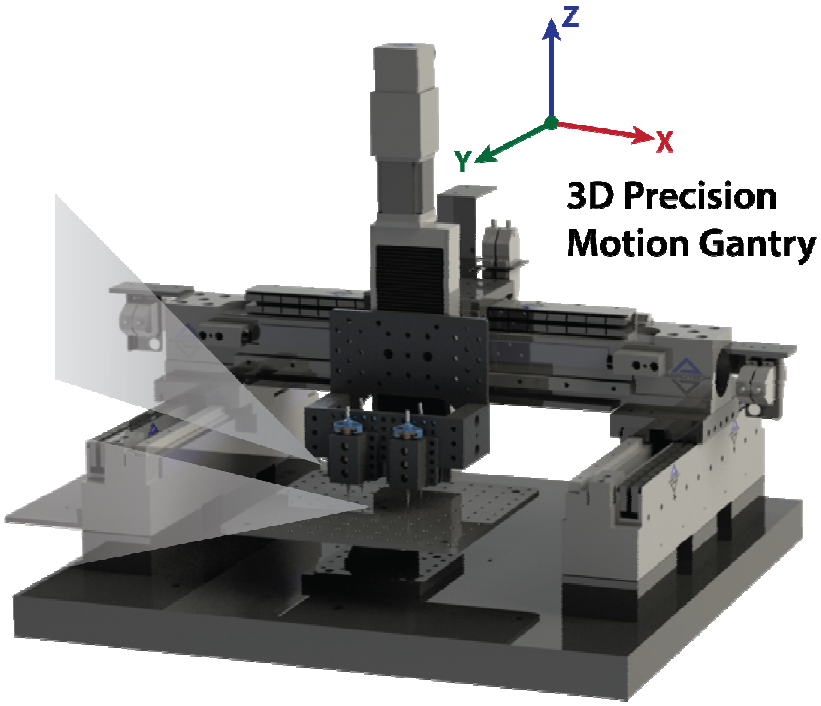


Multi-material 3D Bio-printer



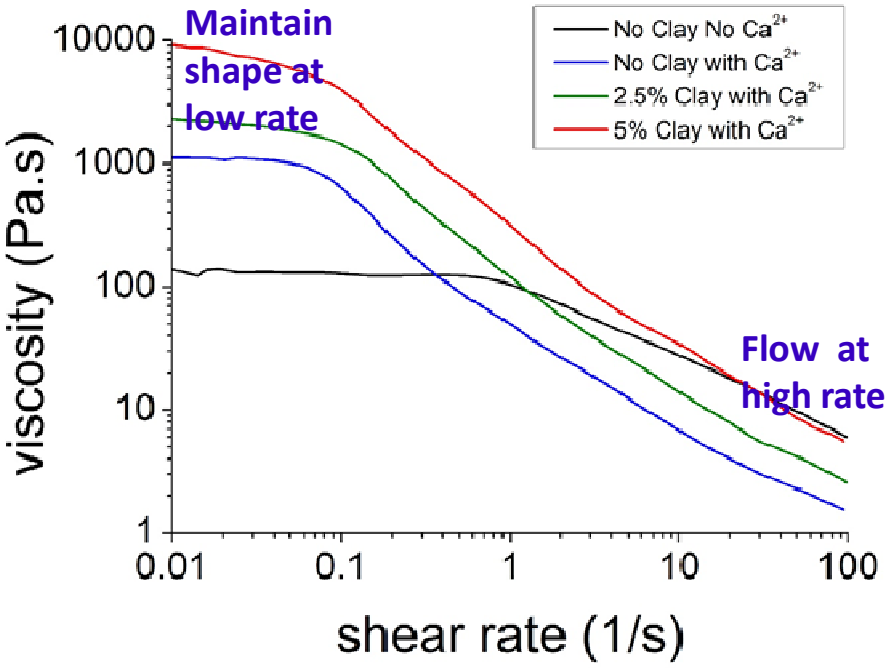


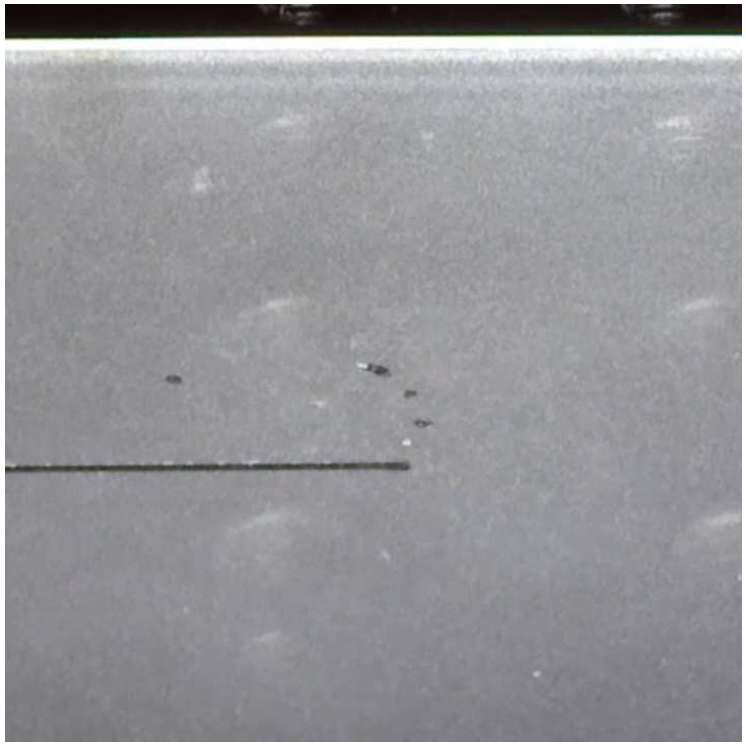
Microscale
Printing of Diverse Materials



- Micro-extrusion based
- Resolution up to **5um**.
- Printing **multiple** materials in one structure
- Particularly suitable for **soft materials and biomaterials**.

Microstructures Manufactured by 3D Printing

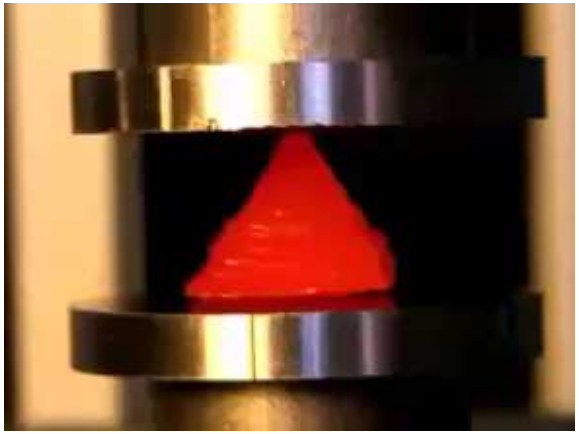




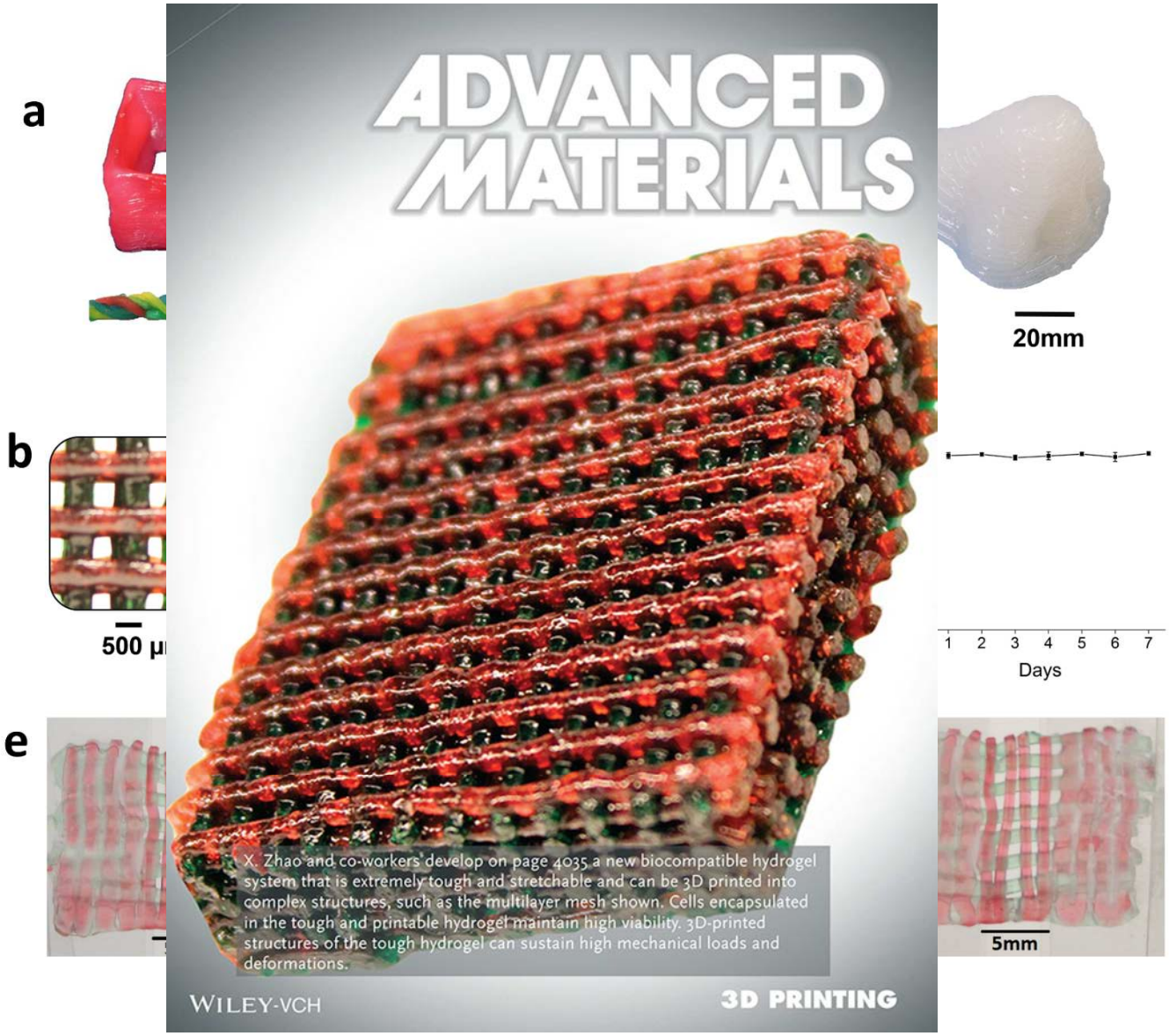
Ink: Shear-thinned polymer solution & Unconventional networks

Hong et al Advance Materials, 27, 4035 (2015)

Tough Soft Microstructures by 3D Printing



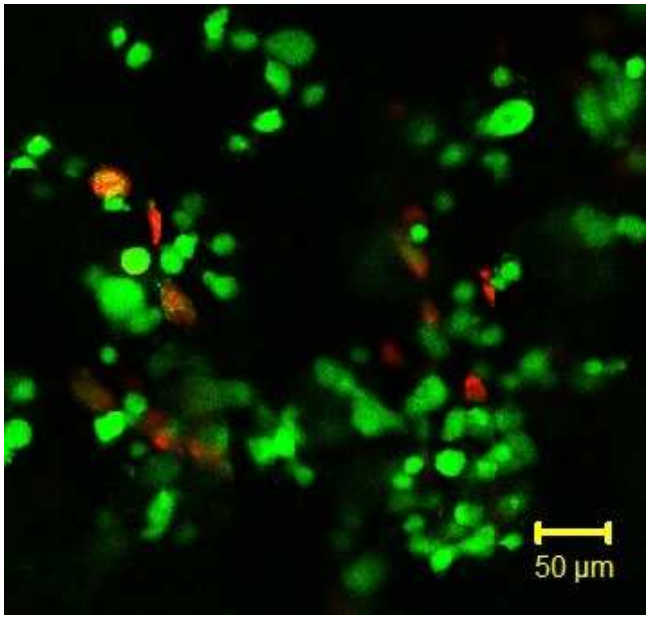
Hong et al Advance Materials, 27, 4035 (2015)



Hydrogels

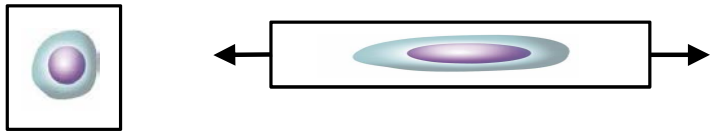
Bio-scaffolds, Electronics, Machines and Robots

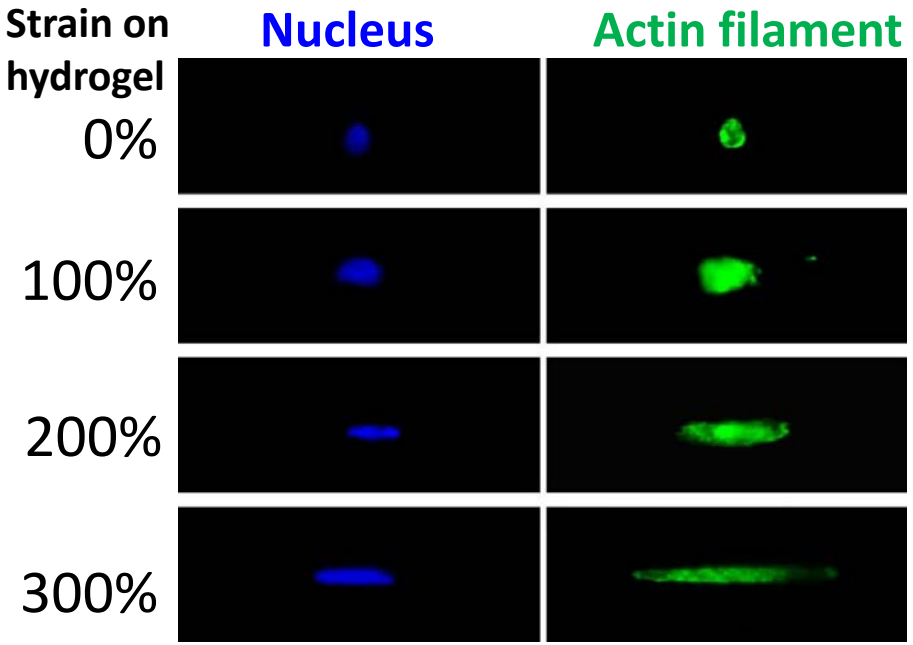
Growing Cells and Tissues in Hydrogel Scaffolds



Human mesenchymal stem cells (hMSC)

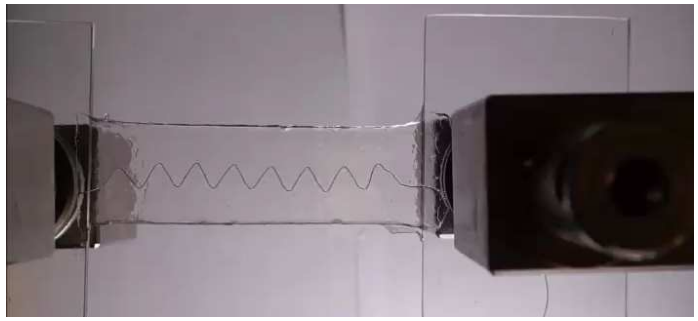
live dead assay



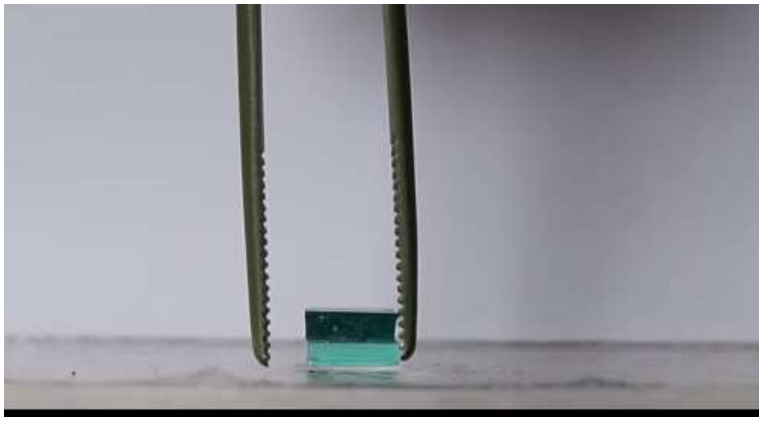


Hong et al Advance Materials, 27, 4035 (2015)

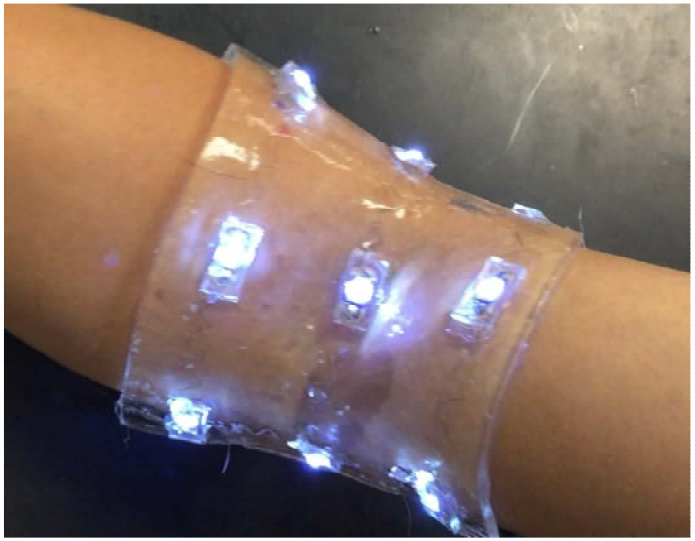
Integrating Electronics with hydrogels (70~90% water)



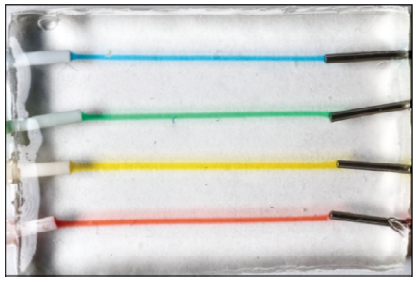
Conductive wires



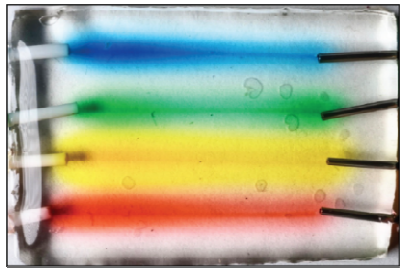
Functional islands



LED arrays



t = 0 min, λ = 1

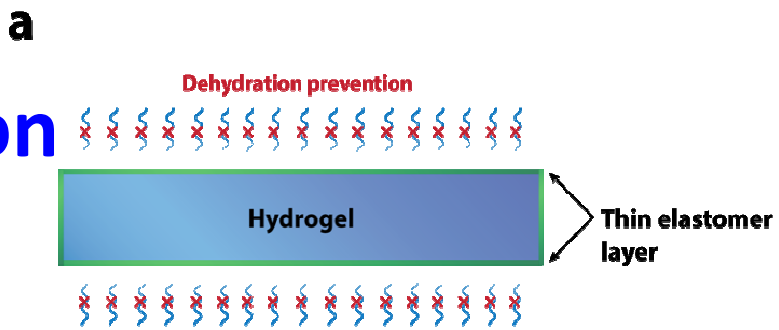


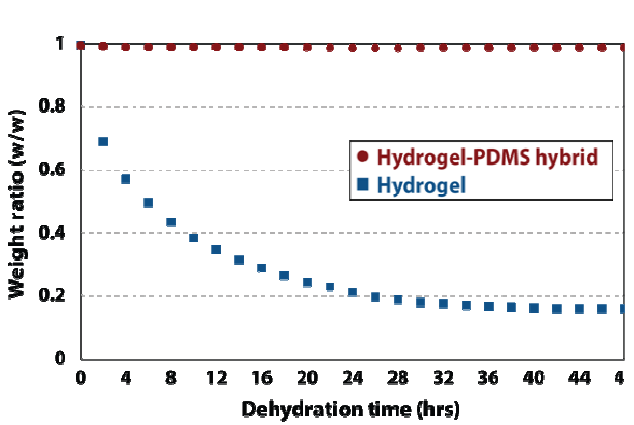
t = 120 min, λ = 1

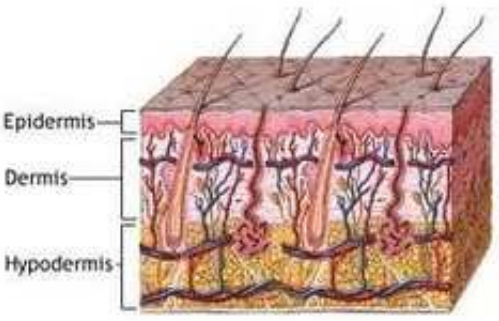
Drug delivery channels

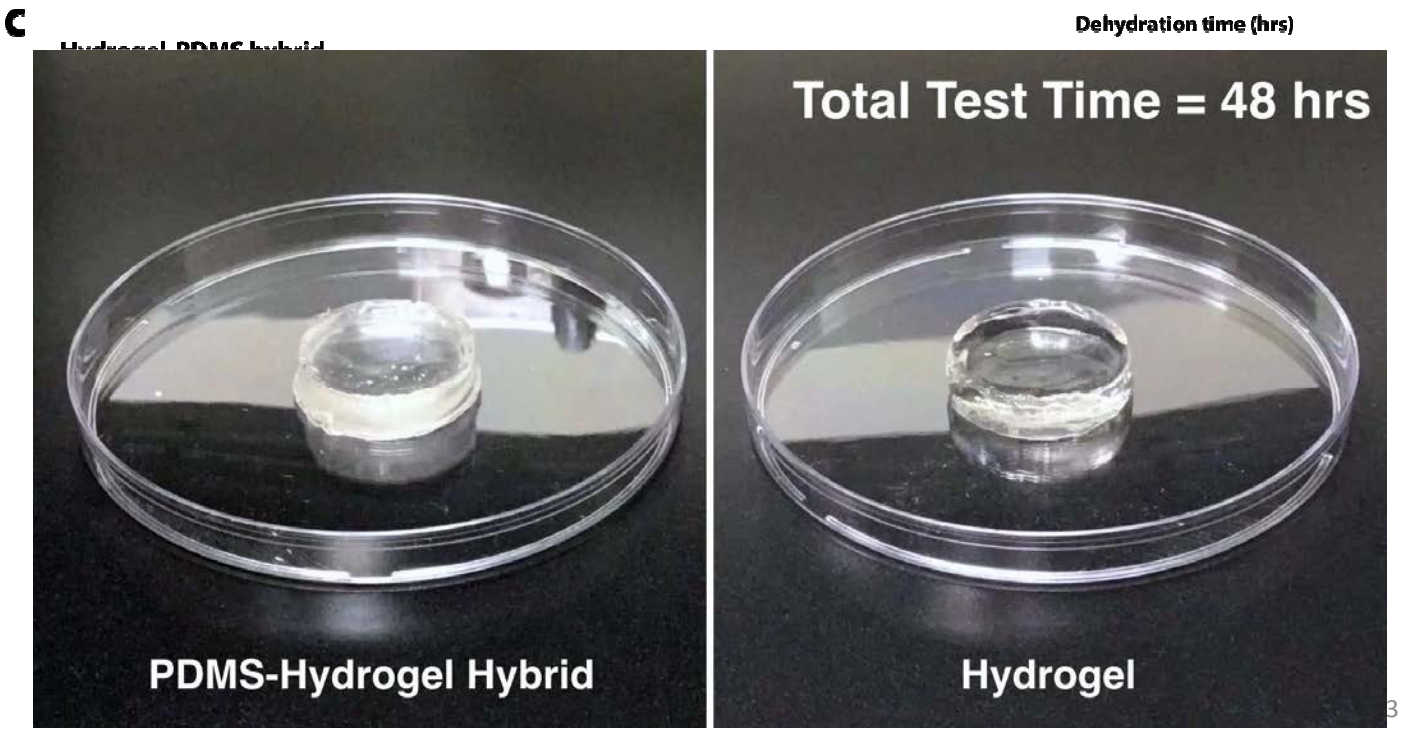
Lin, et al, Advanced Materials, 28, 4497–4505(2016)

Anti-dehydration hydrogel



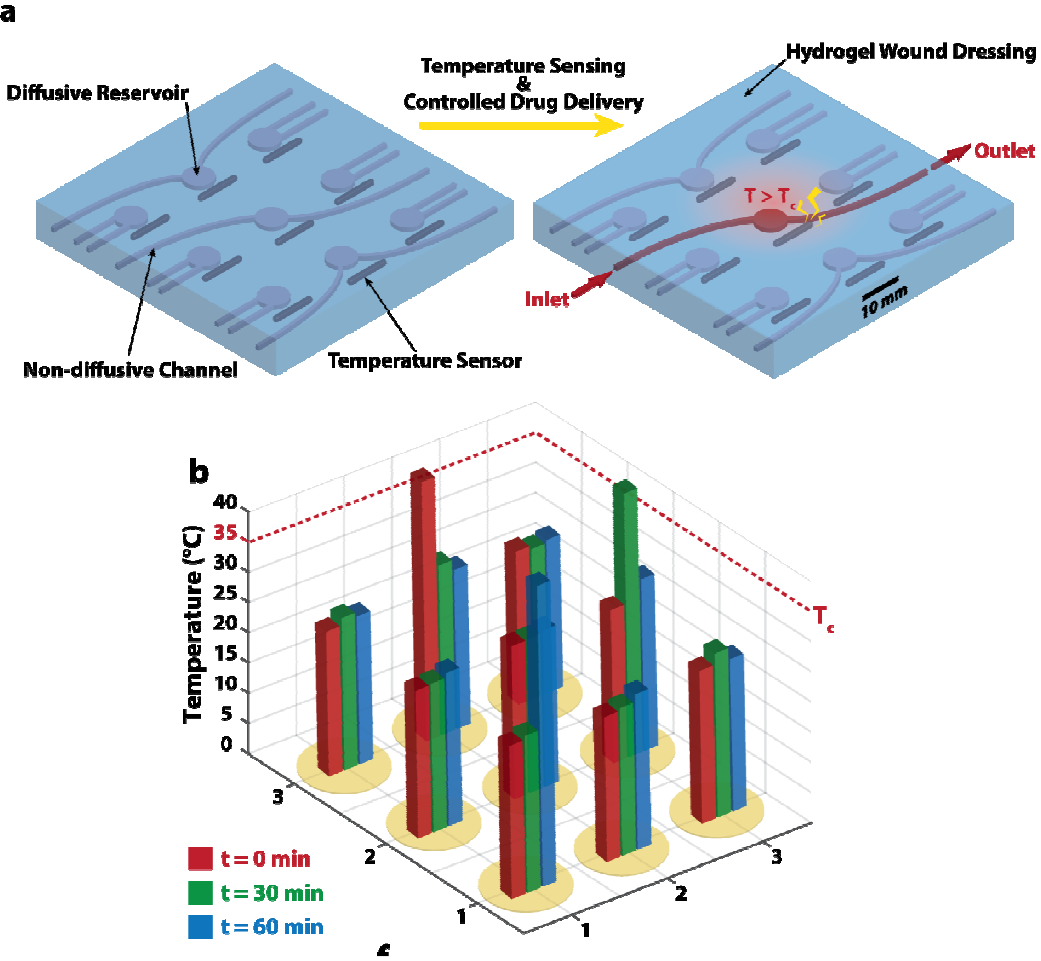


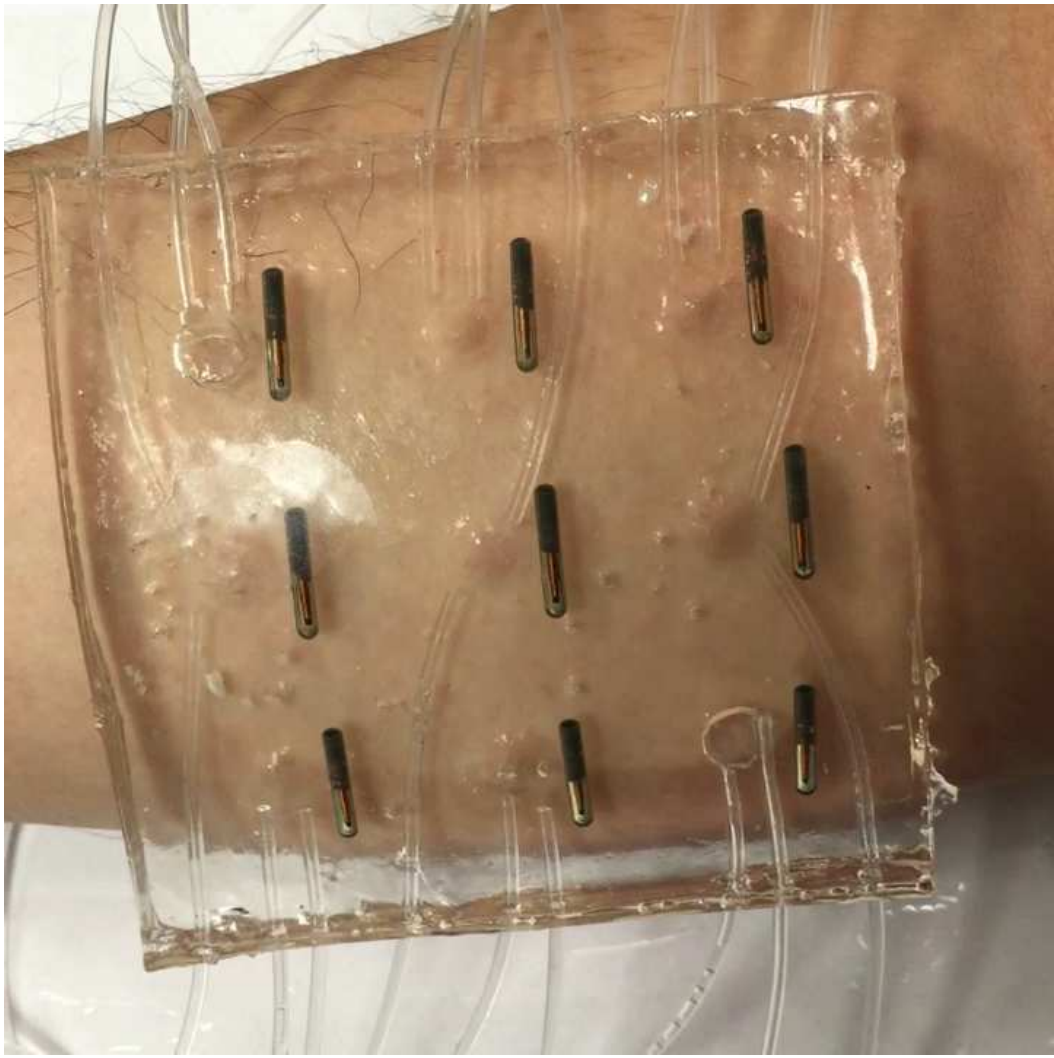




Yuk et al, Nature Communications, In press (2016)

Smart Hydrogel Band-Aid

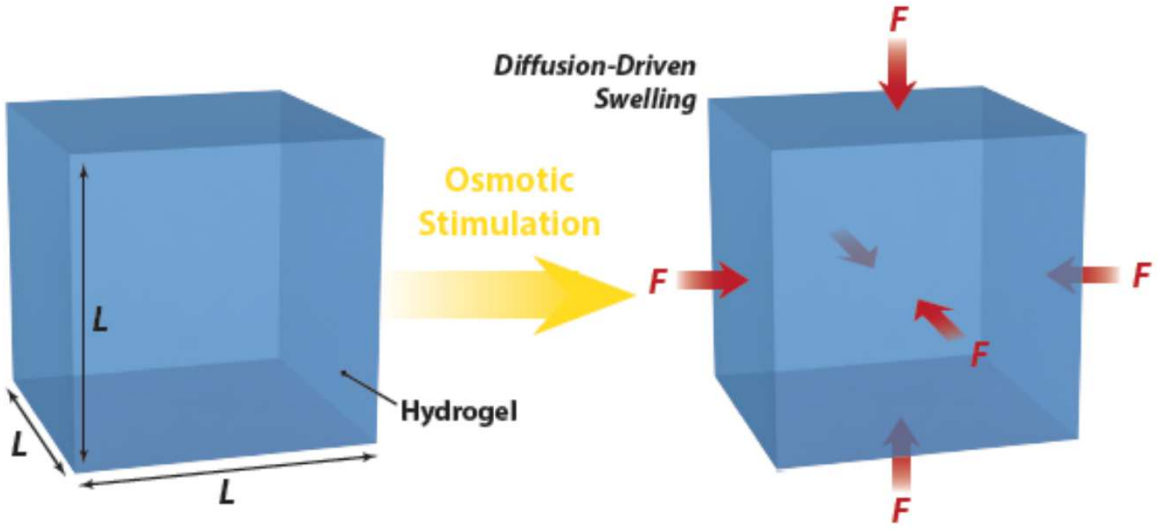




Lin, et al, Advanced Materials, 28, 4497–4505(2016)

Hydrogel Robots

Existing Hydrogel Actuators are Mostly Osmotic-Driven



Toyoichi Tanaka (1946-2000)
Professor of Physics, MIT

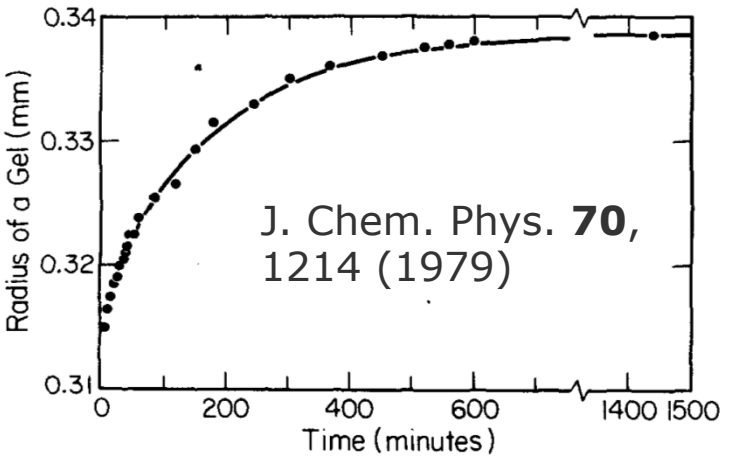
$$F \propto \Delta\Pi L^2 \sim 10N$$

$$t \propto L^2 / D \sim 10^6 s$$

$$\Delta\Pi \sim 100kPa$$

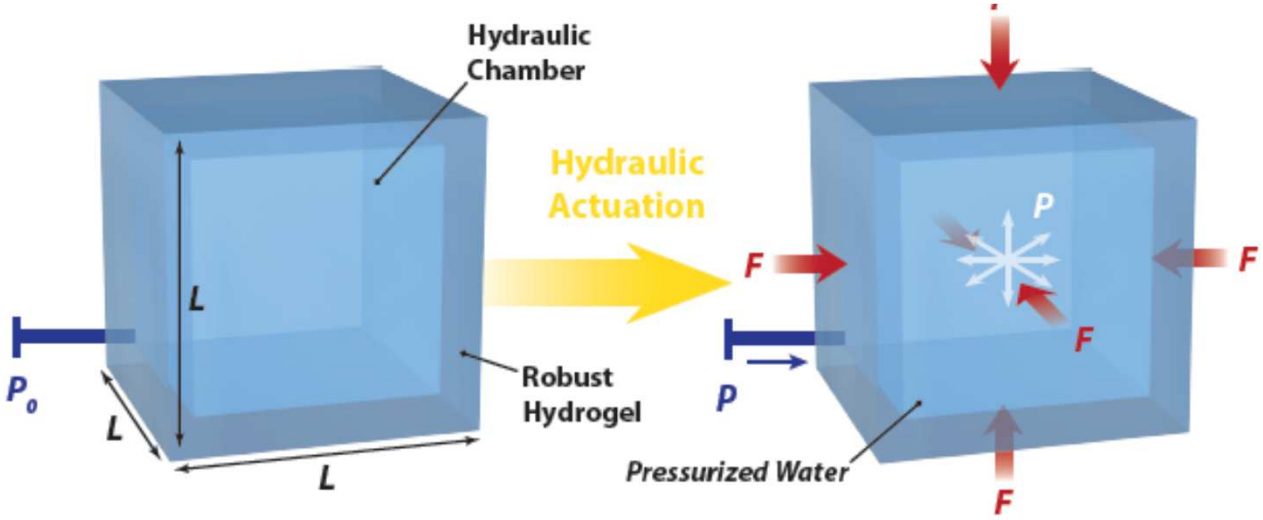
$$L \sim cm$$

$$D \sim 10^{-10} m^2 / s$$



Zhao et al, PNAS, **108**, 67 (2011); Hong et al, JMPS **58**, 558-577 (2010)

Hydraulic Actuation of Tough Hydrogel Structures



$$F \propto \Delta P L^2 \sim 10\,N$$

$$t = t_{external} < 1s$$

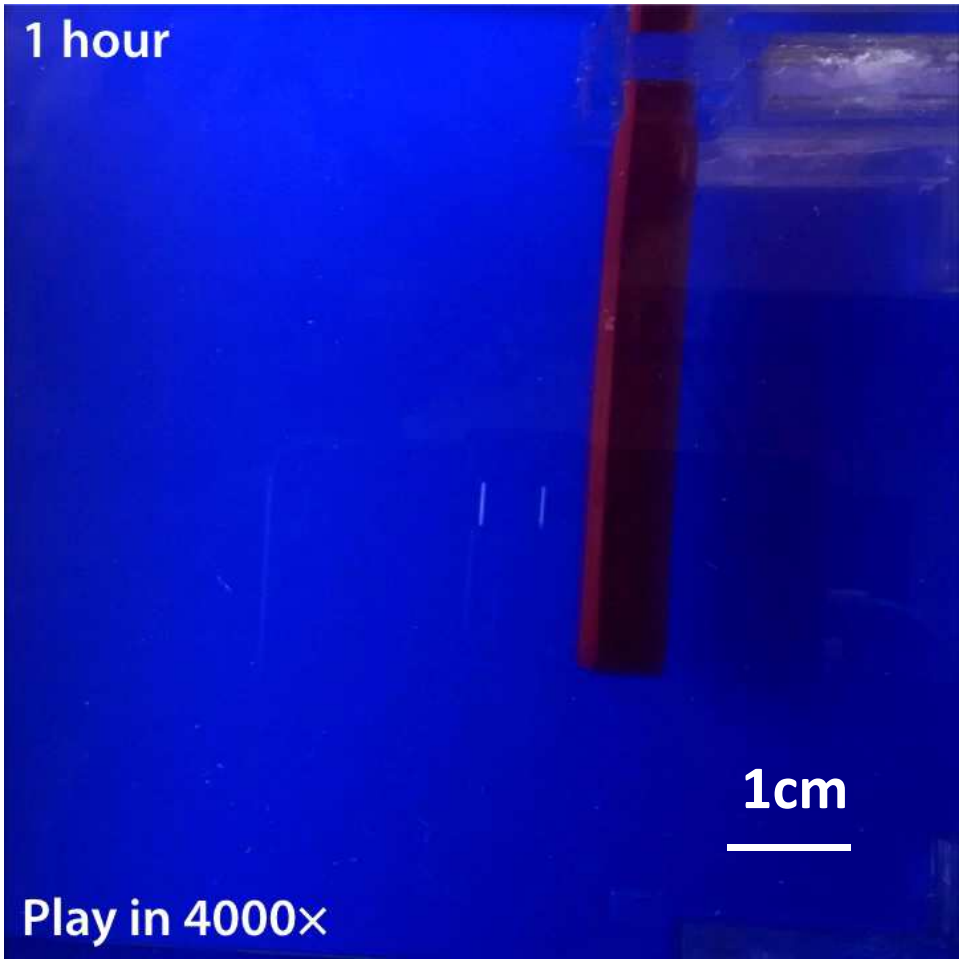
$$\Delta P \sim 100 kPa$$

$$L \sim cm$$

$$t_{external} < 1s$$

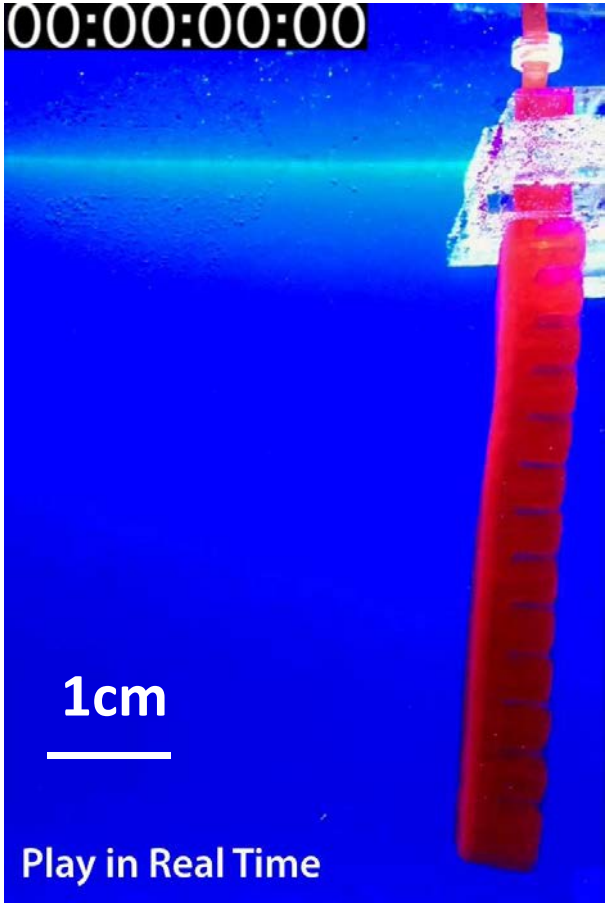
Yuk et al,
Nature Communications,
DOI:10.1038/ncomms14230 (2017)

Osmotic Actuation

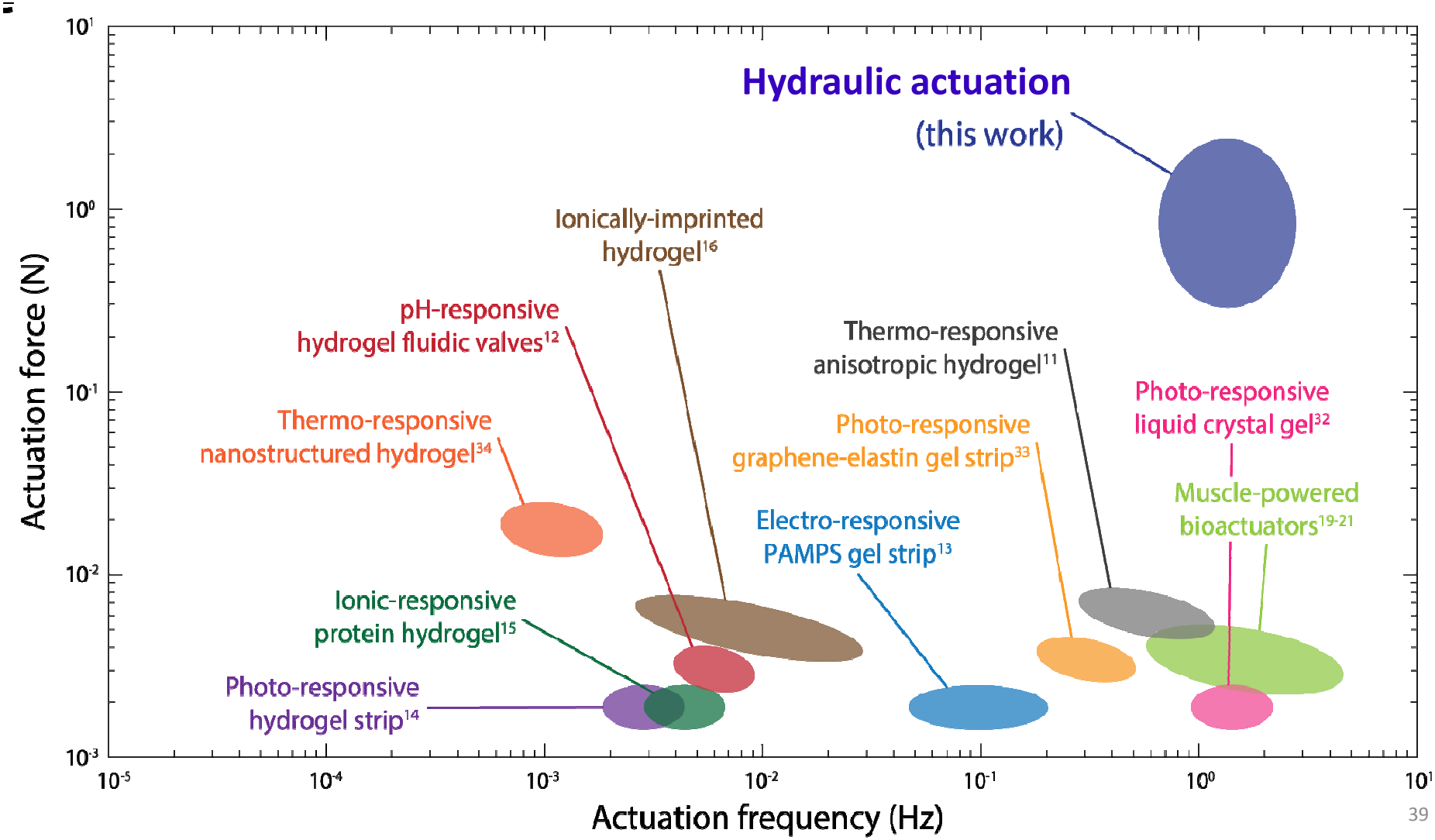


Speed: 4000 X

Hydraulic Actuation



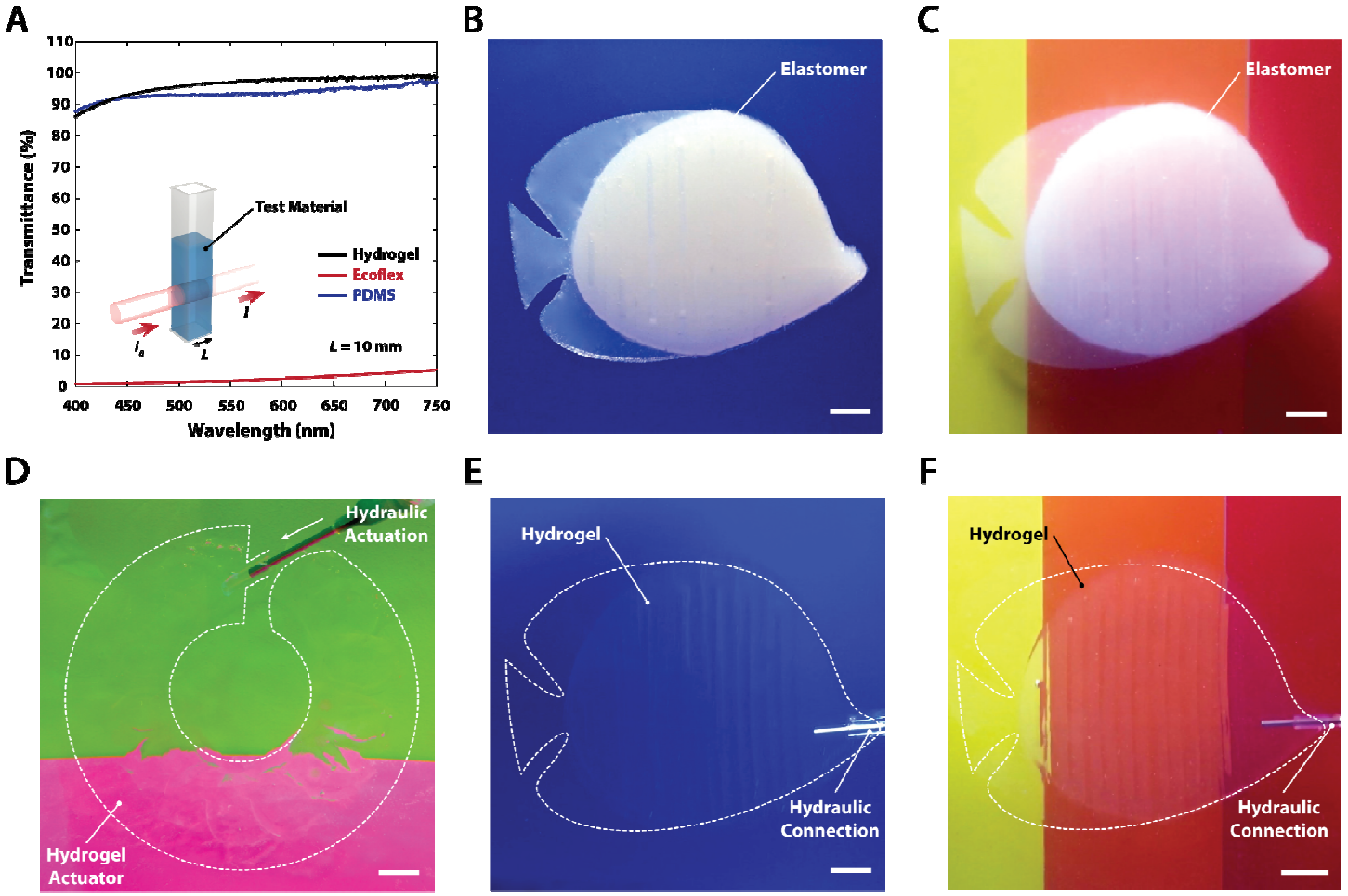
Speed: Real Time


Hydraulic actuation
(this work)
Ionically-imprinted hydrogel[16]
pH-responsive hydrogel fluidic valves[12]
Thermo-responsive anisotropic hydrogel[11]
Photo-responsive liquid crystal gel[32]
Thermo-responsive nanostructured hydrogel[34]
Photo-responsive graphene-elastin gel strip[33]
Muscle-powered bioactuators[19-21]
Electro-responsive PAMPS gel strip[13]
Ionic-responsive protein hydrogel[15]
Photo-responsive hydrogel strip[14]
Actuation force (N)
Actuation frequency (Hz)
10^1
10^0
10^-1
10^-2
10^-3
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1

Optically and Acoustically Invisible in Water

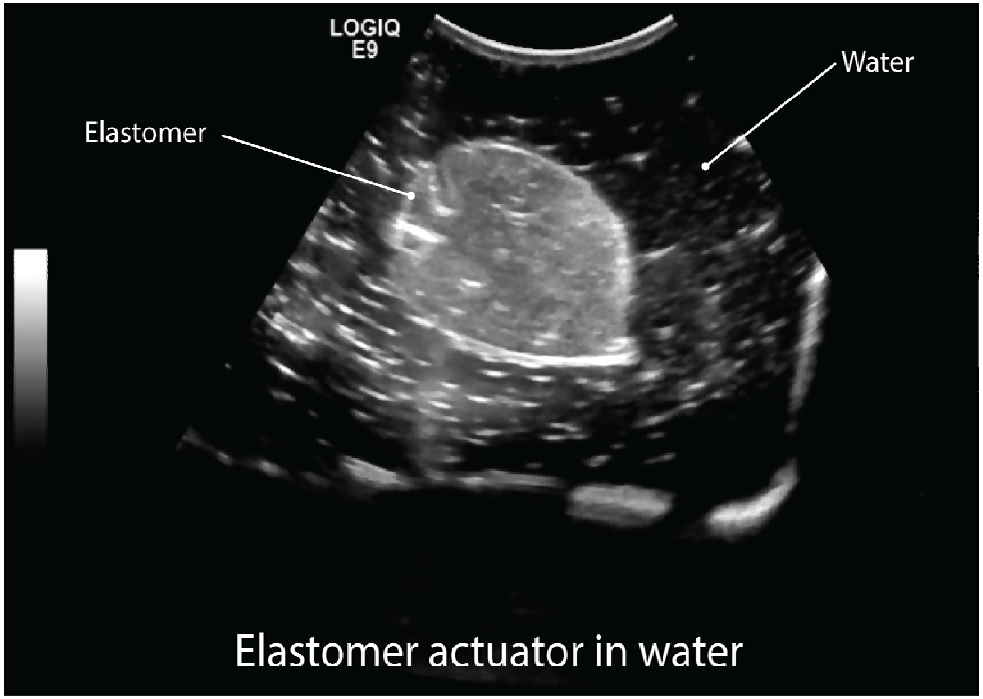
	Water	Hydrogel	Ecoflex	Elastosil	Sylgard 184
n **Refractive Index**	**1.3330**	**1.3365**	N/A†	N/A†	1.4225
I/I_0 **Transmittance (relative to water)**	**100 %**	**> 90 %**	< 5 %	< 0.1 %	> 90 %
$c^{\ddagger}$ **Speed of Sound [m·sec^{-1}]**	**1447.5**	**1485.7**	983.4	979.6	1022.4
z_0 **Acoustic Impedance [Pa·s·m^{-1}]**	**1.448×10^6**	**1.487×10^6**	1.052×10^6	1.058×10^6	1.053×10^6
R **Acoustical Reflection Coefficient**	**0**	**0.013**	0.158	0.156	0.158

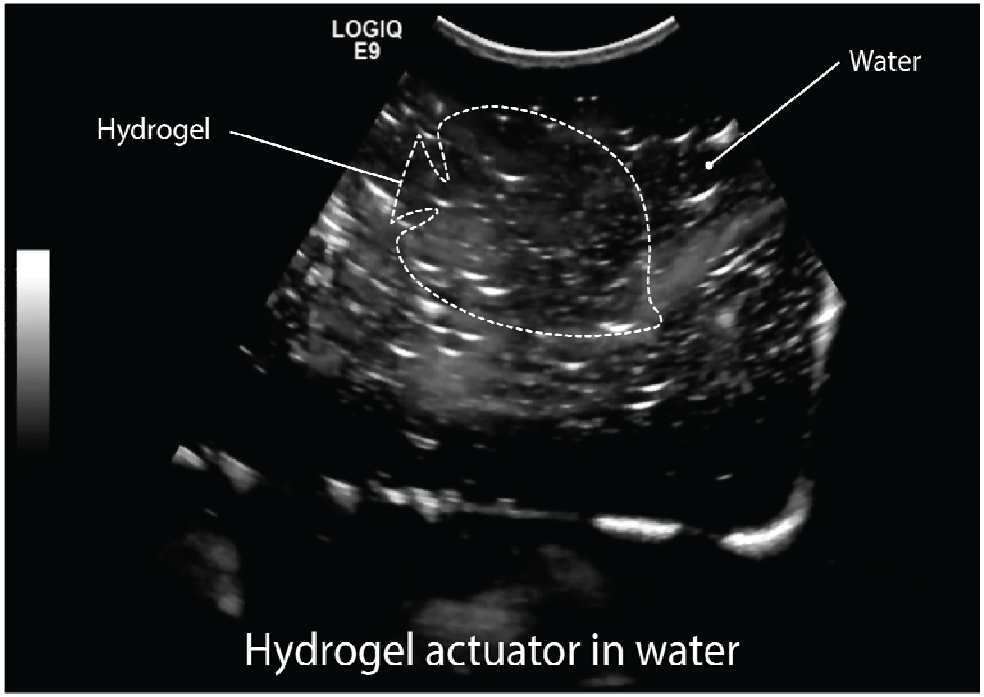
Optically and Acoustically Invisible in Water



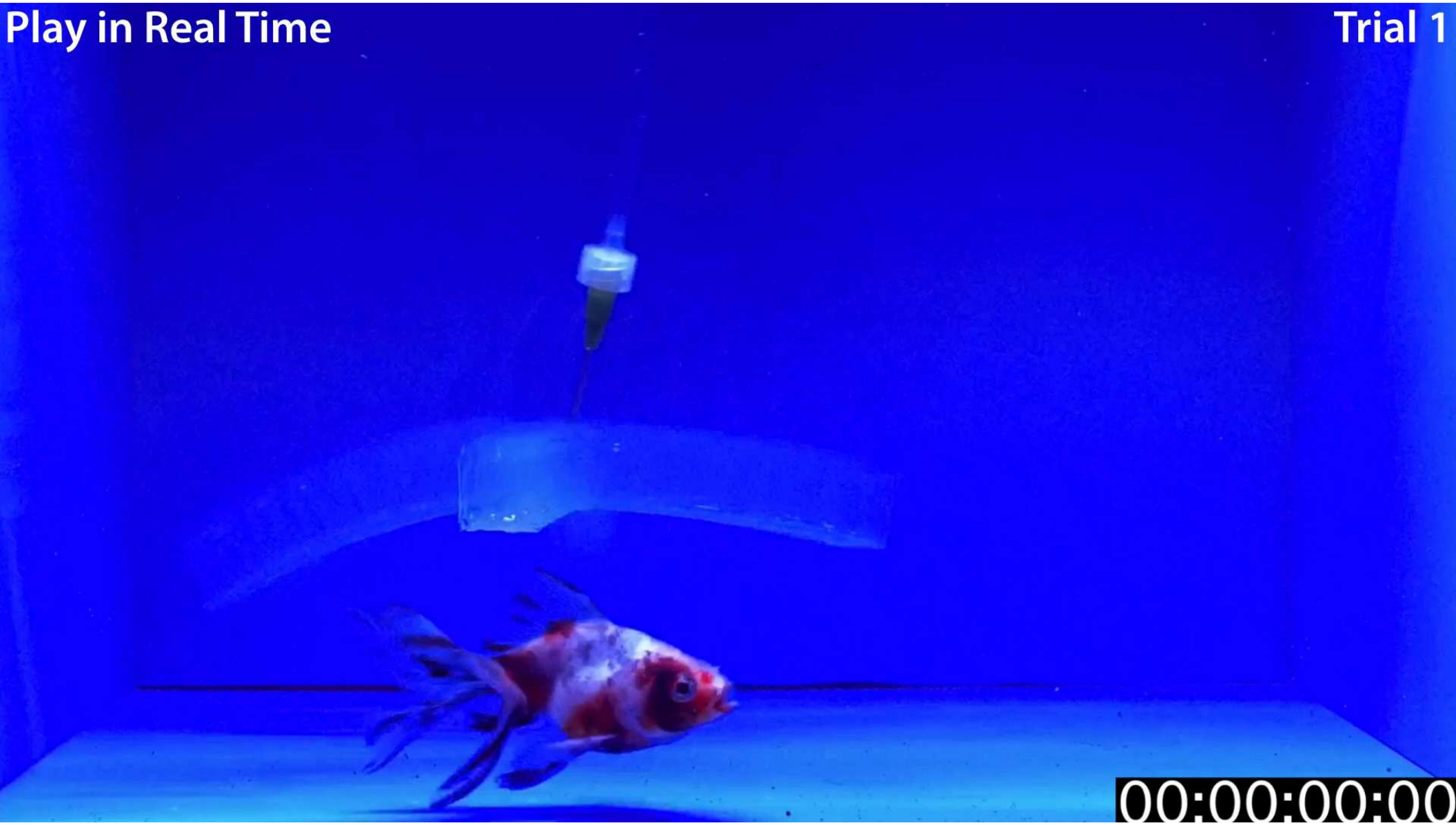
Yuk et al, Nature Communications, (under revision)

Optically and Acoustically Invisible in Water

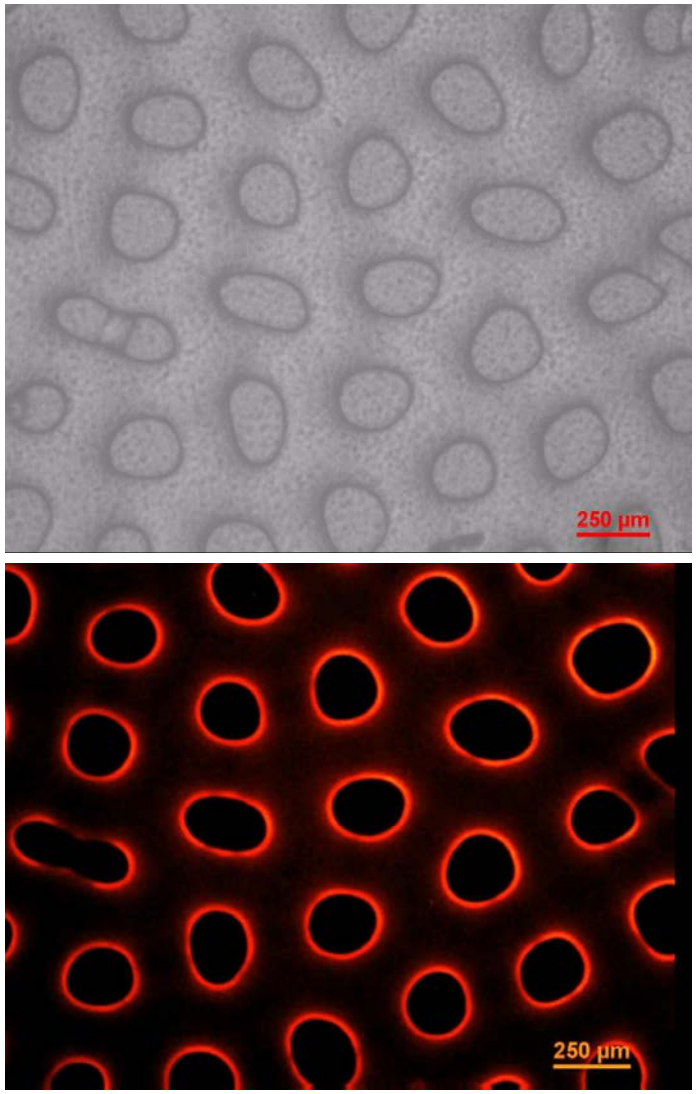




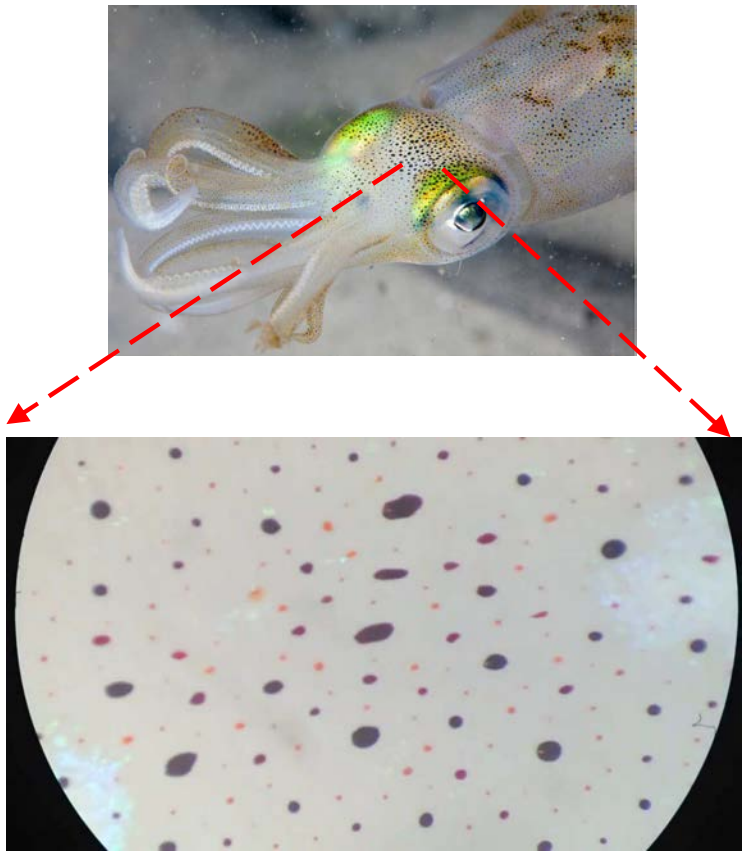
Yuk et al, Nature Communications, (under revision)


Play in Real Time
Trial 1
00:00:00:00

Synthetic Cephalopod Skin changes Texture and Color.



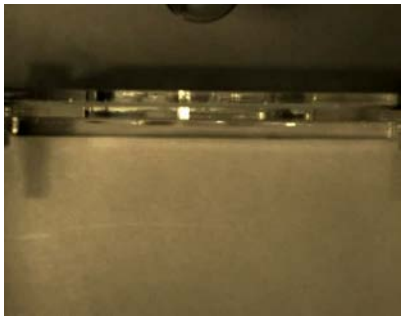
Wang et al, Nature Communications, 5, 4899 (2014)

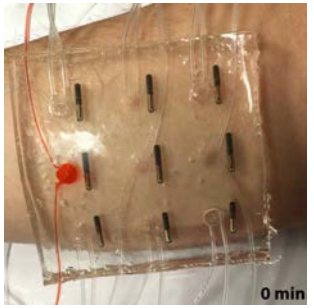


From Youtube

Unconventional Hydrogels

- **Robust Hydrogels:** Build dissipation into stretchy network.
- **Tough Bonding:** Anchor stretchy network on surface.
- **Manufacturing:** Synthetic biology, 3D printing.
- **Applications:** Scaffolds, Hydrogel electronics, Hydrogel robots



- **More information:** zhaox.org

Acknowledgement

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- Hyunwoo Yuk
- Shaoting Li
- German Alberto
- Xinyue Liu
- Mahdi Takaffoli
- Ruike Zhao
- Vivas Chan
- Baoyang Lu
- Zhidong Han
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- Prof. Andy Yun, Harvard
- Prof. Kam Leong, Columbia
- Prof. Farshid Guilak, Duke
- Prof. Gabriel Lopez, Duke
- Prof. Steve Craig, Duke

Funding Supports

NSF CAREER Award

ONR YIP Award