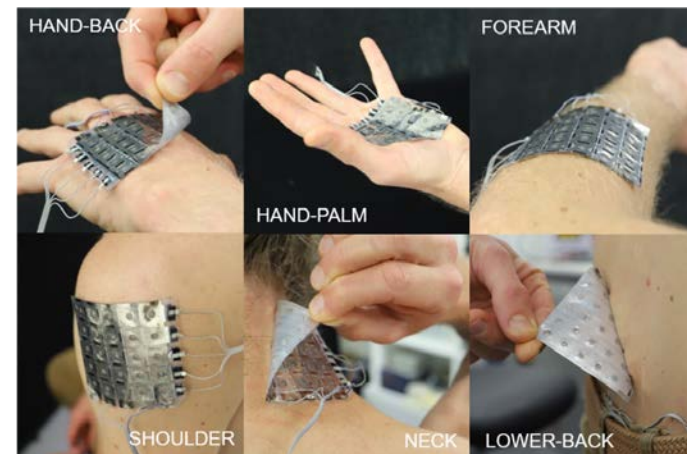


Soft actuators for wearable haptics

Prof. Herbert Shea
EPFL-LMTS



C. Fang *et al*, CHI 2020



E. Leroy *et al*, Adv. Mat. Tech 2023

Outline

0. Soft Actuator intro
1. Why haptics?
2. Human touch perception
3. Actuators for Kinesthetic haptics
 1. Fluidic elastomer actuators & McKibbens
 2. Electrostatic Clutches
4. Actuators for Wearable Cutaneous haptics
 1. Electrostimulation
 2. Soft pneumatic
 3. Electromagnetic
 4. Dielectric Elastomer Actuators
 5. Zipping electrostatics
 6. EHD

Wearable soft robots are coming !

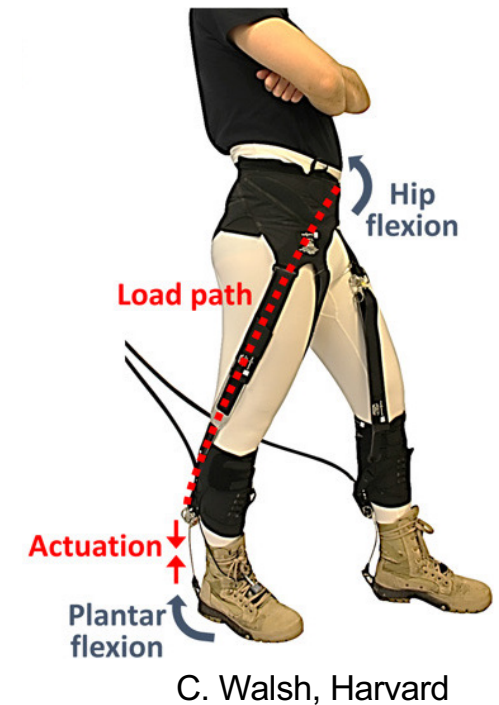
- Haptics for VR / AR
- Sports training
- Medical treatment, rehabilitation
- Supportive exosuits



Dexmo



Facebook reality labs



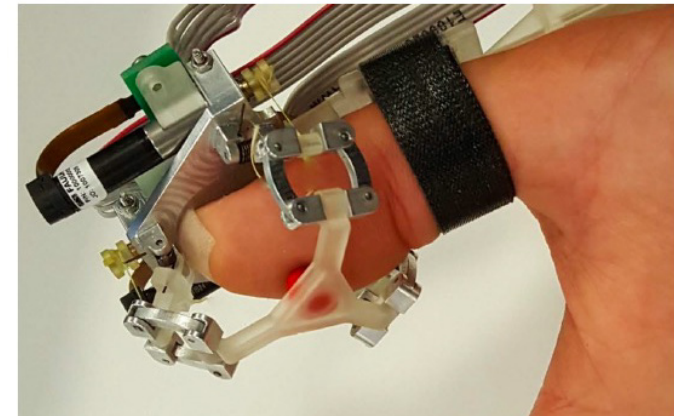
C. Walsh, Harvard

Some Challenges for wearable robots

- Control !
- Actuators that are soft & compliant, yet high force
- Thin, comfortable unobtrusive garment: how to integrate actuator in textile?
- Untethered systems: need energy efficient actuators



Hinchet et al, Adv. Intel. Sys 2022



Schorr and Okamura, CHI 17

How can we make effective artificial muscles?

- So many effective soft technologies !
- Most obvious is pneumatic



Suzumori Lab, Tokyo Tech



Vacuum suction manipulation with continuum robot

Matthew A. Robertson

Jamie Paik

Reconfigurable Robotics Laboratory



Robertson & Paik, Science Robotics (2017)

Many good (soft?) actuation principles

- Pneumatic
- Shape memory alloy
- Electromagnetic
- Ionic electroactive polymer
- Liquid crystal elastomer
- Piezo
- Thermal
- etc.

Some Criteria for choosing:

- Scaling arguments
- Softness / compliance
- Energy + Power density
- Force density
- Power supply + Size of external controller

Some actuator metrics:

- strain
- force density
- power density (peak, average...)
- energy density
- speed
- energy efficiency
- reliability

Combining different operating principles can have major advantages

Table 1 | Comparison of soft actuation methods relevant to applications in untethered robots

Actuation method	Strain (%)	Work density (kJ m ⁻³)	Modulus (MPa)	Power density (kW m ⁻³)	Strain rate (% s ⁻¹)	Frequency (Hz)	Auxiliary equipment	Deformation type
Skeletal muscle	20-40	8-40	10-60	50-300	10-50	1-10	Body metabolism	Contraction
Pneumatic actuator	10-40	1-200	0.1-100	10-1,000	10-70	1-5	Pneumatic pump, valves	Contraction, bending, expansion
Liquid-crystal elastomer	10-50	1-50	0.1-3	0.01-10	1-10	0.001-1	Light or heat source	Contraction, bending
Bio-hybrid actuator	10-25	0.1-10	0.01-1	1-10	10-100	1-5	Biocompatible medium	Contraction
Shape-memory alloy	4-8	10⁴-10⁵	28-75 × 10 ³	10³-10⁵	10-50	0.5-5	Power supply	Contraction, bending
Ionic polymer-metal composite	0.5-10	1-10	25-2,500	0.01-1	1-3	0.1-2	Power supply	Bending
Dielectric elastomer actuator	1-1,000	100-500	0.1-3	10³-10⁵	10²-10⁵	1-100	Power supply	Bending, expansion

Bold denotes better performance. Bulky and more complex auxiliary equipment presents a significant challenge to untethered implementation.

Rich, S. I., Wood, R. J. & Majidi, C. Untethered soft robotics. *Nature Electronics* **1**, 102–112 (2018).

Treat all such tables with great suspicion and care!

1. Why haptics?

2. Human touch perception
3. Kinesthetic haptics
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Many recent reviews on “soft” haptics

S. Biswas, Y. Visell, Emerging Material Technologies for Haptics.
Advanced Materials Technologies, 1900042 (2019).

T.-H. Yang, et al Recent Advances and Opportunities of Active Materials for Haptic Technologies in Virtual and Augmented Reality.
Advanced Functional Materials, 2008831 (2021).

Y. H. Jung, J.-H. Kim, J. A. Rogers, Skin-Integrated Vibrohaptic Interfaces for Virtual and Augmented Reality.
Advanced Functional Materials, 2008805 (2020).

J. Yin, R. Hinchet, H. Shea, C. Majidi, Wearable Soft Technologies for Haptic Sensing and Feedback.
Advanced Functional Materials, 2007428 (2020).

H. Bai, S. Li, R. F. Shepherd, Elastomeric Haptic Devices for Virtual and Augmented Reality.
Advanced Functional Materials. 2009364 (2021)

Ankit, T. Y. K. Ho, A. Nirmal, M. R. Kulkarni, D. Accoto, N. Mathews, Soft Actuator Materials for Electrically Driven Haptic Interfaces.
Advanced Intelligent Systems, 2100061 (2021).

More general haptics references

C. Hatzfeld, T. A. Kern,
Engineering Haptic Devices
(Springer London, London, 2014), *Springer Series on Touch and Haptic Systems*.
<http://link.springer.com/10.1007/978-1-4471-6518-7>

H. Culbertson, S. B. Schorr, A. M. Okamura,
Haptics: The Present and Future of Artificial Touch Sensation.
Annual Review of Control, Robotics, and Autonomous Systems. **1**, 385–409
(2018).



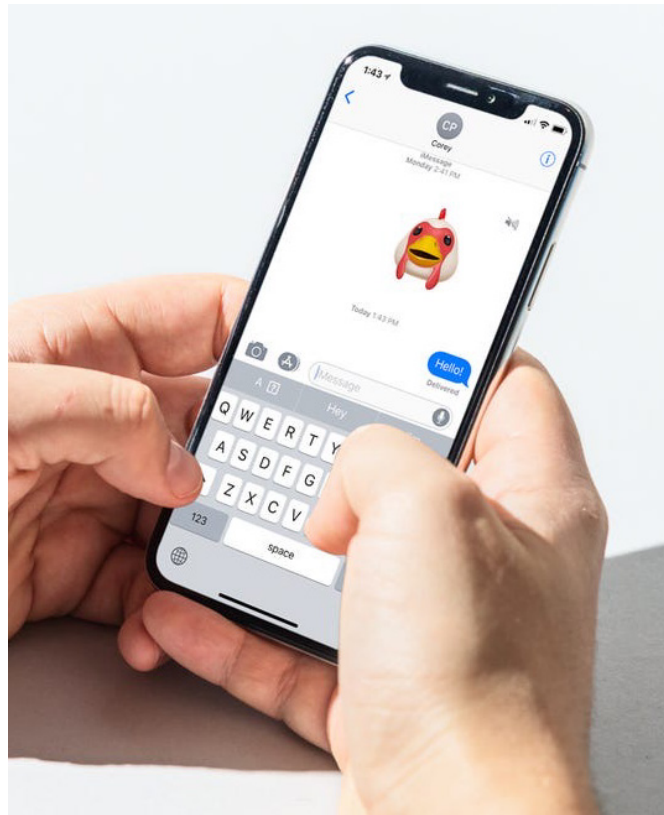
<https://www.pnbank.com.au/power-of-and/2015/power-of-touch/>



<https://www.plt.org>

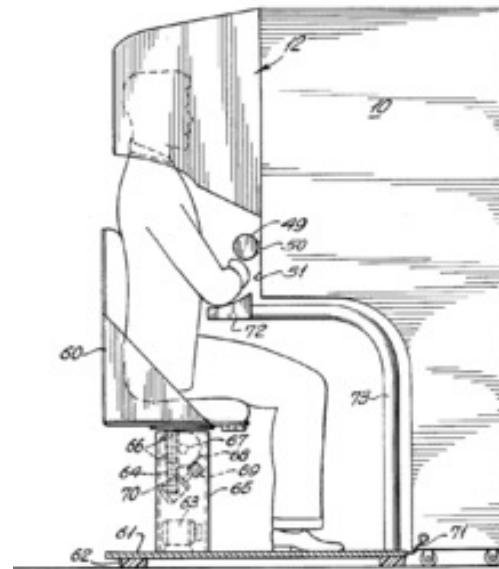
- Touch conveys a lot of information
- Touch has a strong emotional impact
- Touch requires little cognitive effort to decipher

Human Machine interfaces - tactile



Sensorama - Morton H. Eilig 1962

- First immersive “VR” device that featured:
 - Stereoscopic 3D display
 - Body tilting
 - Stereo sound
 - Wind simulator
 - Aroma simulator



The Sword of Damocles - Ivan Sutherland 1965-1968

“The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would kill.”

*The Ultimate Display*¹. I. Sutherland



1. <http://goo.gl/6D8B4V>

VR today

- High-res, low-cost head-mounted displays
- Excellent surround audio
- **Other senses under-explored**



Oculus Quest 2. 300\$

Eyes = cm^2
Skin = m^2



Google cardboard 2015, 20 \$
(smartphone not included)



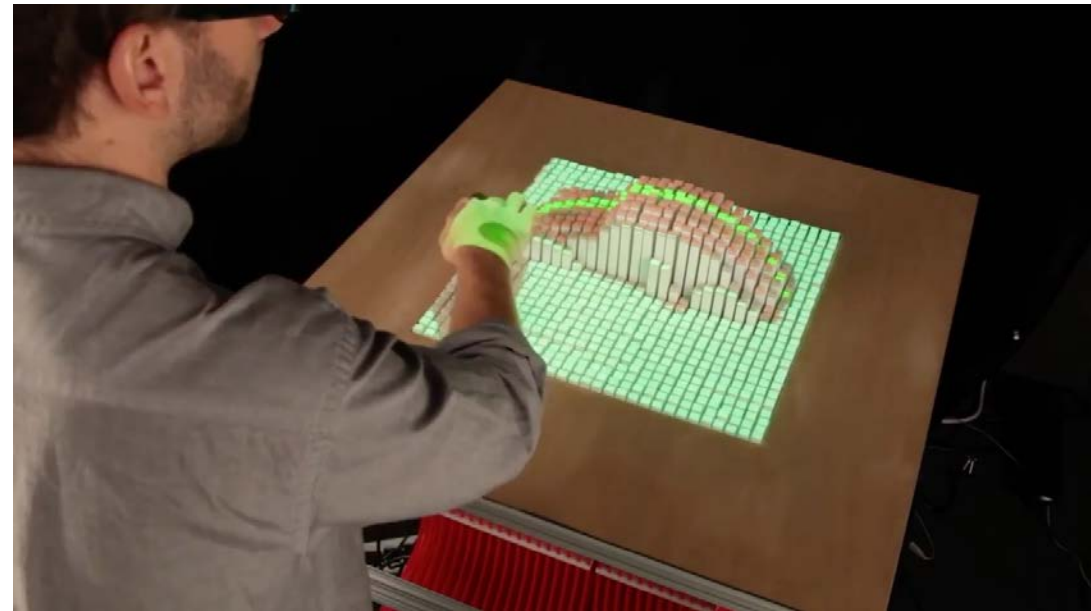
MS HoloLens 2: 3500 \$

**Complex touchable Haptic displays have been realized...
but it is extremely very difficult to make flexible actuators.**

**Wearable actuators are even more challenging to develop! (and
how do we get enough force?)**



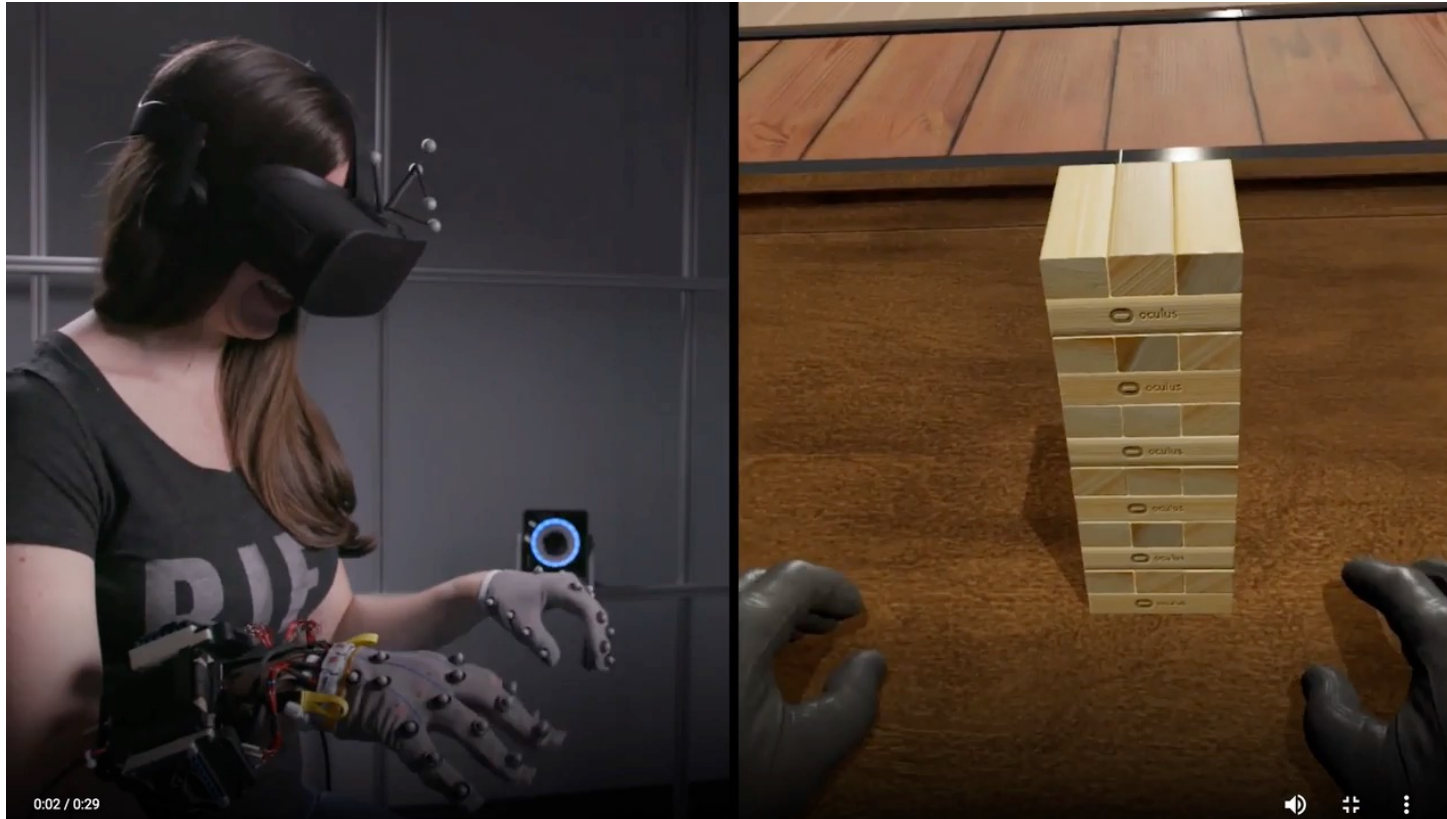
[Da Vinci,
by Intuitive Surgical]



[MIT Media Lab:
Tangible - InForm]

<https://tangible.media.mit.edu/project/inform/>

“Real” things are touchable



<https://www.facebook.com/TechAtFacebook/videos/469676557151816/>

© Facebook Reality Labs

Missing:

- blocking fingers to make objects feel solid
- sense of touch beyond buzzers

Haptics: What for?

- Gaming: casual or serious?
- Training – medical (Surgical simulator)
- Training - industrial
- Teleoperation
- AR
- Gentle notification

Haptics: What to wear?

- VR headset
- and glove/
- suit
- AR glasses
- Game controller
- Haptics in device



How many DOF? From 2 to 2000...

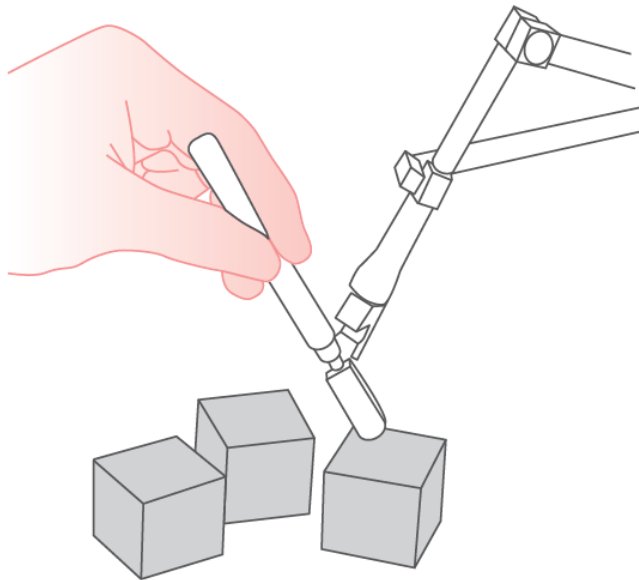


<https://archvirtual.com/wp-content/uploads/2018/10/Envision3.jpg>

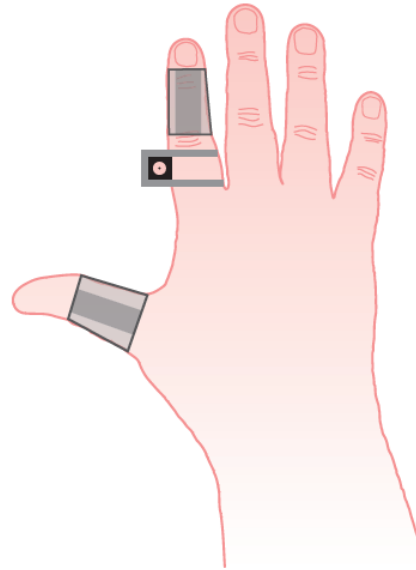


Haptic classification

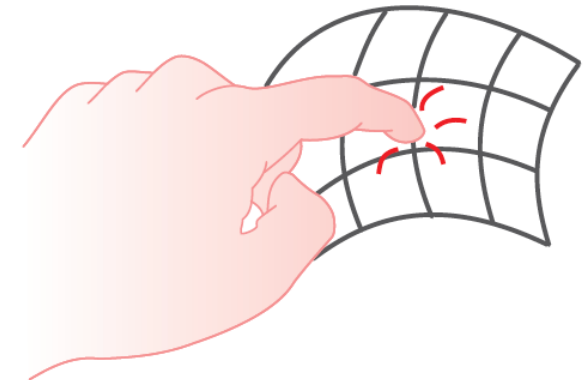
Graspable



Wearable



Touchable



H. Culbertson, S. B. Schorr, A. M. Okamura, Haptics: The Present and Future of Artificial Touch Sensation. *Annual Review of Control, Robotics, and Autonomous Systems*. **1**, 385–409 (2018).

Grounded kinesthetic haptics

A Articulated arms station



B Motors + arms with cables

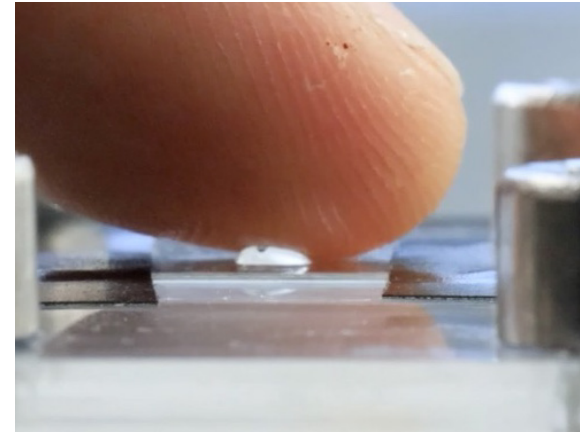


C Motors + grabber



Cutaneous vs. kinesthetic

Cutaneous haptics stimulates tactile feeling (i.e., sense of touch we usually get from our fingertips)



Kinesthetic or proprioception sensation haptics are related to the awareness of the position and of the movement of body parts, and the forces and torques exerted on them

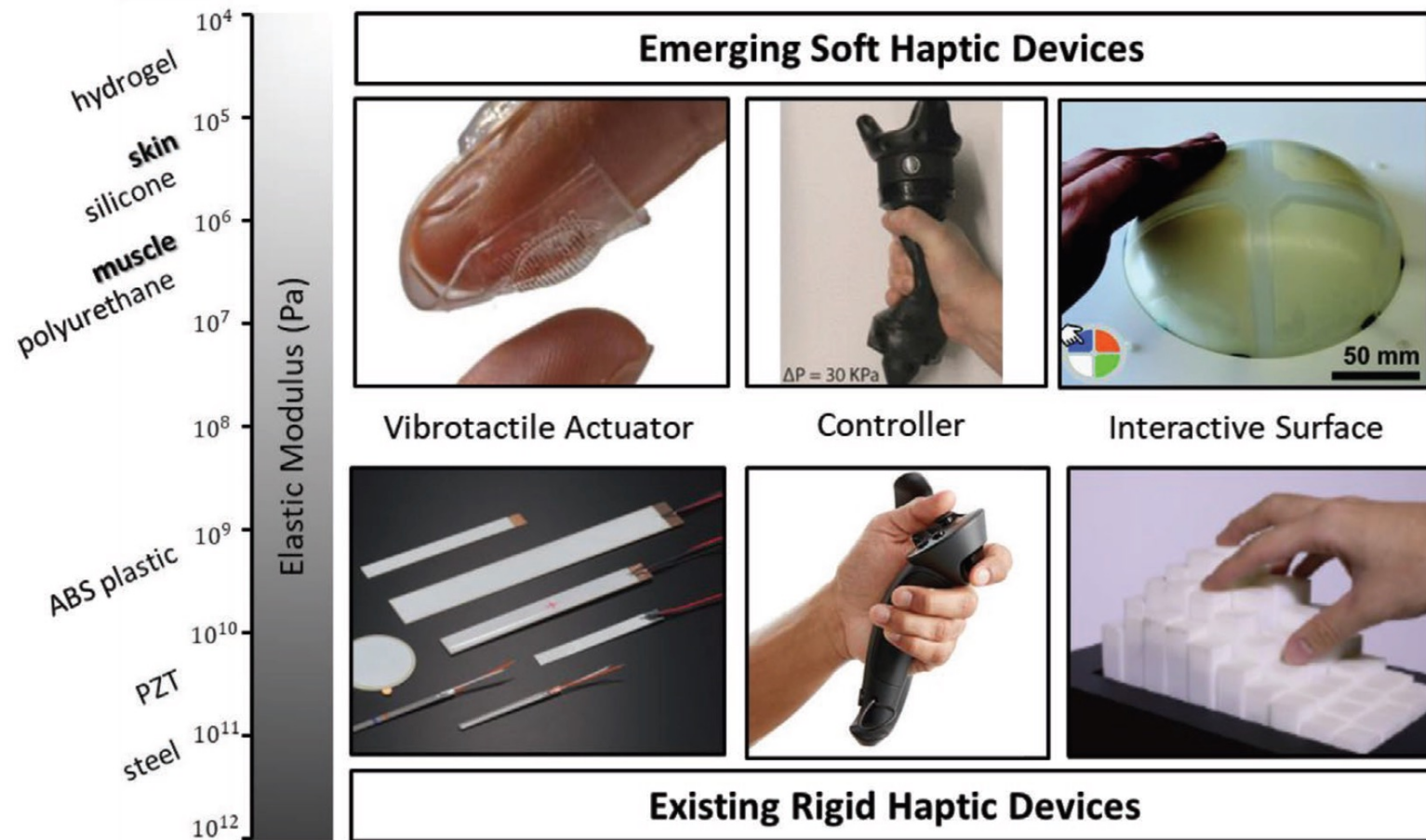


Dexmo



DextreES

Different material set for soft haptics than for hard devices



H. Bai, S. Li, R. F. Shepherd, Elastomeric Haptic Devices for Virtual and Augmented Reality. *Advanced Functional Materials*. 2009364 (2021)

1. Why haptics?

- 2. Human perception**

3. Kinesthetic haptics

1. Fluidic elastomer actuators
2. Clutches

4. Wearable Cutaneous haptics

1. Electrostimulation
2. Soft pneumatic
3. Electromagnetic
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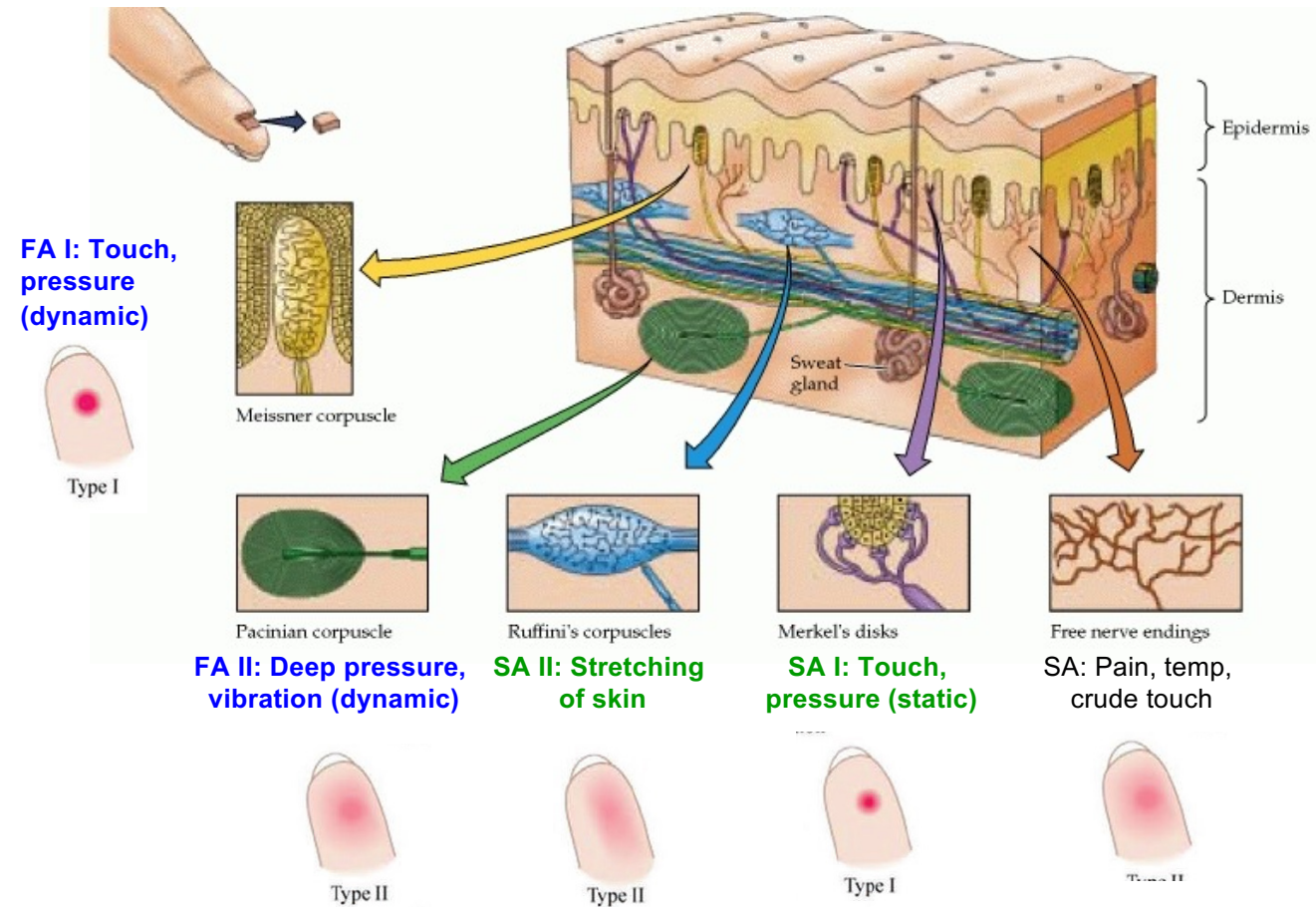
Cutaneous sensations: our skin receptors

M. W. Halterman, *Neuroscience, 3rd Edition. Neurology. 64, 769–769 (2005)*

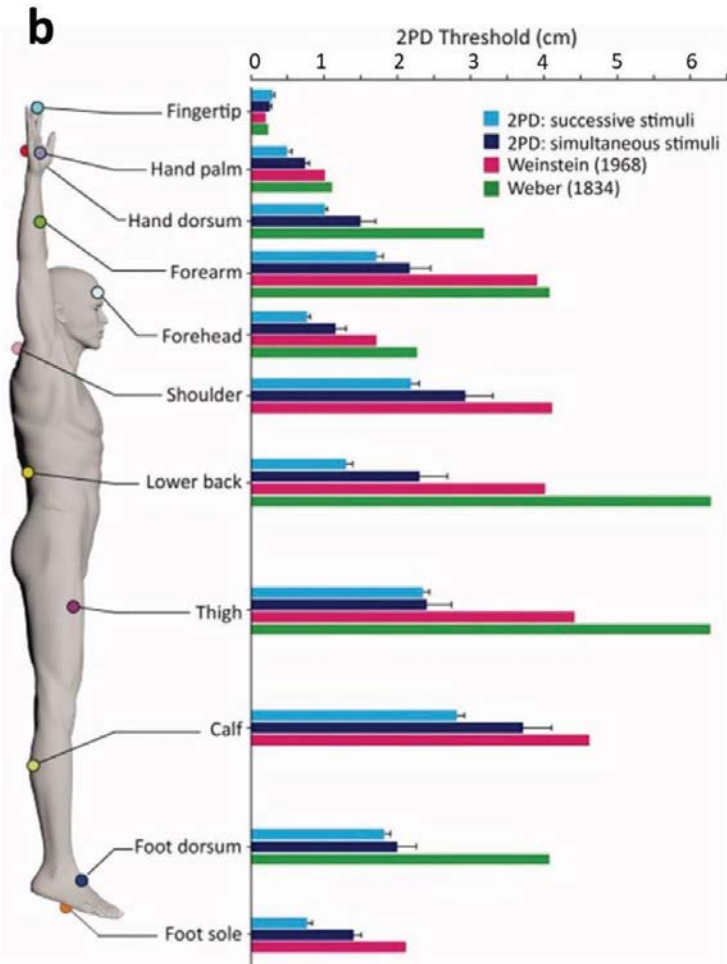
Several m² of sensors
Gives us information on:
contact, shape, material
and texture.

- **Fast Adapting** (vibrations & shocks)
- **Slow Adapting** (contact & pressure)

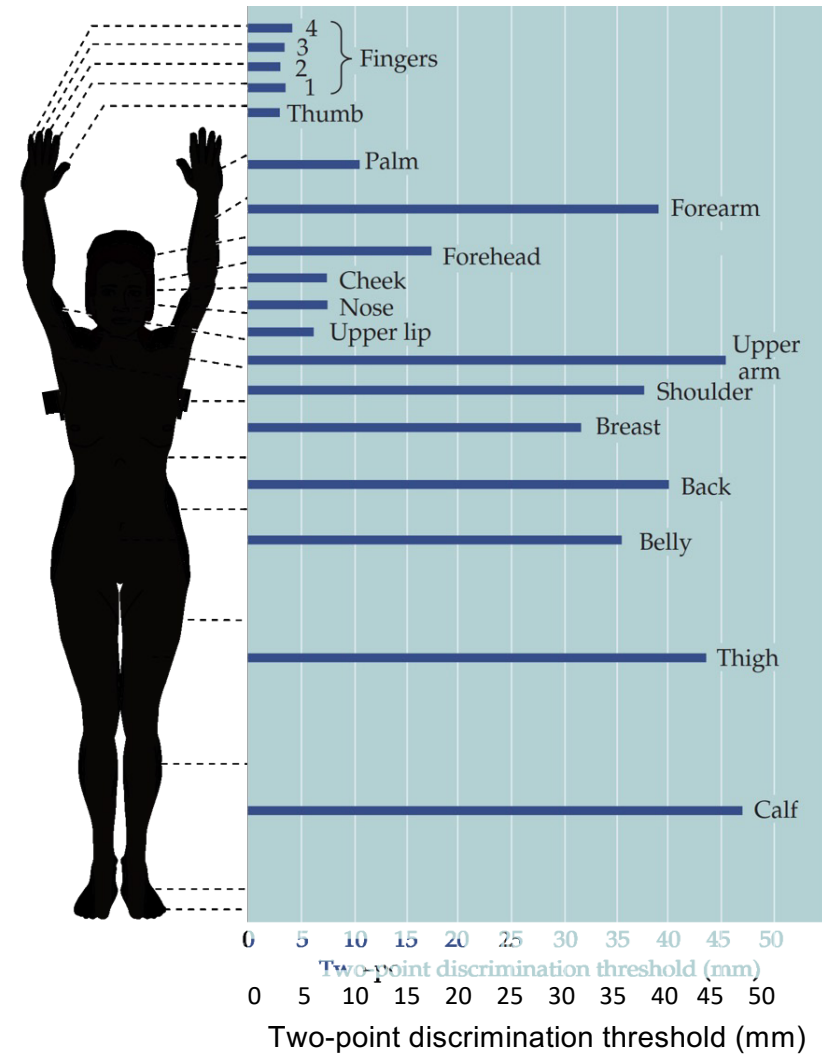
SA1, SA 2: low freq (< 5 Hz)
FA-I: 5-40 Hz
FA-II: 40-400 Hz



Cutaneous sensations depends on location on the body



F. Mancini, A. Bauleo, J. Cole, F. Lui, C. A. Porro, P. Haggard, G. D. Iannetti, *Ann. Neurol.* 2014, 75, 917.



M. W. Halterman, *Neuroscience, 3rd Edition. Neurology.* 64, 769–769 (2005)

Tactile perception threshold vs. frequency

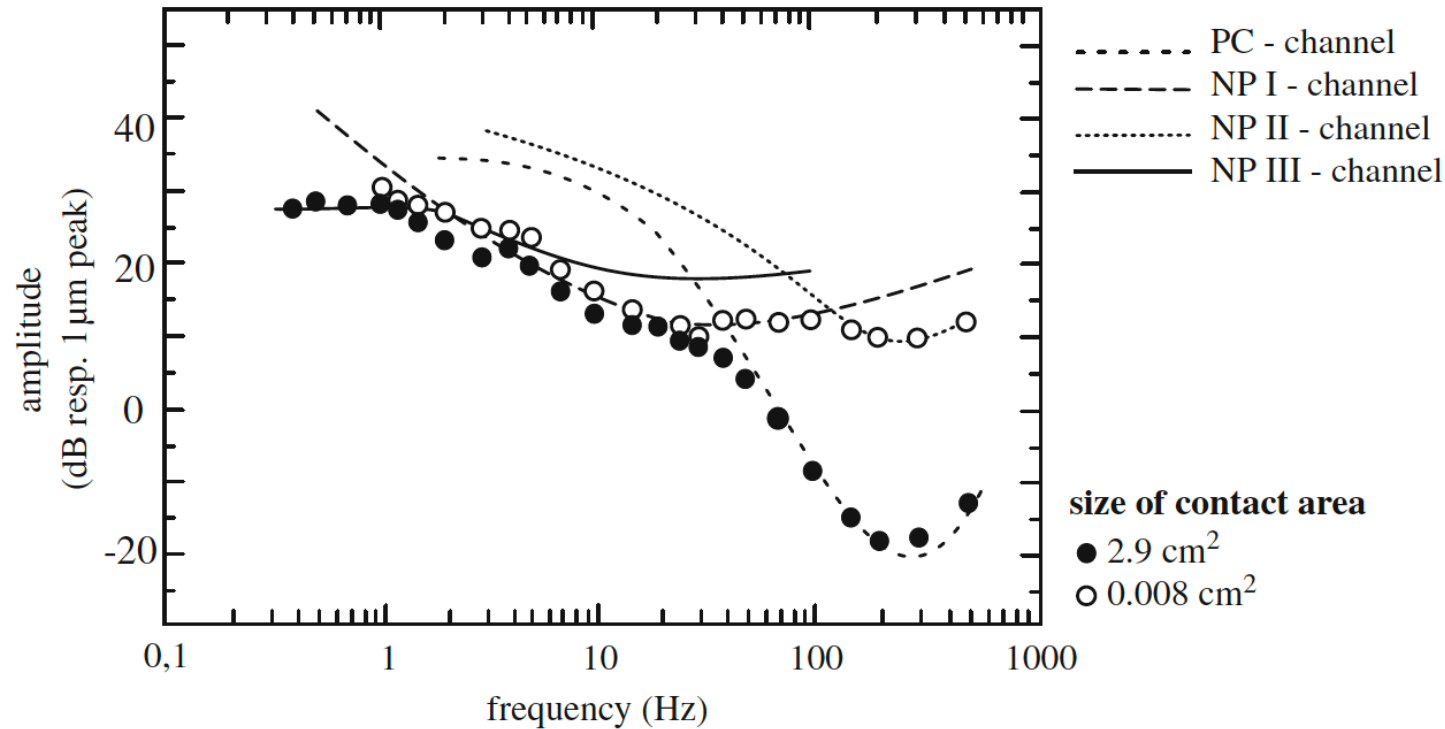


Fig. 2.15 Absolute threshold of tactile perception channels at the thenar eminence with respect to contact size. Measurements were taken with closed-loop velocity control of the stimuli. To address individual channels, combinations of frequencies, intensities, contact areas, and masking effects are employed. The psychometric procedure used converges at a detection probability of $p = 0.75$.

Gescheider GA, Bolanowski SJ, Hardick KR (2001) The frequency selectivity of information—processing channels in the tactile sensory system. *Somatosens Motor Res* 18(3):191–201. doi:10.1080/01421590120072187

Cutaneous thresholds depends on the task

- Depends on **location**, **age** and **gender**
- Depends on **tasks** and **objects**

No clear target in terms of:

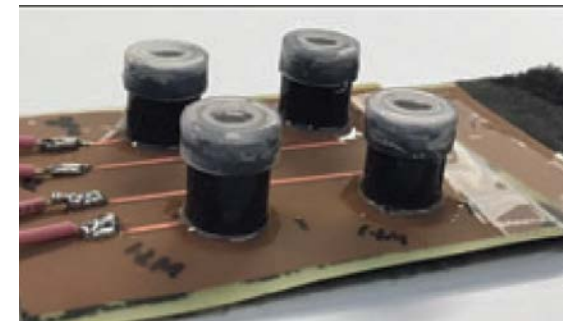
- force (stress)
- stroke (strain)
- speed (frequency)
- size (density)

Wearable devices

- performance to size or weight ratio
- energy efficiency

Eg, 2x2 array of “pins” on forearm

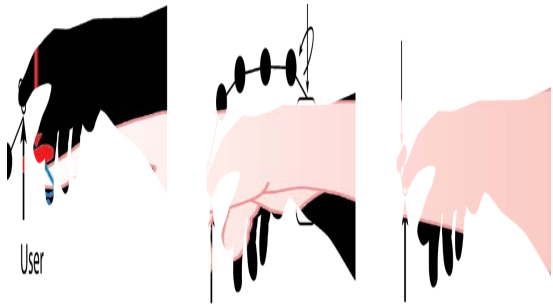
- What shape bump
- How soft the bump
- How hard to push, how far to push
- What spacing?
- Static or vibrating? What frequency?
- Crosstalk
- Mounting on body
- Comfort vs. sensation



H. Zhao *et al.*, “A Wearable Soft Haptic Communicator Based on Dielectric Elastomer Actuators,” *Soft Robotics*, vol. 7, no. 4, p. 451, 2020,

Requirements of cutaneous haptic feedback actuators

Finger cutaneous

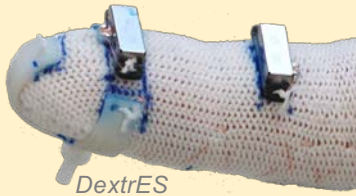


Ex: Touch notification, Small forces, Texture/Roughness, Stickiness

- multiple type of stimulus: normal/lateral, static/dynamic
- small forces (20-1000 mN) and displacements (10-1000 μm)
- high density (mm to cm pitch)
- integration on the 2D curved surface of skin

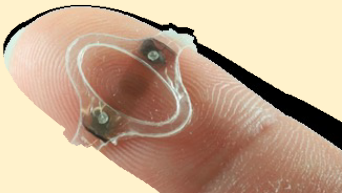


Piezo-vibrators (Murata)



DEA-vibrator (LMTS)

by Xiaobin Ji



Pneumatic

Lacour /Paik labs



Electro-static (LMTS)



Kinesthetic feelings arise from muscle receptors

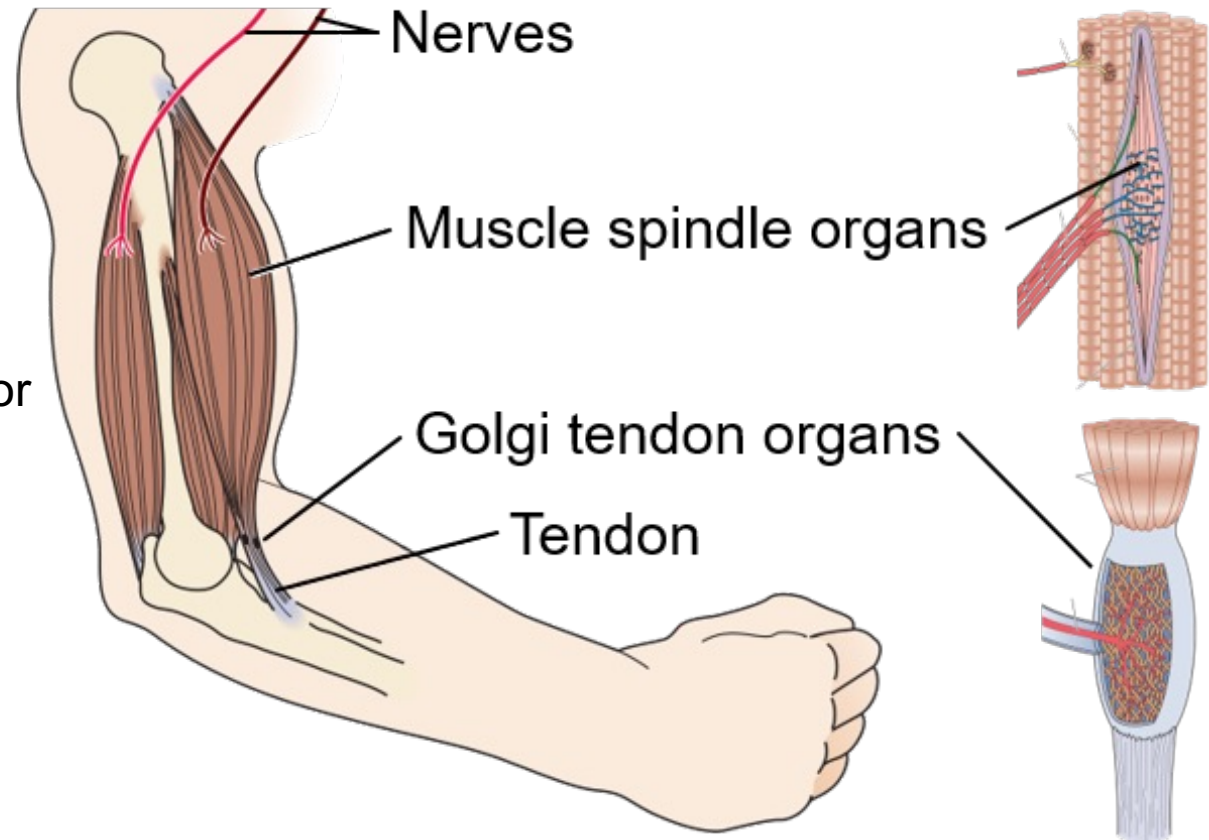
Kinesthetic sensation arise from muscle, tendon, and joint receptors
It provides information about

- position and movement of the limbs
- the force exerted.
- **Hand kinesthetic** (grab an object)
- **Grounded kinesthetic** (touch a wall or table)

Compared to cutaneous:




- higher force
- lower speed /vibrations!
- higher displacement
- lower density

- **Challenging integration on body**



Challenging integration of kinesthetic devices on hand and on body

“The effectiveness of any haptic feedback system relies on its ability to integrate with existing human neurosensory pathways” *Juo, Y.-Y. et al. Center for Advanced Surgical and Interventional Technology Multimodal Haptic Feedback for Robotic Surgery. in Handbook of Robotic and Image-Guided Surgery 285–301 (Elsevier, 2020). doi:10.1016/B978-0-12-814245-5.00017-7*

-  Cutaneous device integrated on the 2D curved surface of skin
-  Hand kinesthetic integrated on the changing 3D structure of the hand with fingers' hinges and thumb's pivot
-  Grounded kinesthetic integrated on the breathing and changing 3D structure of the body with limbs and pivots

3 type of integration on the hand:

Finger digit based



Hand palm based

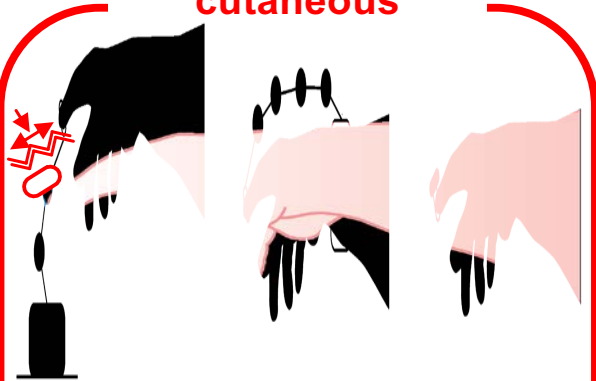


Hand dorsal based



Scaling issues for haptic actuators

Finger cutaneous

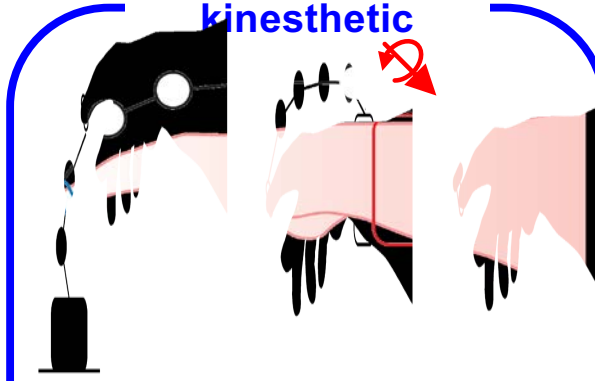


Ex: touch a button

- Small forces
- Touch notification
- Texture & roughness
- Tackiness

100mN **100μm** **mm** **2D**

Hand kinesthetic

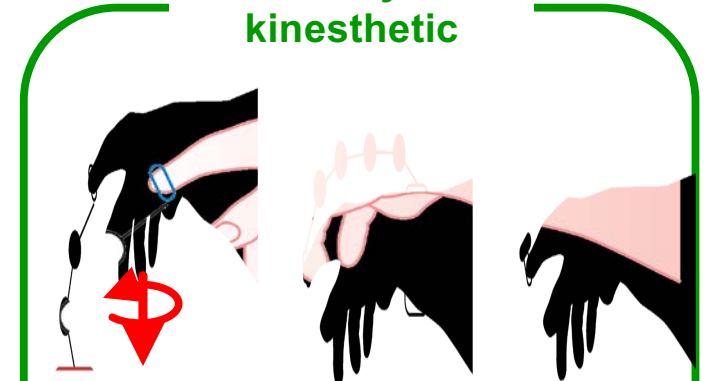


Ex: grab an object

- Medium forces
- Compliance, stiffness
- Shape

10N **cm** **cm** **3D**

Body kinesthetic



Ex: touch a wall or table

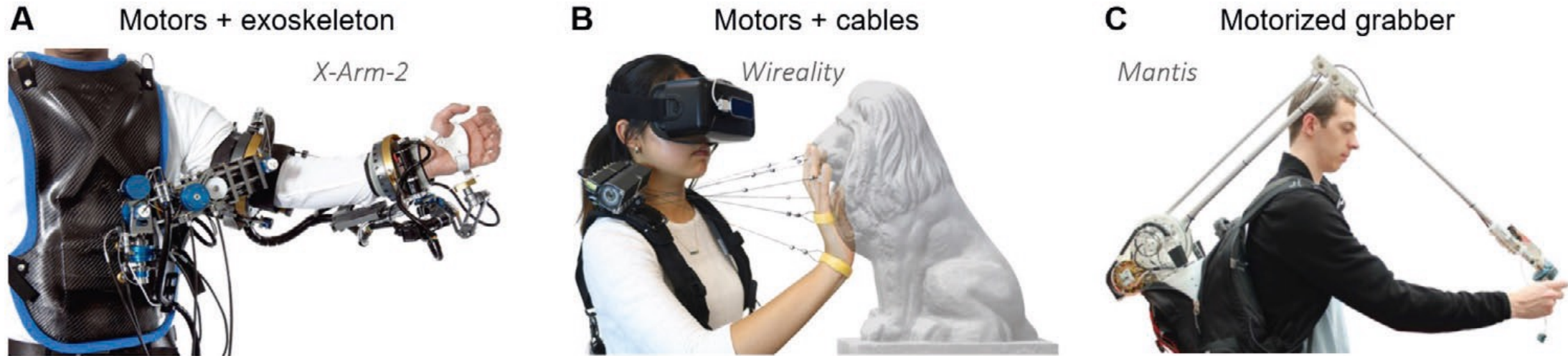
- High forces
- Weight & density

100N **dm** **dm** **3D⁺⁺**

1. Why haptics?
2. Human perception
- 3. Kinesthetic haptics (actuators for)**
 1. Fluidic elastomer actuators
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WEARABLE KINESTHETICS

Wearable grounded kinesthetic feedback devices



Wearable grounded kinesthetic feedback devices based on A) motors on an exoskeleton,[166] B) motors with cable attached to fingertips,[66] and C) motors on a grabber.[171]

J. Yin, R. Hinchet, H. Shea, and C. Majidi, "Wearable Soft Technologies for Haptic Sensing and Feedback," *Advanced Functional Materials*, vol. 31, p. 2007428, 2021, doi: [10.1002/adfm.202007428](https://doi.org/10.1002/adfm.202007428).

Not really soft...

Real versus Virtual



A Electromagnetic
Motors + cable



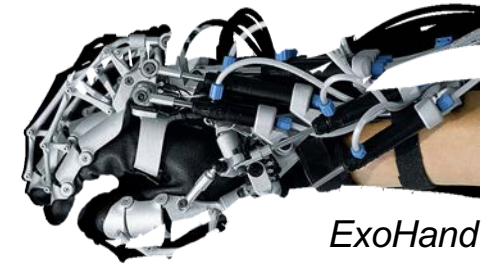
B Electromagnetic
Motors + TSA



C DEA
stack



Hydraulic exoskeleton



D Fluidic
PneuNet



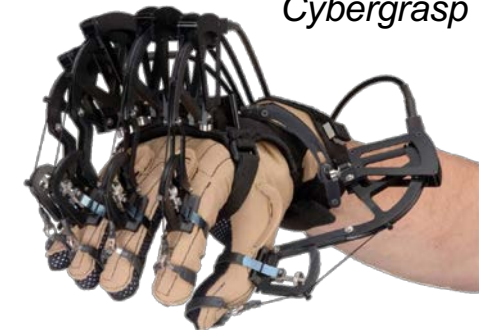
E Pneumatic
McKibben + cable



F Electrostatic
Clutch



2007: Cables



Kinesthetic haptic feedback gloves.

Issues: sizing to user, putting on/ taking off, force, control, power supplies

Fluidic Elastomer Actuators (FEA)

Advantages:

- Large shape change
- High forces
- Intrinsically compliant

For wearables, the need for compressed air (or pressured liquid) is a challenge
Tubing + valves

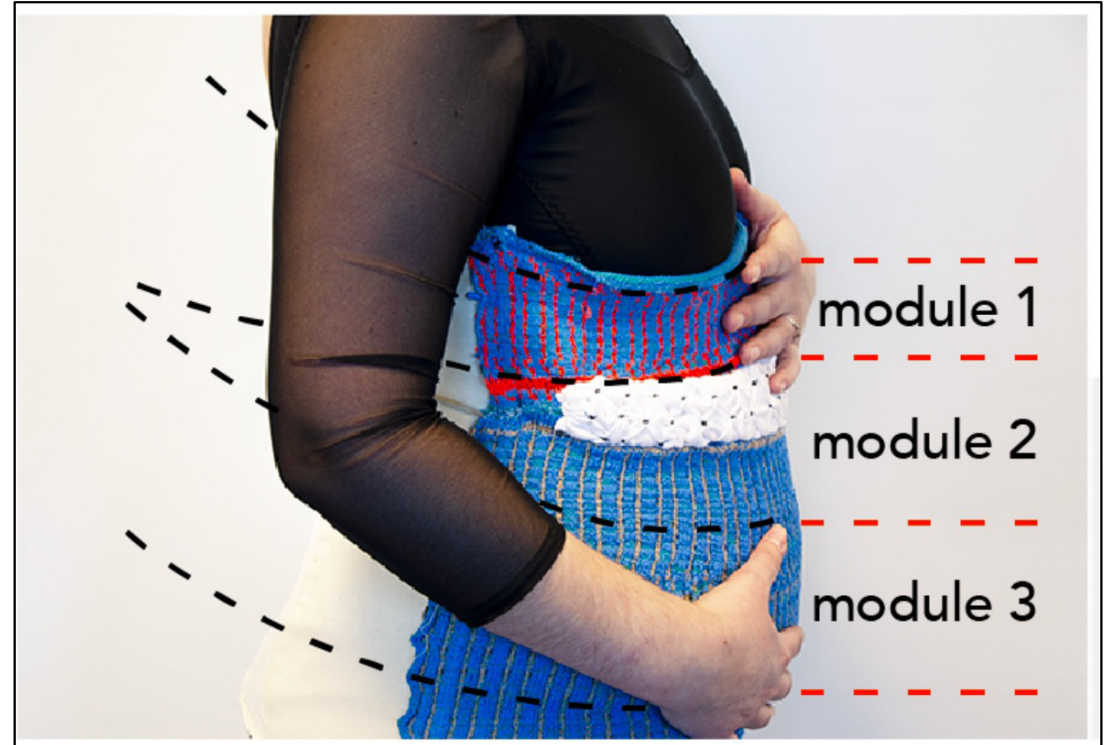
Best suited for cm-scale devices for speed reasons (slow)
Uses lots of power

How to mount on hand?

Pneumatic actuation: compliant, can generate high forces here examples of thin McKibben actuators



Abe T, et al.
IEEE Robotics and Automation Letters. 2019
S-muscle (Suzumori, Tokyo Tech)



Kilic Afsar, O. *et al.*
OmniFiber:
UIST 2021

Fluidic actuation is great for soft robotics



Facebook reality labs



But these technologies are far from being untethered



But these technologies are far from being untethered

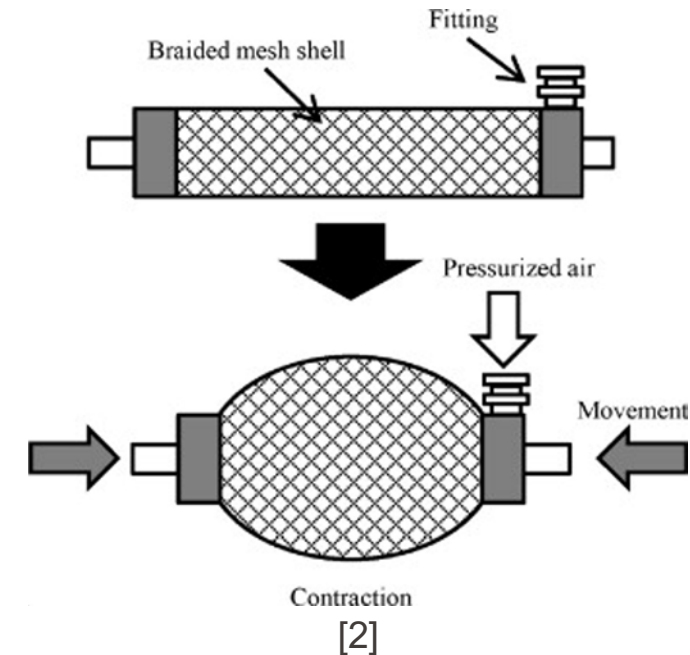


The McKibben actuator

- McKibben actuators are:
 - Named after Joseph L. McKibben in the 1950s
 - The oldest & most mature soft pneumatic actuator technology
 - Commercially available (eg [Festo](#))

- Here is how it works:
 - Inflatable tube inside
 - Inextensible mesh outside
 - The tube inflates, it's diameter increases
 - The mesh converts the diameter increase into longitudinal contraction

- Can only pull, cannot push
- Decreasing force with increasing contraction



[1] Ching-Ping Chou, and B. Hannaford. "Measurement and Modeling of McKibben Pneumatic Artificial Muscles." IEEE Transactions on Robotics and Automation, 1996 <https://doi.org/10.1109/70.481753>.

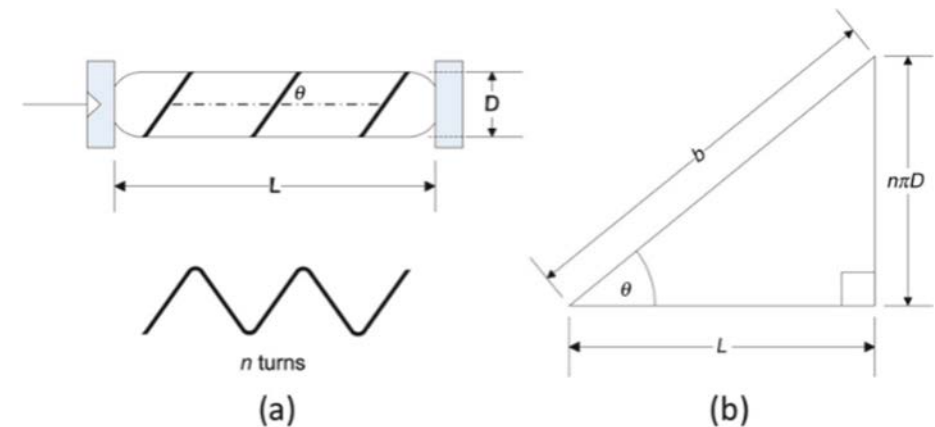
[2] Tiwari et al, "Hydraulic Artificial Muscles." Journal of Intelligent Material Systems and Structures 2012.

[3] Daerden, Frank, and Dirk Lefeber. "Pneumatic artificial muscles: actuators for robotics and automation." European journal of mechanical and environmental engineering 2002

Simple quasi-static McKibben model

- Quasi-static model: relevant for both pneumatic and hydraulic McKibbens
- Simplified model: only the McKibbens most important parameters
- Basic trigonometry: relationship between the actuator diameter, length, and braid angle θ
- Assumes no friction, no stored energy, no tube or braid thickness

$$F = \frac{\pi P' D_0^2}{4} (3 \cos^2 \theta - 1) \quad \text{with} \quad D_0 = \frac{b}{n\pi}$$

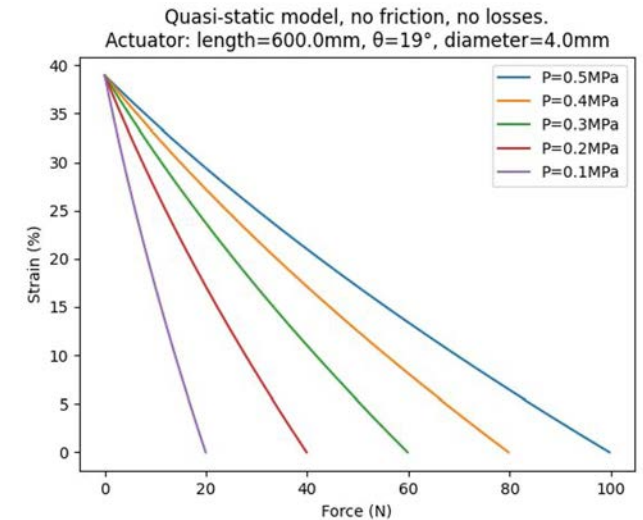
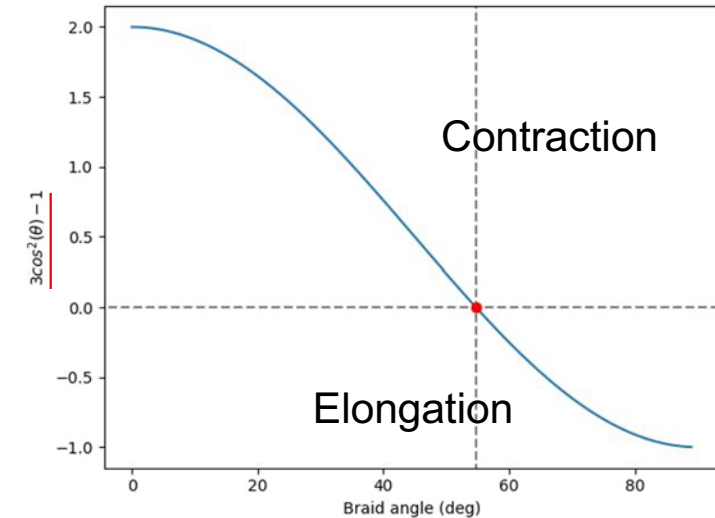


- D : the actuator diameter
- L : the actuator length
- n : a single thread's number of turns around the actuator
- θ : a single thread's angle with the actuators' long axis
- b : a braid single thread's total length
- P' : the actuator's relative pressure

Force depends on: θ , P' and D_0

$$F = \frac{\pi P' D_0^2}{4} (3 \cos^2 \theta - 1) \quad \text{with} \quad D_0 = \frac{b}{n\pi}$$

- D_0 is a scalar corresponding to the actuator theoretical maximum diameter
1. The initial braid angle commands the actuator behaviour:
 - a. Contraction: $\theta < 54.7^\circ$
 - b. Elongation: $\theta > 54.7^\circ$
 2. **In theory**, the lower the braid angle (θ), the higher the actuator's contractile performance
 3. As the actuator internal relative pressure (P') increases, the output force increases linearly
 4. Actuator forces increase as a function of the square of the actuator's diameter



Thin McKibben actuators

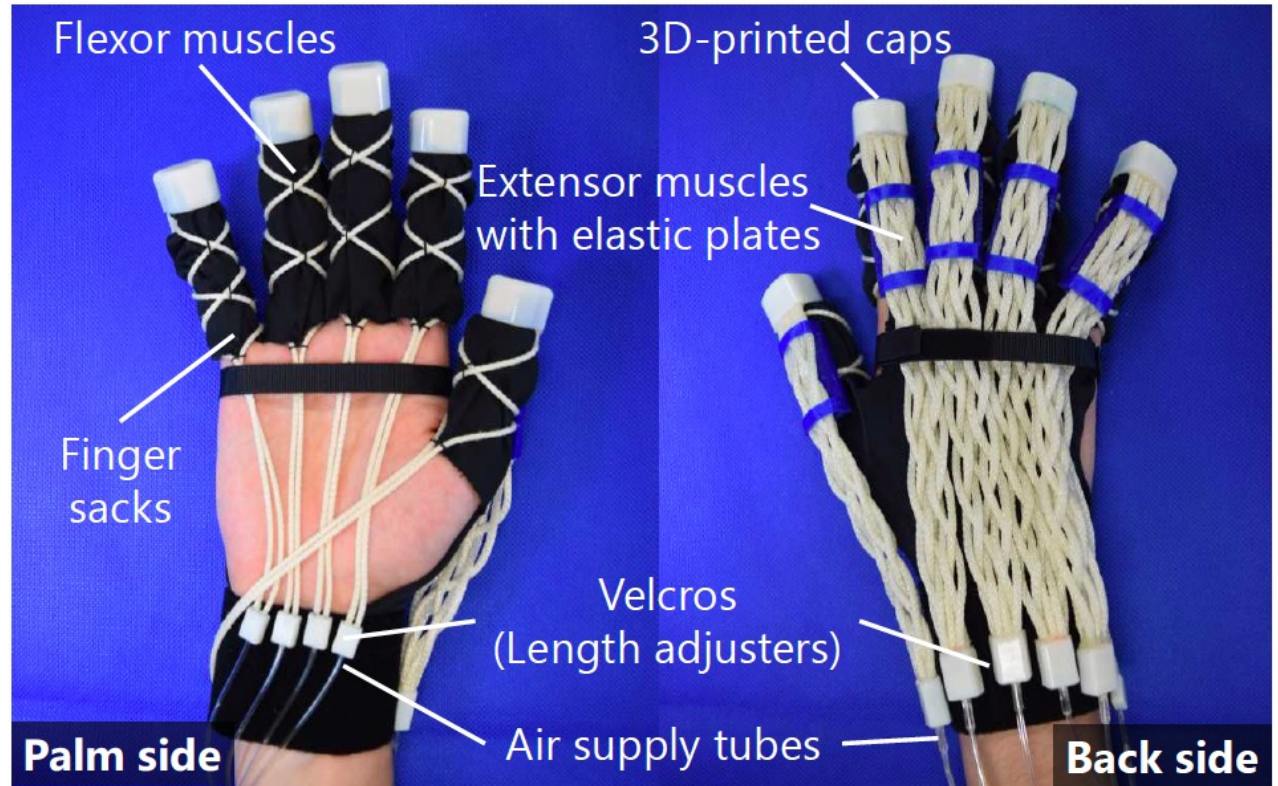
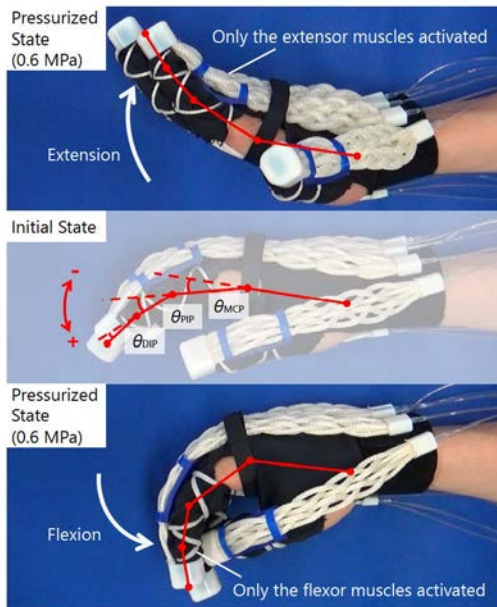
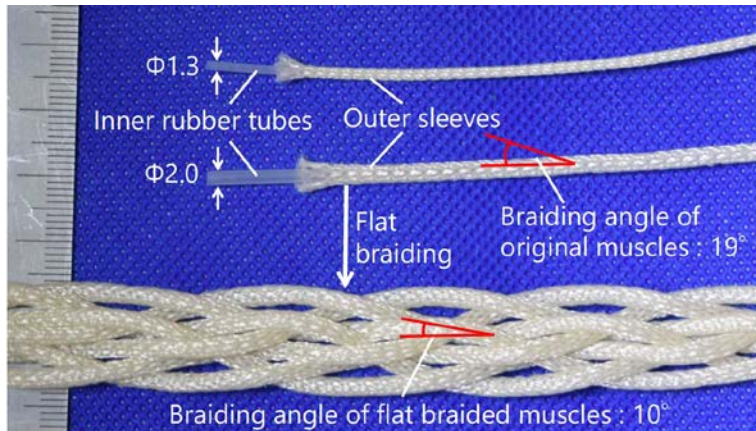
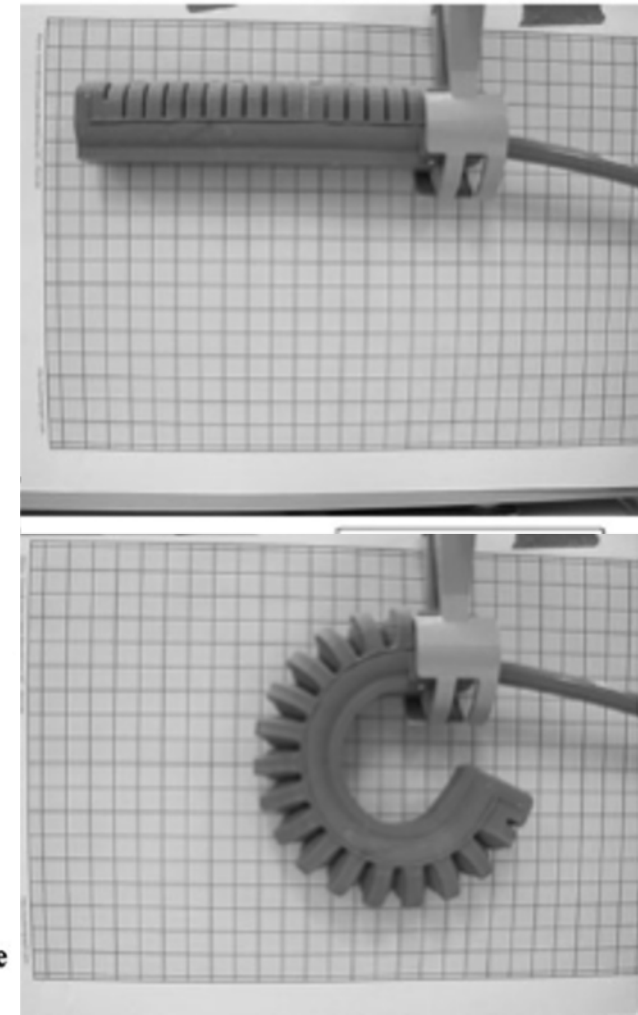
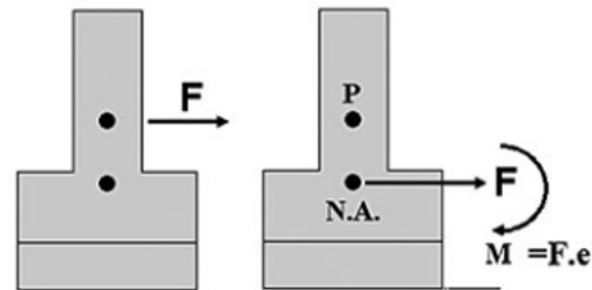


Fig. 2. Overview of soft robotic glove with thin McKibben muscles (64.7 g without air supply tubes, 10 DoF)

S. Koizumi, et al
 Soft Robotic Gloves with Thin McKibben Muscles for Hand Assist and Rehabilitation
 2020 IEEE/SICE International Symposium on System Integration (SII), pp. 93–98.

Soft pneumatic actuators (SPAs)

- Pneumatic network (**PneuNets**) are soft pneumatic actuators made of a series of channels and cavities molded in an elastomer
- They bend when inflated, this is due to:
 - Air pressure expanding the actuator cavities
 - The cavities not being aligned with the actuator neutral axis
 - The cavities internal pressure creates a torque at the actuator's neutral axis



Soft pneumatic actuators (SPAs)

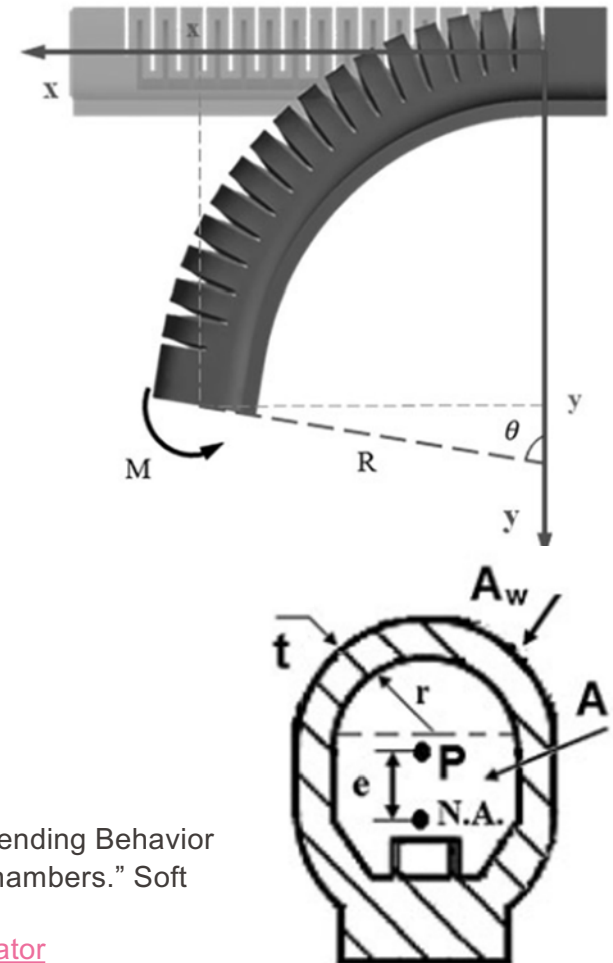
- The actuator angle θ is given as a function of the pressure P , in a steady state model:

$$\theta(P) = \frac{L_i A^2 e}{A_w E^2 I} P^2 + \frac{L_i A e}{EI} P$$

- Using the following notation:

- The actuator's chambers of internal and external cross sectional area, A and A_w , respectively
- The actuator Young's modulus, E
- The area moment of inertia, I
- The distance between an actuator's chamber center of pressure and its neutral axis, e
- The length of a single chamber and gap between chambers, L_i

- Alici, G et al., "Modeling and Experimental Evaluation of Bending Behavior of Soft Pneumatic Actuators Made of Discrete Actuation Chambers." *Soft Robotics* 2018 <https://doi.org/10.1089/soro.2016.0052>.
- <https://softroboticstoolkit.com/book/pneunets-bending-actuator>

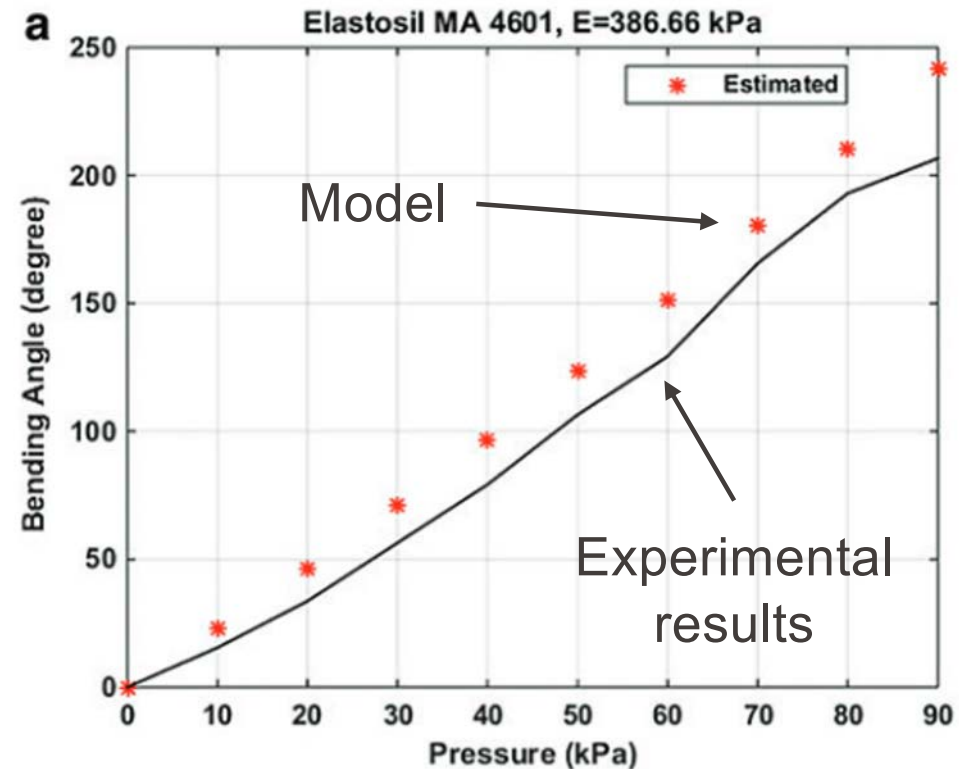


Soft pneumatic actuators (SPAs)

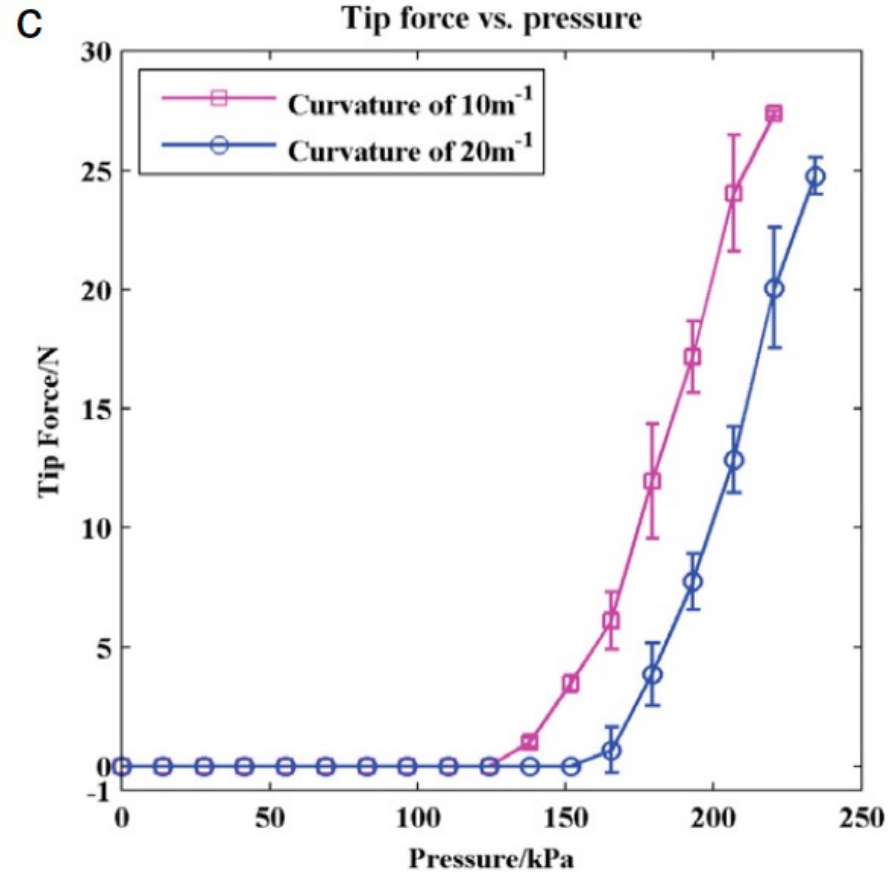
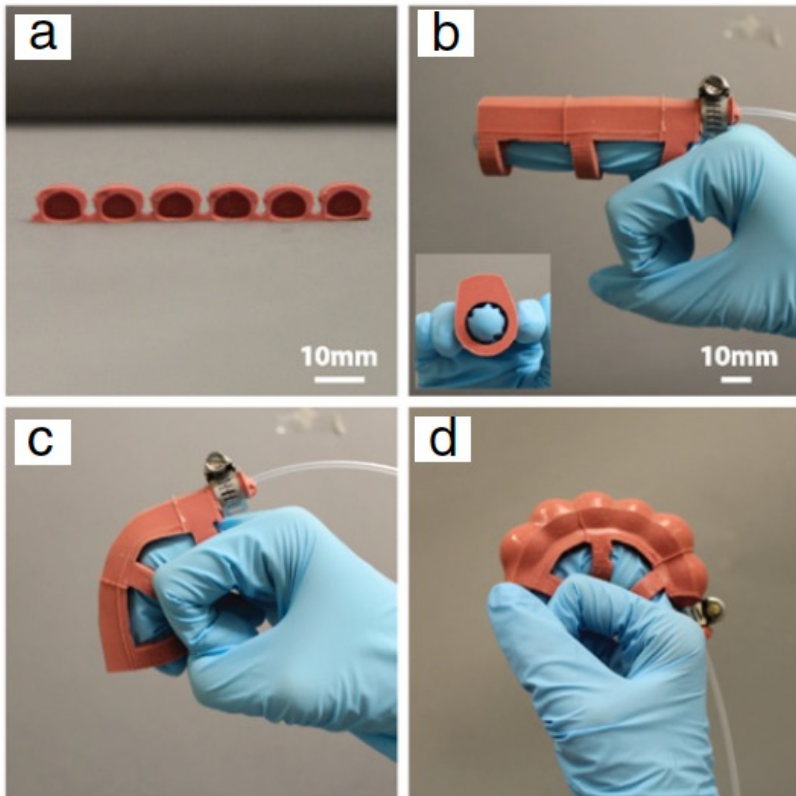
- We can deduce:
 - a. The actuator bending is a non-linear function of pressure
 - b. **IF** the Young's modulus (E) is high enough, the left part of the equation may be ignored. In that case the relationship **is** linear

$$\theta(P) = \frac{L_i A^2 e}{A_w E^2 I} P^2 + \frac{L_i A e}{EI} P$$

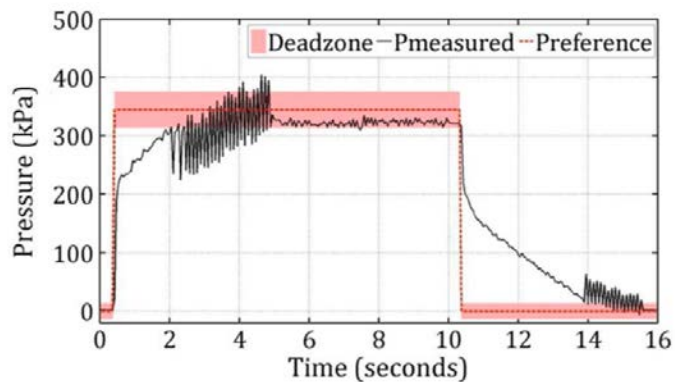
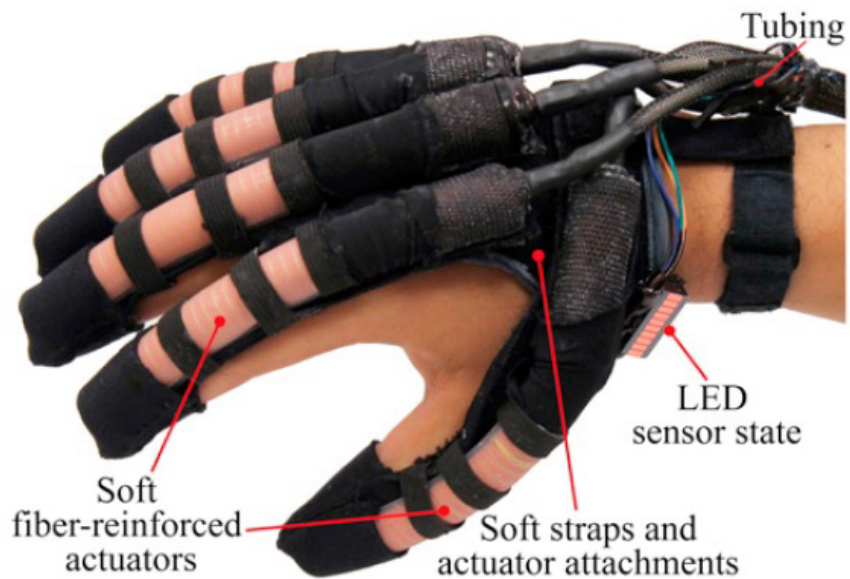
- Alici, G et al., "Modeling and Experimental Evaluation of Bending Behavior of Soft Pneumatic Actuators Made of Discrete Actuation Chambers." *Soft Robotics* 2018 <https://doi.org/10.1089/soro.2016.0052>.
- <https://softroboticstoolkit.com/book/pneunets-bending-actuator>



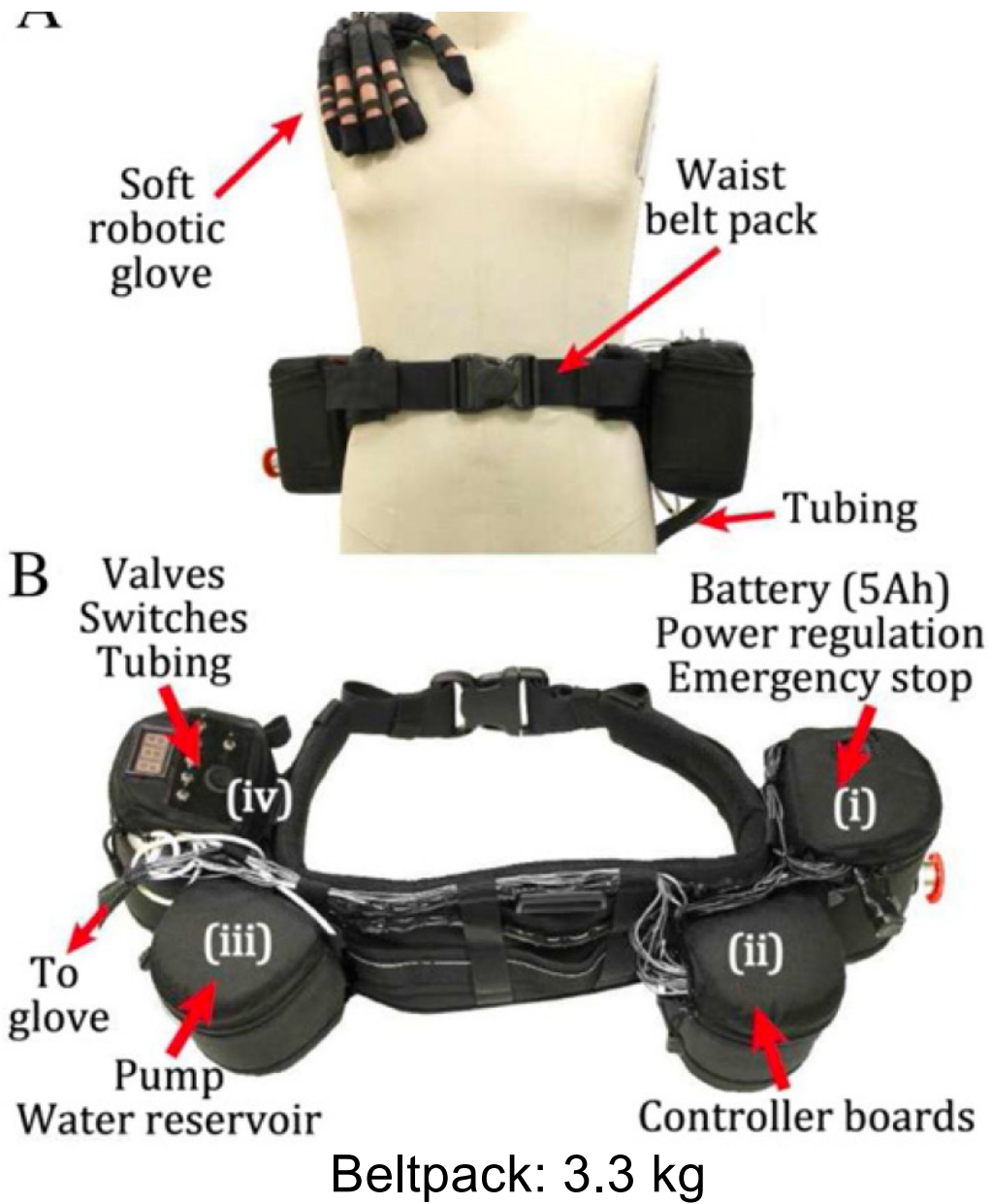
Fluidic Elastomer Actuators. Monolithic can generate large forces on body



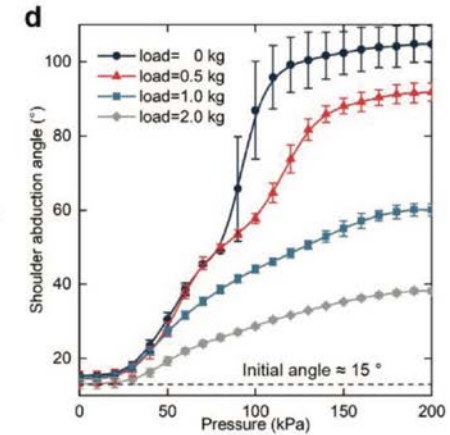
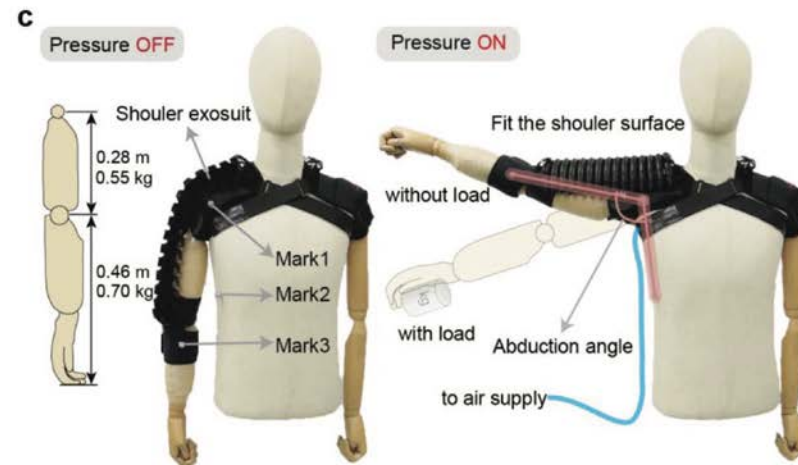
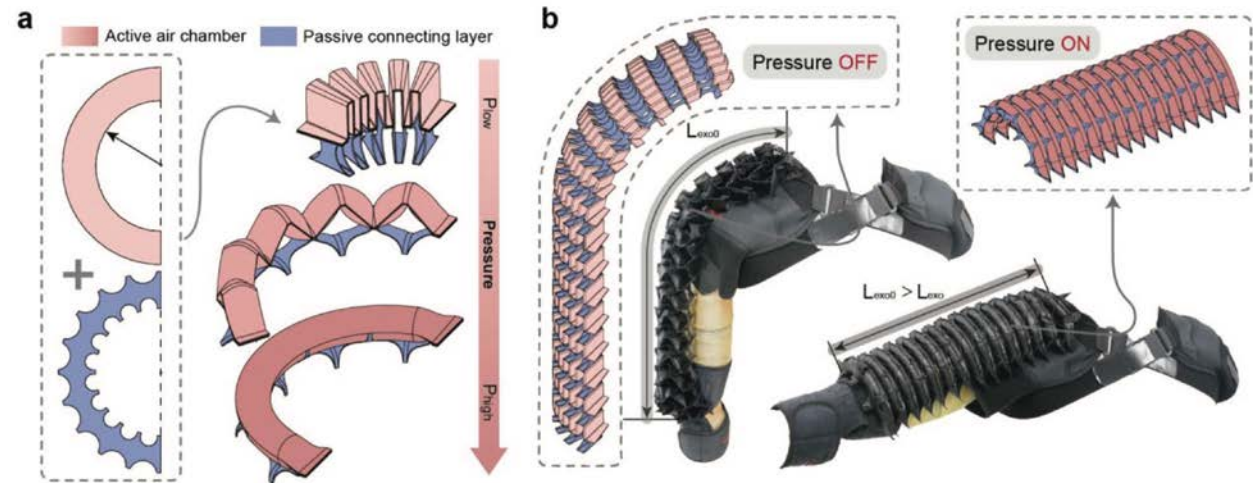
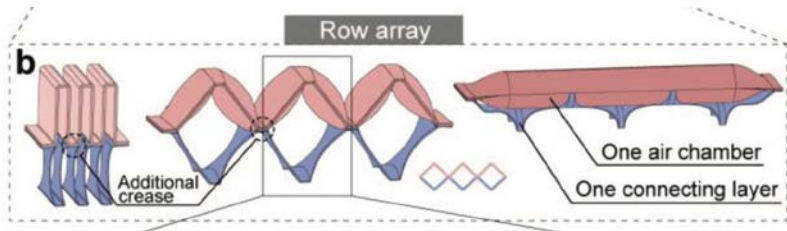
H. Zhao, Y. Li, A. Elsamadisi, R. Shepherd,
 Scalable manufacturing of high force wearable soft actuators.
Extreme Mechanics Letters. **3**, 89–104 (2015).



P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, "Soft robotic glove for combined assistance and at-home rehabilitation," *Robotics and Autonomous Systems*, vol. 73, pp. 135–143, Nov. 2015

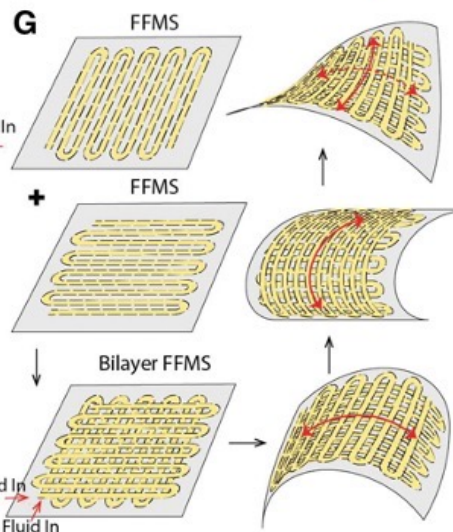
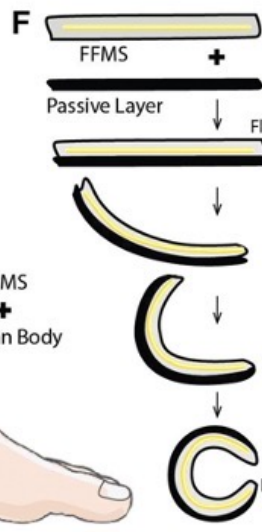
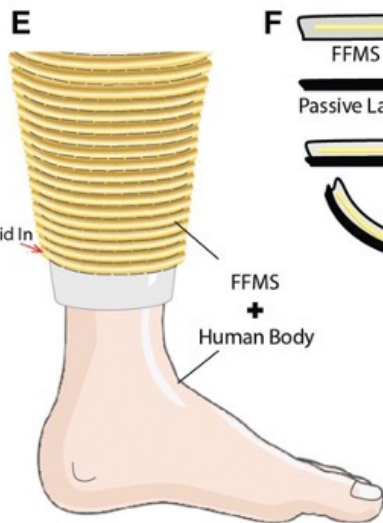
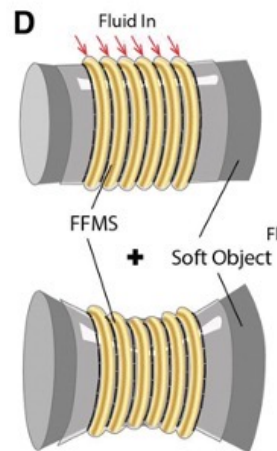
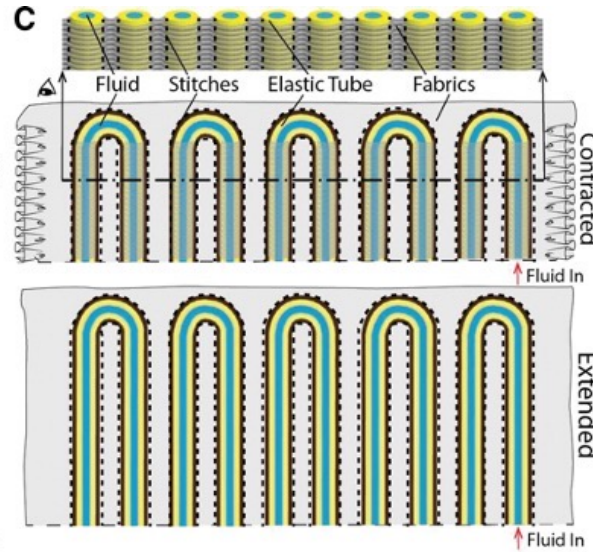
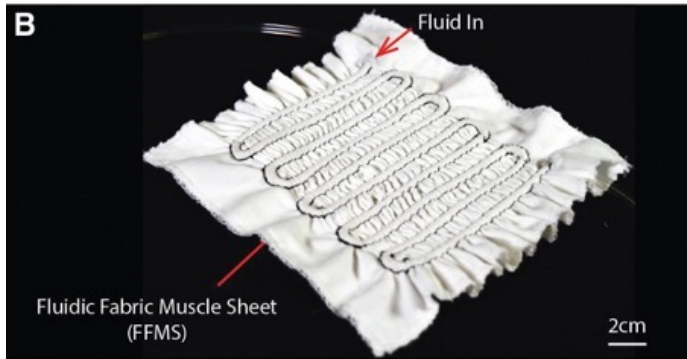
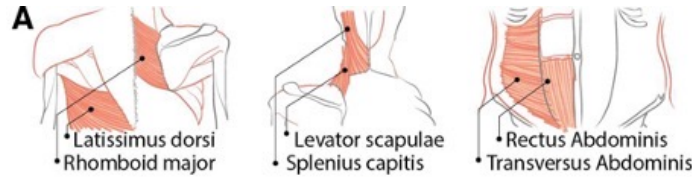


Other fluidic actuation concepts



D. Yang, M. Feng, G. Gu, High-stroke, High-Output-Force, Fabric-Lattice Artificial Muscles for Soft Robots. *Advanced Materials* **36**, 2306928 (2024).

Fluidic Fabric Muscle Sheet



Lengthens when pressurized

M. Zhu, T. N. Do, E. Hawkes, Y. Visell, Fluidic Fabric Muscle Sheets for Wearable and Soft Robotics. *Soft Robotics*. 7, 179–197 (2020).

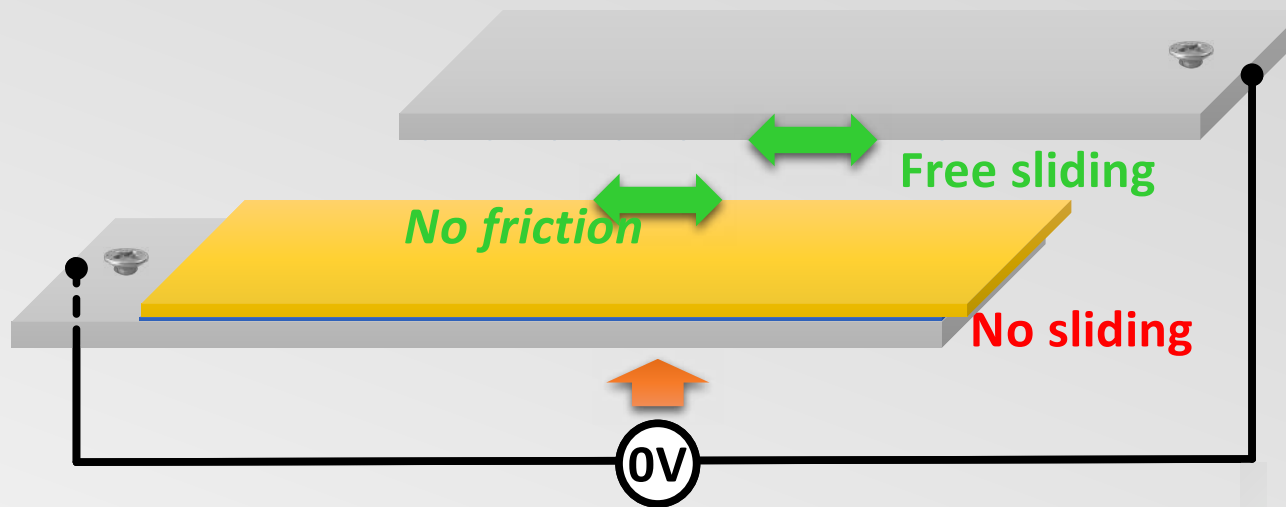
CLUTCHES FOR KINESTHETIC HAPTICS

What if only block motion?

Could still convey stiffness and be quite convincing...

With extremely low energy consumption

How does the ES clutch block motion?



No voltage

➤ Finger is free

Voltage on

➤ Finger is blocked

$$F_{ES} = \frac{1}{2} \epsilon_0 \epsilon_r A E^2$$

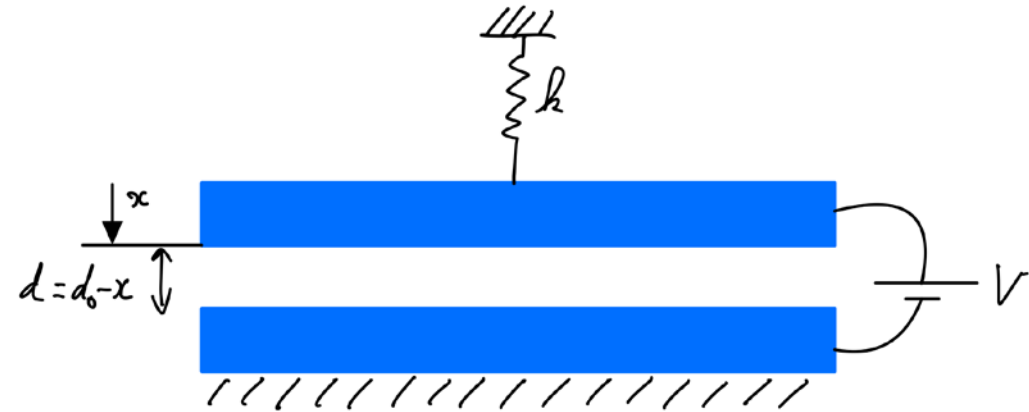
$$F_{fric} = \mu \frac{1}{2} \epsilon_0 \epsilon_r A E^2$$

Parallel plates electrostatic actuator

- Electrostatic energy in a capacitor $E_{es} = \frac{1}{2} CV^2$
- Normal electrostatic force for an applied voltage V :

$$F_{es} = \frac{dE_{es}}{dx} = \frac{1}{2} \frac{dC}{dx} V^2 = \frac{1}{2} \frac{CV^2}{d} \propto 1/d^2$$

$$F_{es} = \frac{\epsilon_0 AV^2}{2d^2} = \frac{\epsilon_0 A}{2} E^2$$



ES Force (when driven by a voltage) is always attractive!

Parallel plate electrostatic actuator

- Normal electrostatic force for an applied voltage V :

$$F_{es} = \frac{\epsilon_0 AV^2}{2d^2} = \frac{\epsilon_0 A}{2} E^2$$

- Energy density

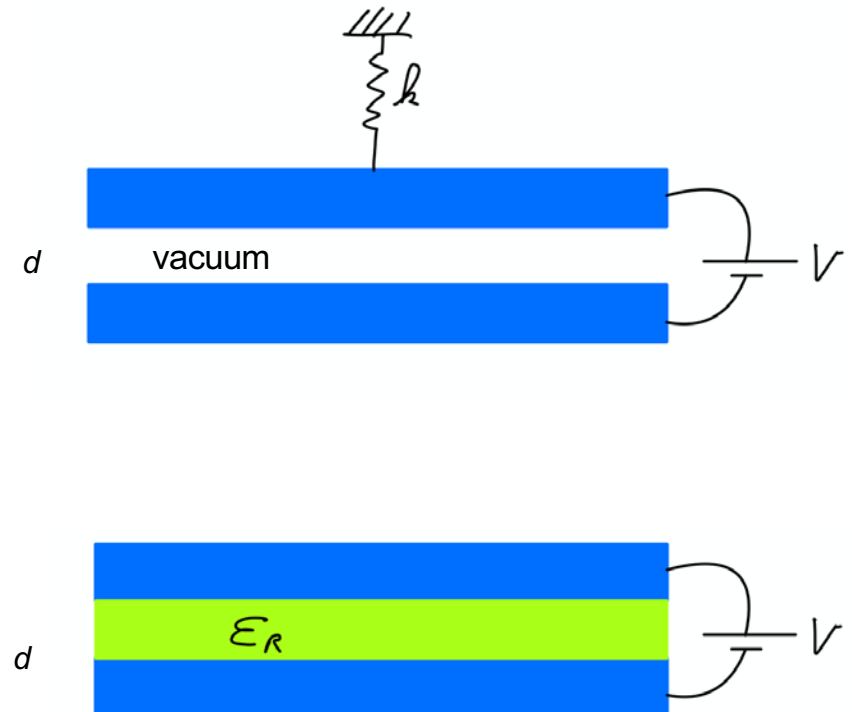
$$w_{ES} = \frac{1}{2} \epsilon_0 E^2$$

- If add a dielectric between the electrodes

$$w_{ES} = \frac{1}{2} \epsilon_0 \epsilon_r E^2$$

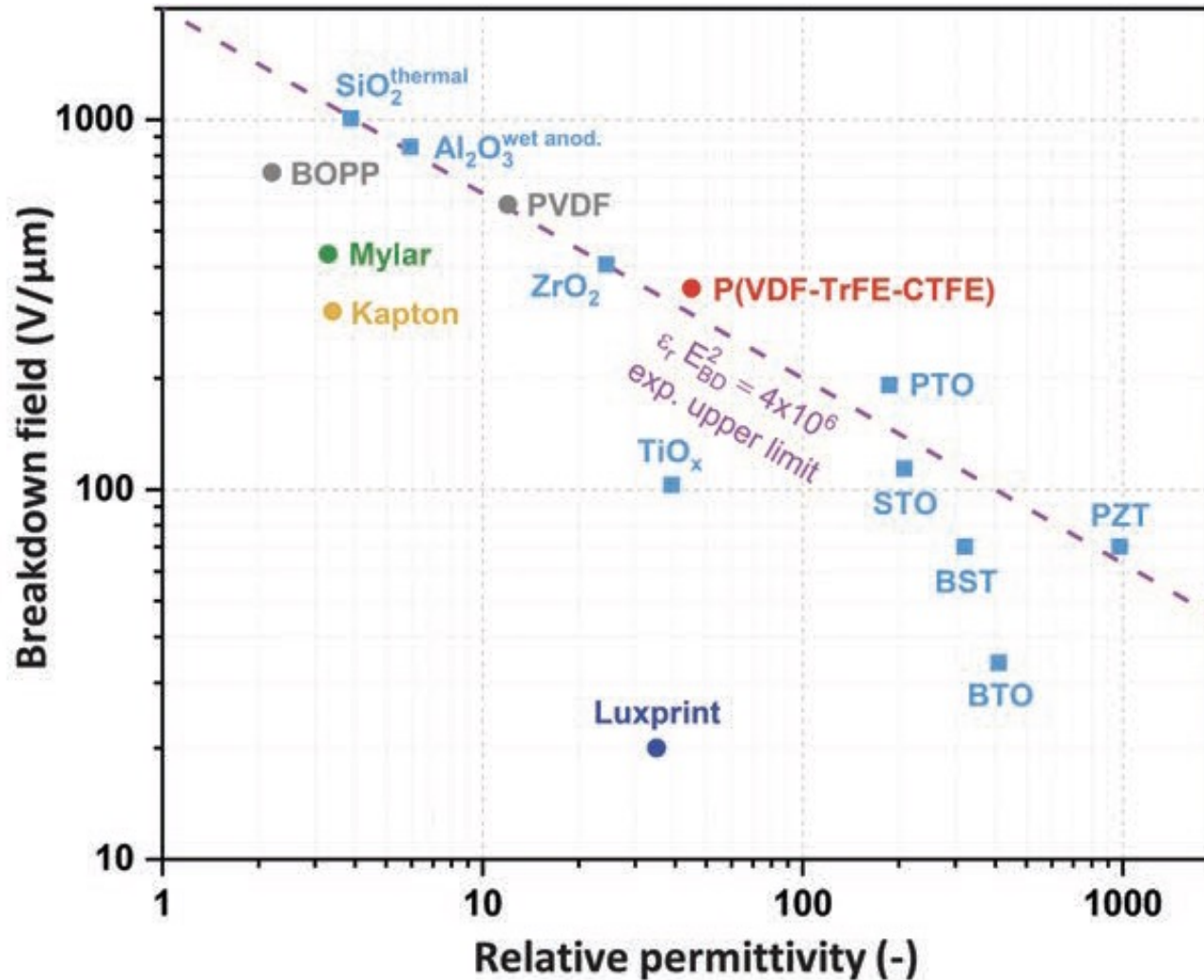
$$F_{ES} = \frac{1}{2} \epsilon_0 \epsilon_r A E^2$$

- Maximum energy density is limited by breakdown field E_{BD}



E =electric field, V =voltage,
 d =insulator thickness, A = electrode area

There is an empirical upper limit to $\epsilon_r \cdot E_{BD}^2$ product for solid dielectrics



- Want materials with high ϵ_r **and** high $E_{\text{breakdown}}$
- (Softer materials have lower breakdown field...)

Hinchet et al. *Advanced Materials Technologies* **5**, 1900895 (2019)

How fast can one operate?

1. Mechanical response time, given roughly by mechanical resonant frequency

$$\tau_{mech} = \sqrt{\frac{m}{k}}$$

m: mass. k: spring constant

2. Electrical response. Time to charge / discharge the capacitor

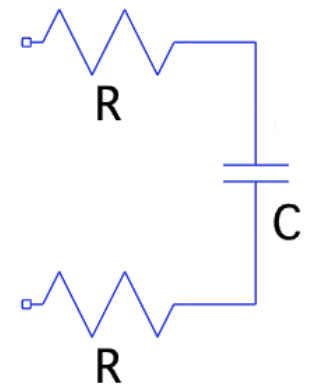
simplest model: $\tau_{electrical} = RC$

R: resistance of electrodes (or series resistance)

C: capacitance of the actuator

- Eg if desire an electrical bandwidth of 1kHz
 - 1cm² actuator 25μm thick: C≈100 pF

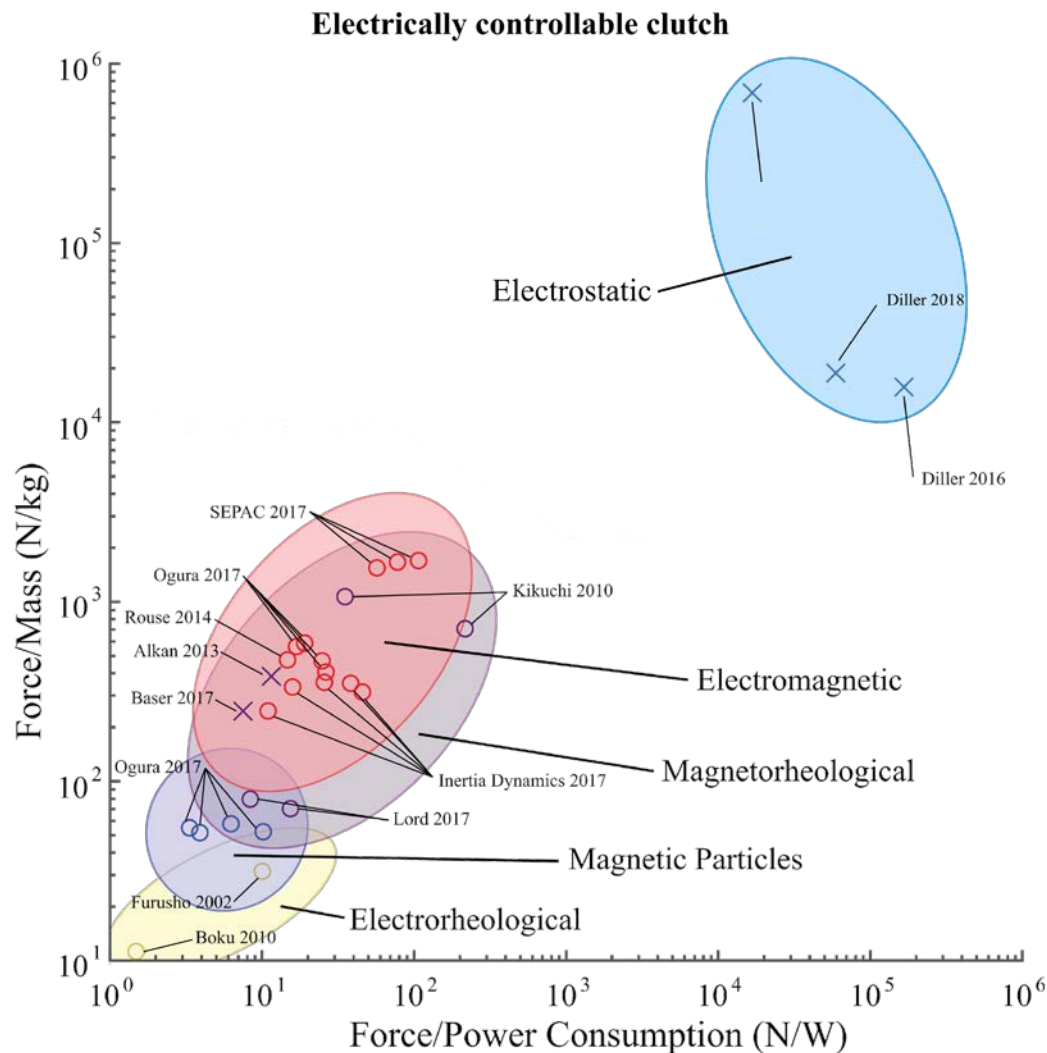
$$f_c = \frac{1}{2\pi 2RC} \geq 1kHz \Rightarrow R = \frac{1}{4\pi f_c C} \leq 800k\Omega$$



Energy used in an ES clutch

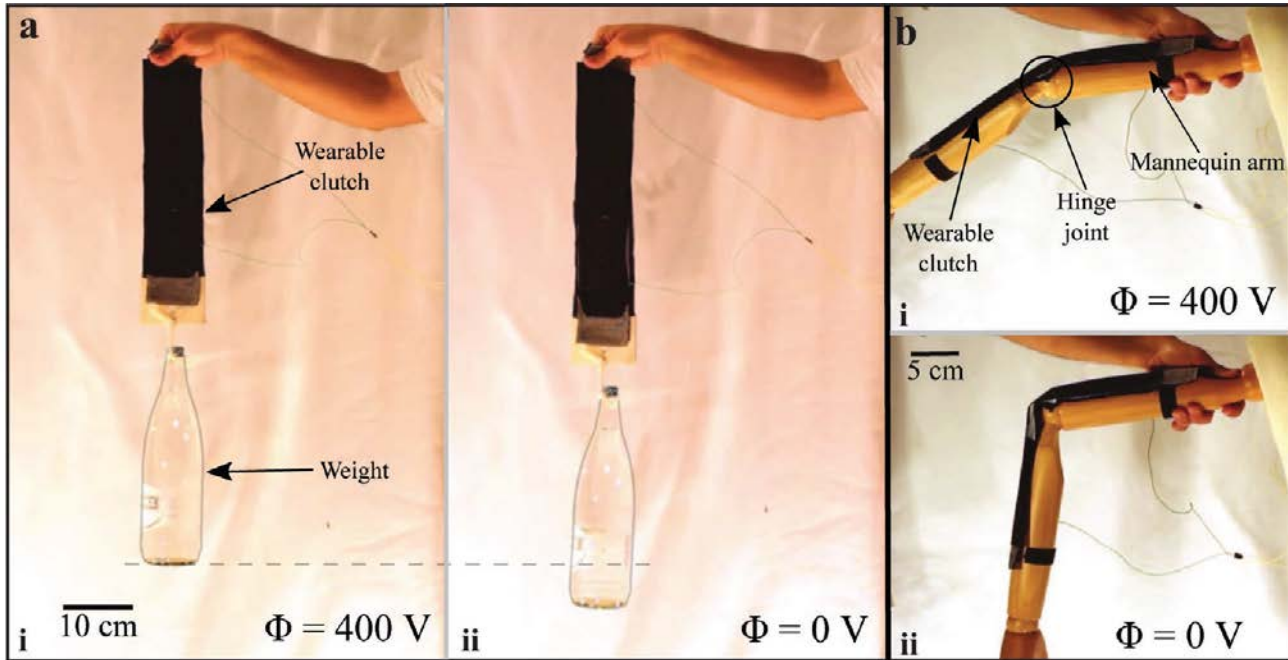
- Power = $\frac{1}{2} C V^2 f$
- Operate at 10 Hz bipolar to avoid charging of the dielectric
- Example to block about 10N: 1 nF, 300V, 10 Hz = 1 mW

Solution to charging in zipping electrostatics published recently:
I.-D. Sîrbu, et al. Electrostatic actuators with constant force at low power loss using matched dielectrics. *Nat Electron*, 1–12 (2023).



- In principle, blocking motion costs zero energy (no motion = no work !)
- ElectroStatic brakes offer exceptionally low power consumption

Diller et al, *The effects of electroadhesive clutch design parameters on performance characteristics*. Journal of Intelligent Material Systems and Structures, (2018).



V. Ramachandran, J. Shintake, D. Floreano, All-Fabric Wearable Electroadhesive Clutch. *Advanced Materials Technologies*, 1800313 (2018).



S. Diller, C. Majidi, S. H. Collins, A lightweight, low-power electroadhesive clutch and spring for exoskeleton actuation. *Proceedings - IEEE International Conference on Robotics and Automation*. 2016



Haptic glove for VR + AR

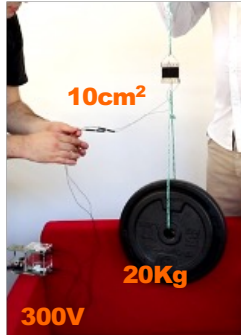
Electrostatic brake blocks finger motion to make virtual objects feel solid (or squishy)

EPFL Textile ESclutch can block 2 kg/cm² at 300 V

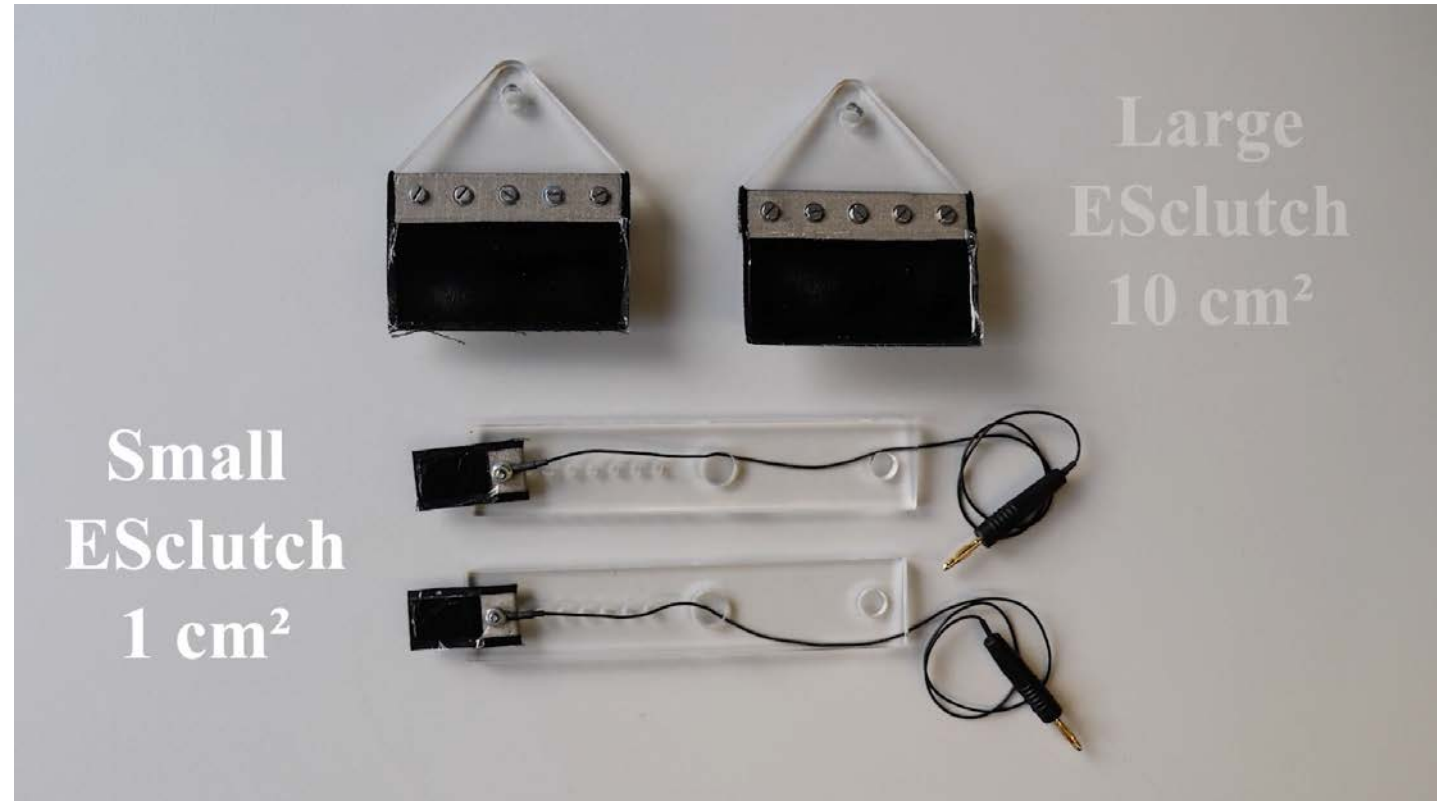
Small ESclutch



Large ESclutch



- High holding force : **20 N/cm² at 300 V**
- low power **1.2 mW/cm²**
- Flexible, Lightweight **30 mg/cm²**
- Fast **< 15 ms**
- Tuneable Stiffness



- Performance comes from use of $\epsilon_r=40$ material, with $E_{BD} > 100 \text{ V}/\mu\text{m}$ and from fabrication method.
- mW power enables use in in exoskeletons and full-body haptics
- Textile format

**Flexible actuator, with very high holding force, “easy”
... Tricky part was integration in textile and on the body**



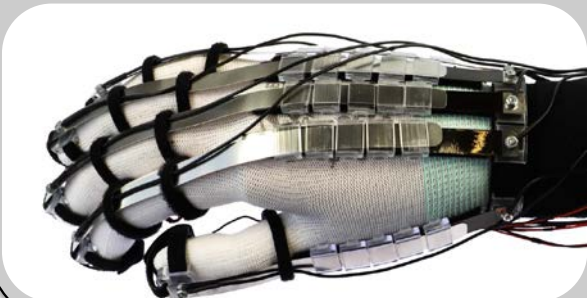
- Grounding
- Finger & hand Size
- Comfortable
- Easy to don & doff

Evolution of our ES clutch glove

DextrÉS v1

Proof of concept

- Metal shim
- Low force, high voltage
- 3D printed guide integration
- Hard to fit
- Not very comfortable
- Only On/Off



DextrÉS v2

Improvement of actuators

- Textile ESclutch
- **High force, low voltage**
- Floating elastic integration
- Takes long to put on
- Only On/Off
- **Comfortable**



DextrÉS v3

Better actuators & integration

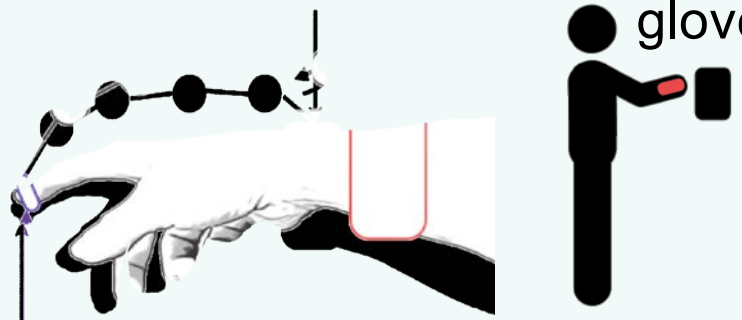
- PET film ESclutch
- High force low voltage
- **Variable stiffness**
- **Soft textile integration**
- **Quick and easy to fit**
- Very comfortable





Extend concept to elbow and shoulder for grounded kinesthetic feedback


Hand kinesthetic Haptic glove



For interacting with objects

The diagram shows a hand with a device consisting of a series of black spheres connected by a thin rod, extending from the wrist to the fingers. A red rectangular area is highlighted on the back of the hand. To the right, a stick figure is shown wearing a red haptic glove and holding a black rectangular object.

Grounded kinesthetic Haptic sleeve



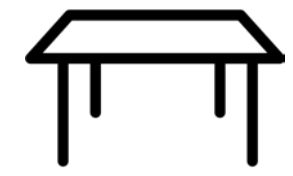
For interacting with furniture

The diagram shows a hand with a device consisting of a series of white spheres connected by a thin rod, extending from the wrist to the fingers. A red rectangular area is highlighted on the back of the hand. To the right, a stick figure is shown wearing a red haptic sleeve and holding a black rectangular object.

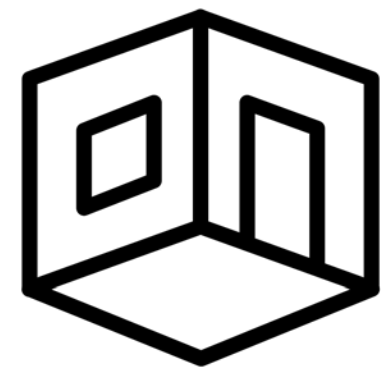
To feel weight



To touch tables



Feel virtual walls



Feel large objects



Feeling inertia in body-grounded haptics

EPFL



Ronan Hinchet
Herbert Shea
(hebert.shea@epfl.ch)

■ École
polytechnique
fédérale
de Lausanne


LMTS lab 2021

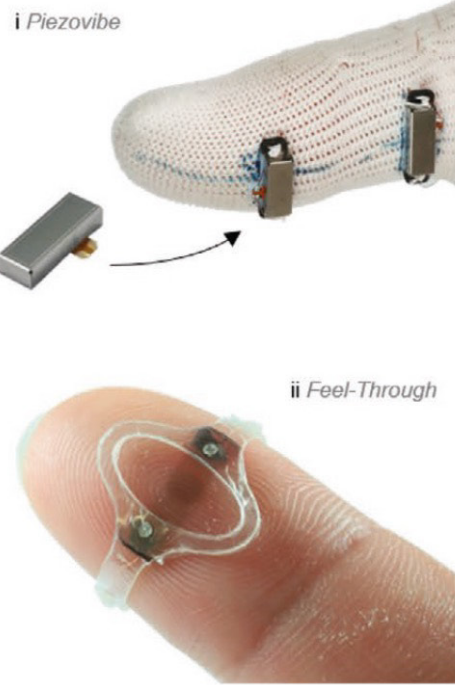
Hinchet and Shea, Adv. Intell Sys, 2022


1. Why haptics?
2. Human perception
3. Kinesthetic haptics
 1. Fluidic elastomer actuators
 2. Clutches
- 4. Wearable Cutaneous haptics**
 1. Electrostimulation
 2. Soft pneumatic
 3. Electromagnetic
 4. DEA
 5. Zipping
 6. EHD

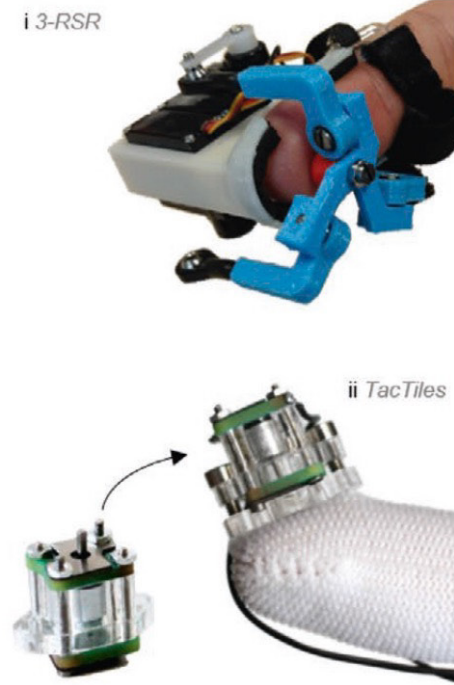
ACTUATORS FOR WEARABLE CUTANEOUS HAPTICS

WEARABLE CUTANEOUS

A. vibrations 



B. normal indentation 



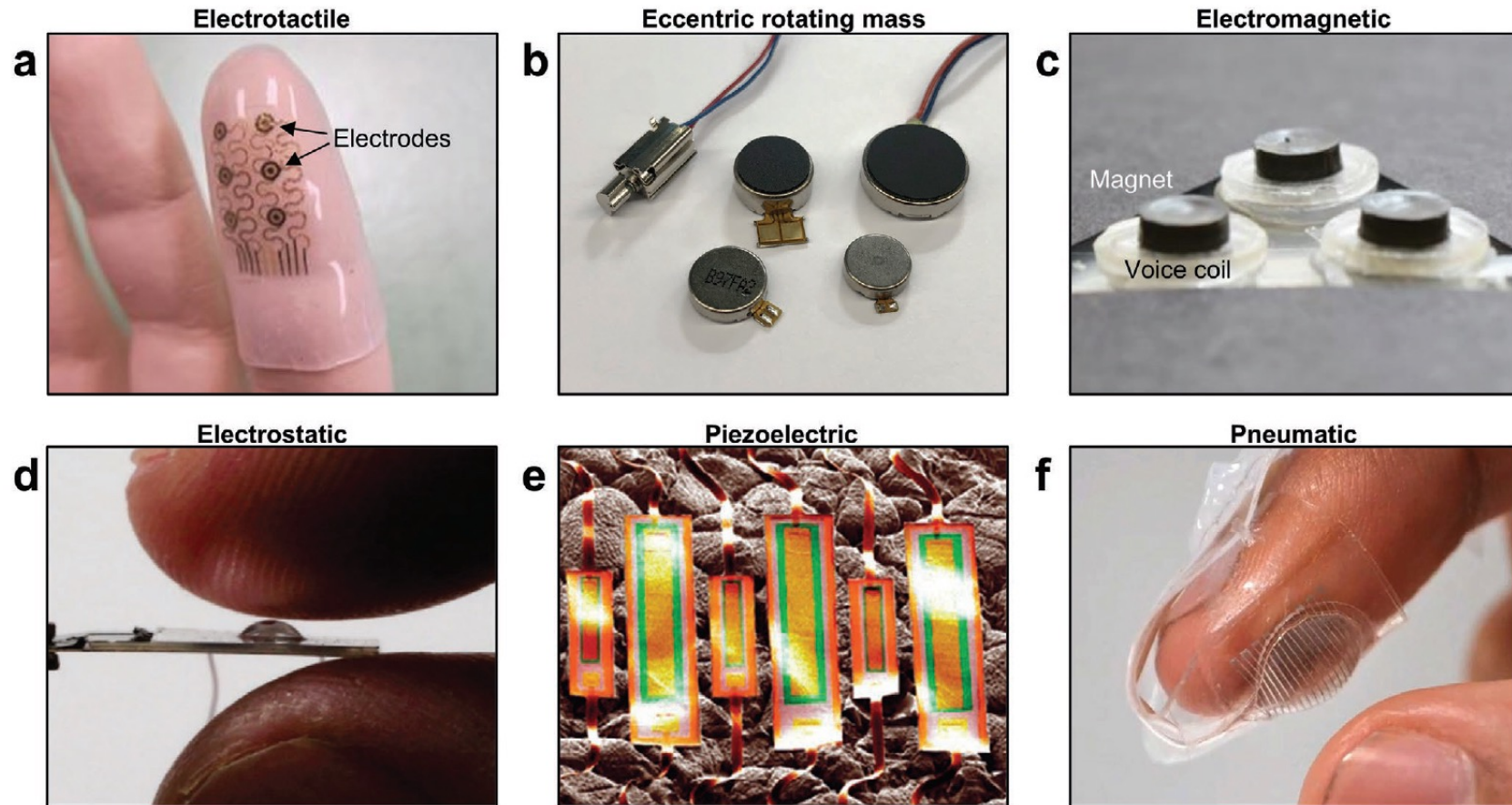
C. lateral stretching 



- Skin integrated
- VS
- On skin

J. Yin, R. Hinchet, H. Shea, C. Majidi, Wearable Soft Technologies for Haptic Sensing and Feedback. *Advanced Functional Materials*, 2007428 (2020).

On Skin devices: need low profile and compliant



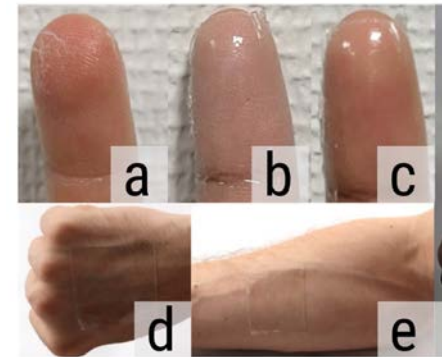
Y. H. Jung, J.-H. Kim, J. A. Rogers,
 "Skin-Integrated Vibrotactile Interfaces for Virtual and Augmented Reality".
Advanced Functional Materials. 2008805 (2020).

How soft/thin must a device be so as not to feel it?

The resistance to bending is given in by the flexural rigidity D

$$D = \frac{E h^3}{12(1 - \nu^2)}$$

- h thickness of the film
- E material's constant Young's modulus (GPa for solid metals, MPa for elastomers, kPa for hydrogels)
- ν Poisson ratio



A. S. Nittala, et al, "Like A Second Skin: Understanding How Epidermal Devices Affect Human Tactile Perception" *CHI 2019*

Need to use FEM for more complex multilayer cases like metal traces on silicone

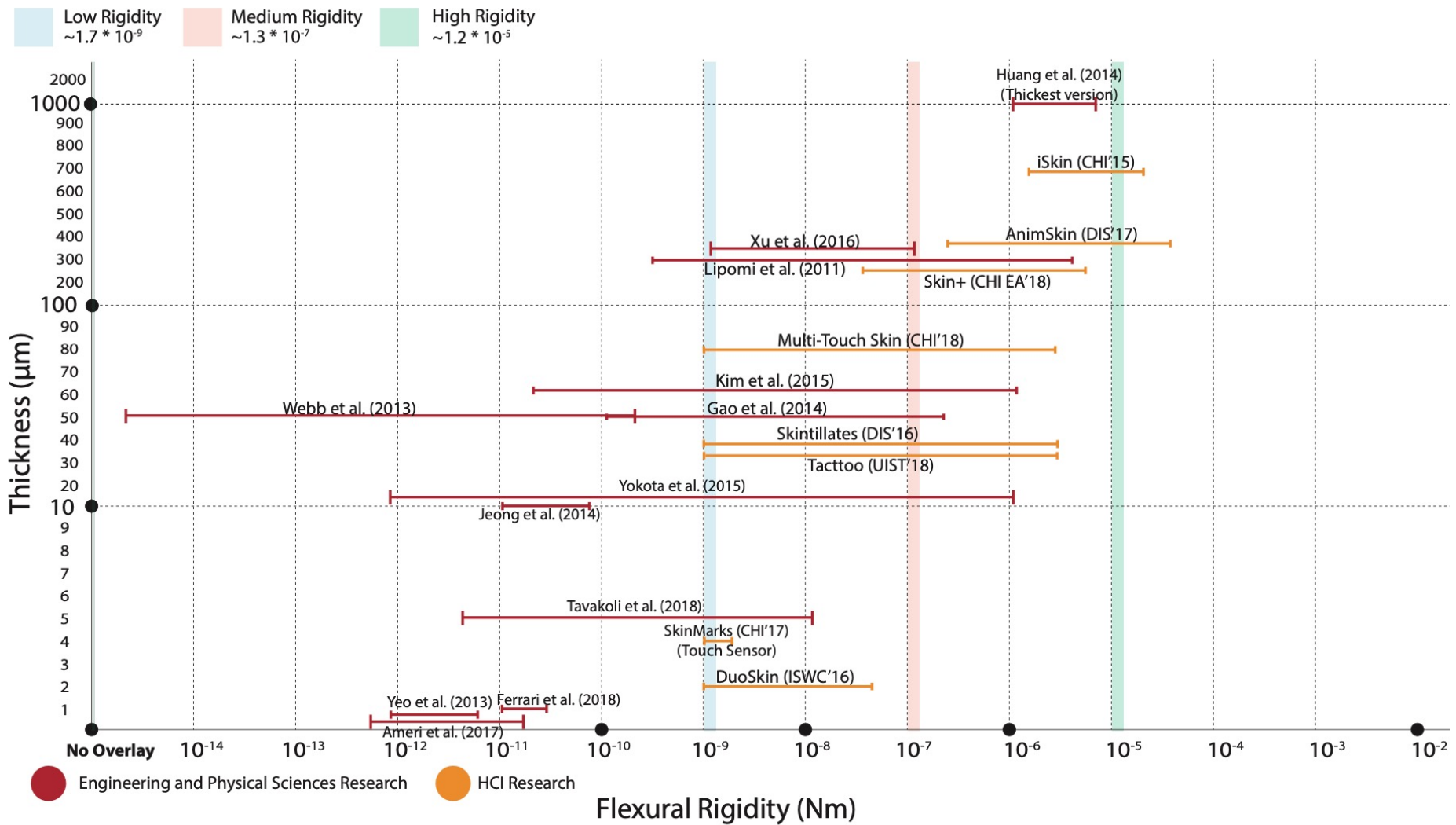
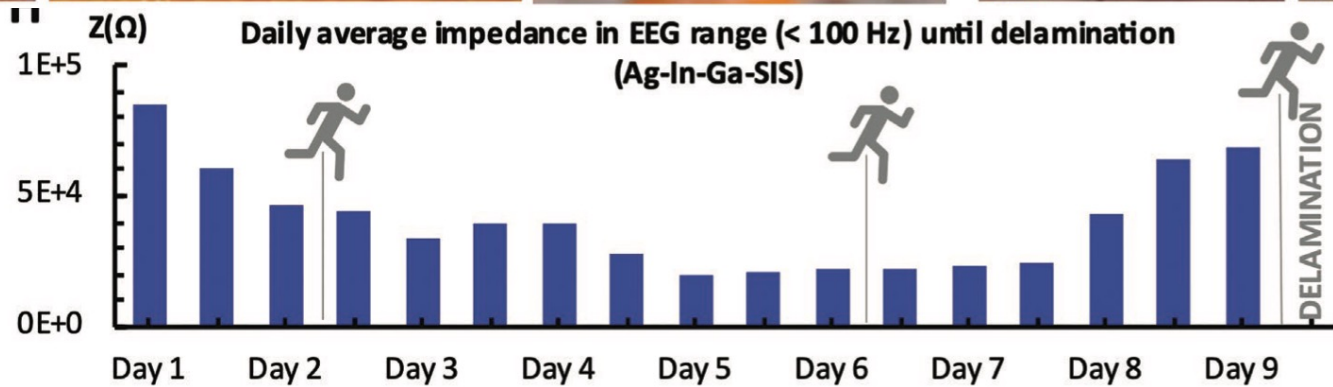
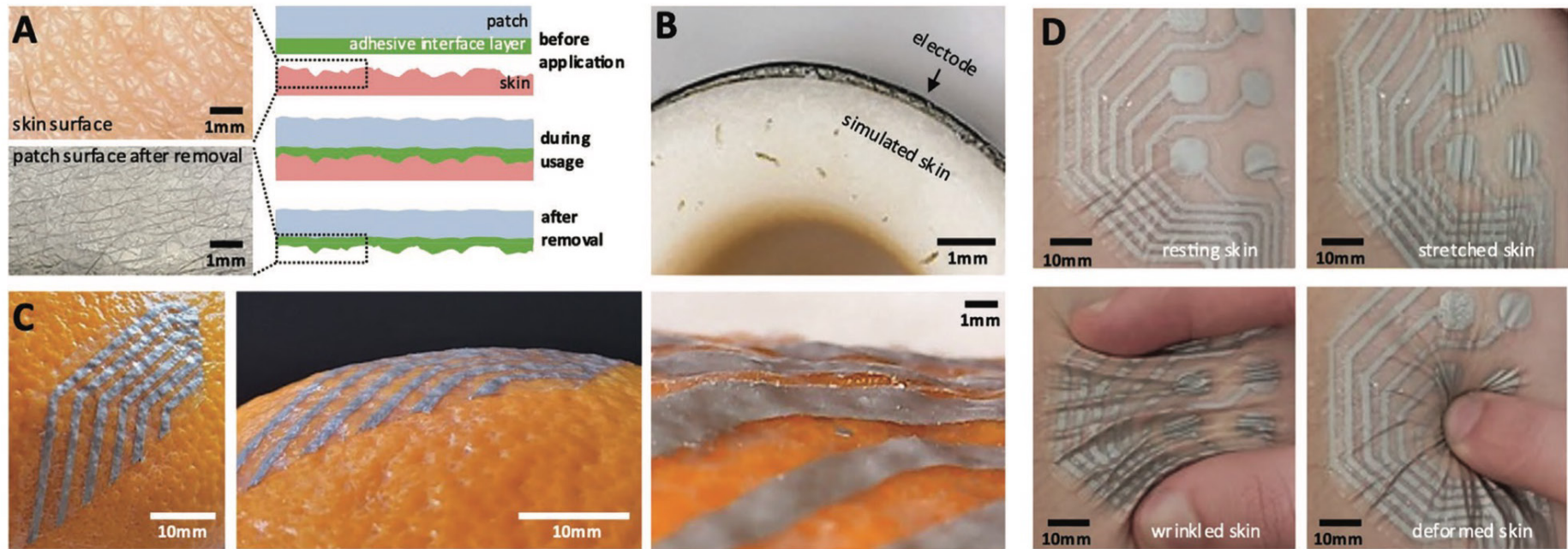
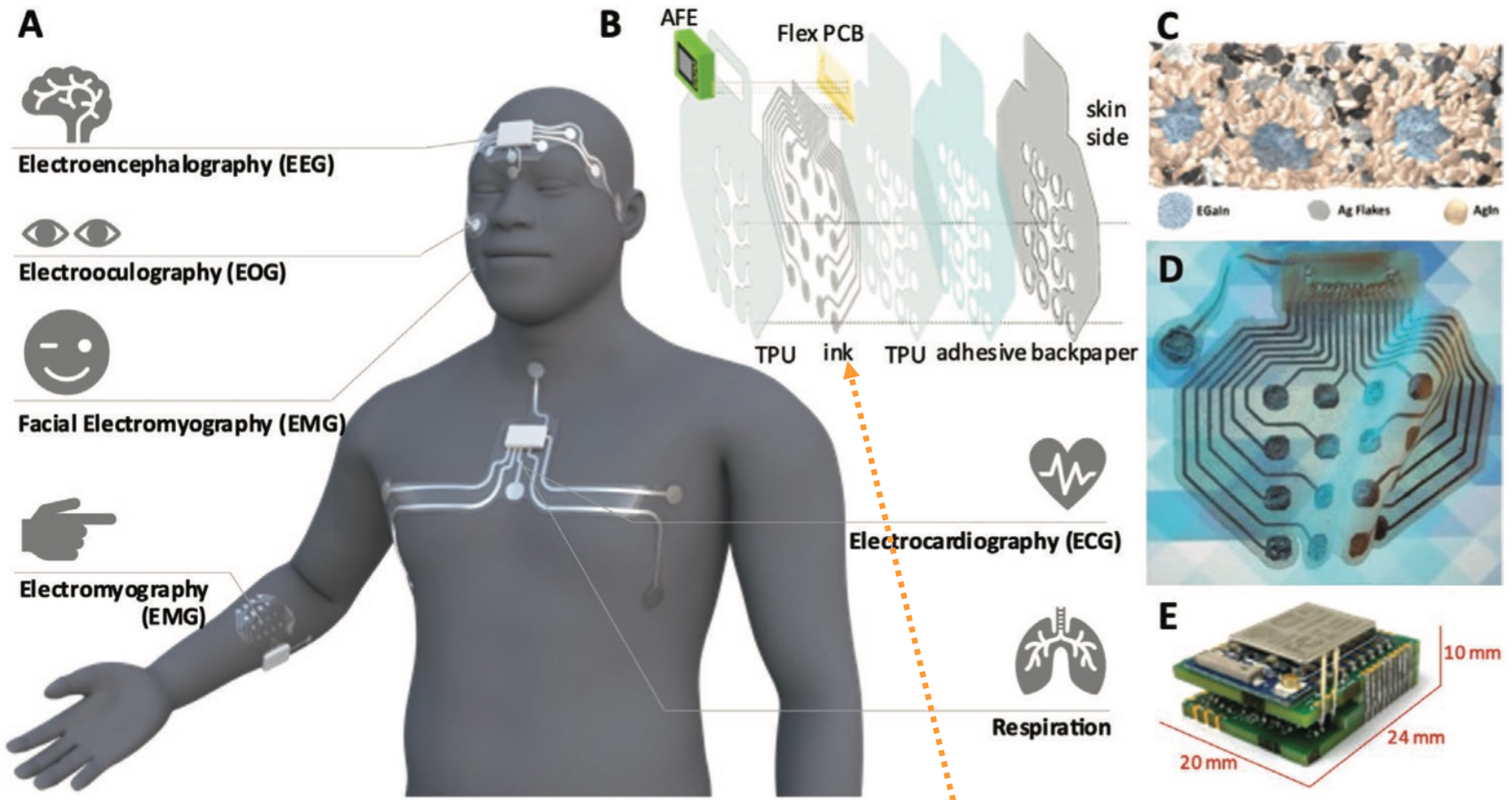


Figure 1: Classification of prior work based on flexural rigidity (ranges shown for devices made of multiple materials). Vertical axis shows total device thickness.

A. S. Nittala, et al, "Like A Second Skin: Understanding How Epidermal Devices Affect Human Tactile Perception" CHI 2019 <http://doi.acm.org/10.1145/3290605.3300610>

Link to paper 1 “Multi-Electrode Printed Bioelectronic Patches for Long-Term Electrophysiological Monitoring” M.R. Carneiro et al, Adv. Func. Mat 2022





Ink: Ag-In-Ga-SIS polymer

4.1 Electrostimulation / electrotactile

Drive current through the skin to directly stimulate nerves

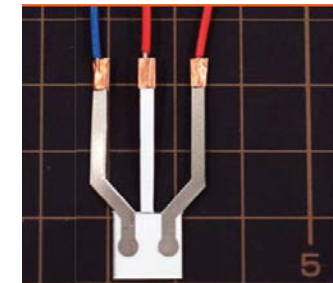
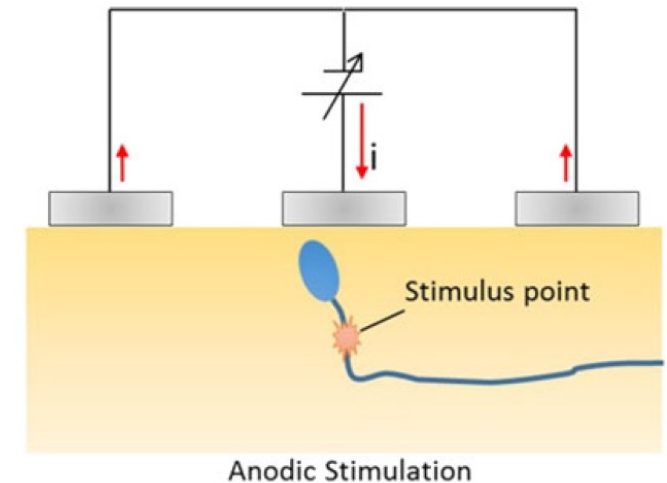
Goal: stimulate only nerve stems of mechanoreceptors, which the brain interprets as mechanical vibrations

good electrical contact to the skin needed, as need approx. 0.1 to $10 \text{ mA}\cdot\text{cm}^{-2}$

Requires 50 - 500 V

Skins impedance changes ...

Feeling is not like mechanical stimulation



V. Yem and H. Kajimoto, "Comparative Evaluation of Tactile Sensation by Electrical and Mechanical Stimulation," *IEEE Transactions on Haptics*, vol. 10, no. 1, pp. 130–134, 2017

mean current density thresholds on the skin for electrotactile feedback

- 0.21 mA cm⁻² for touch,
- 0.28 mA cm⁻² for pressure,
- 0.39 mA cm⁻² for buzz,
- 0.49 mA cm⁻² for vibration,
- 0.66 mA cm⁻² for numb,
- 0.90 mA cm⁻² for pain.

Energy efficient

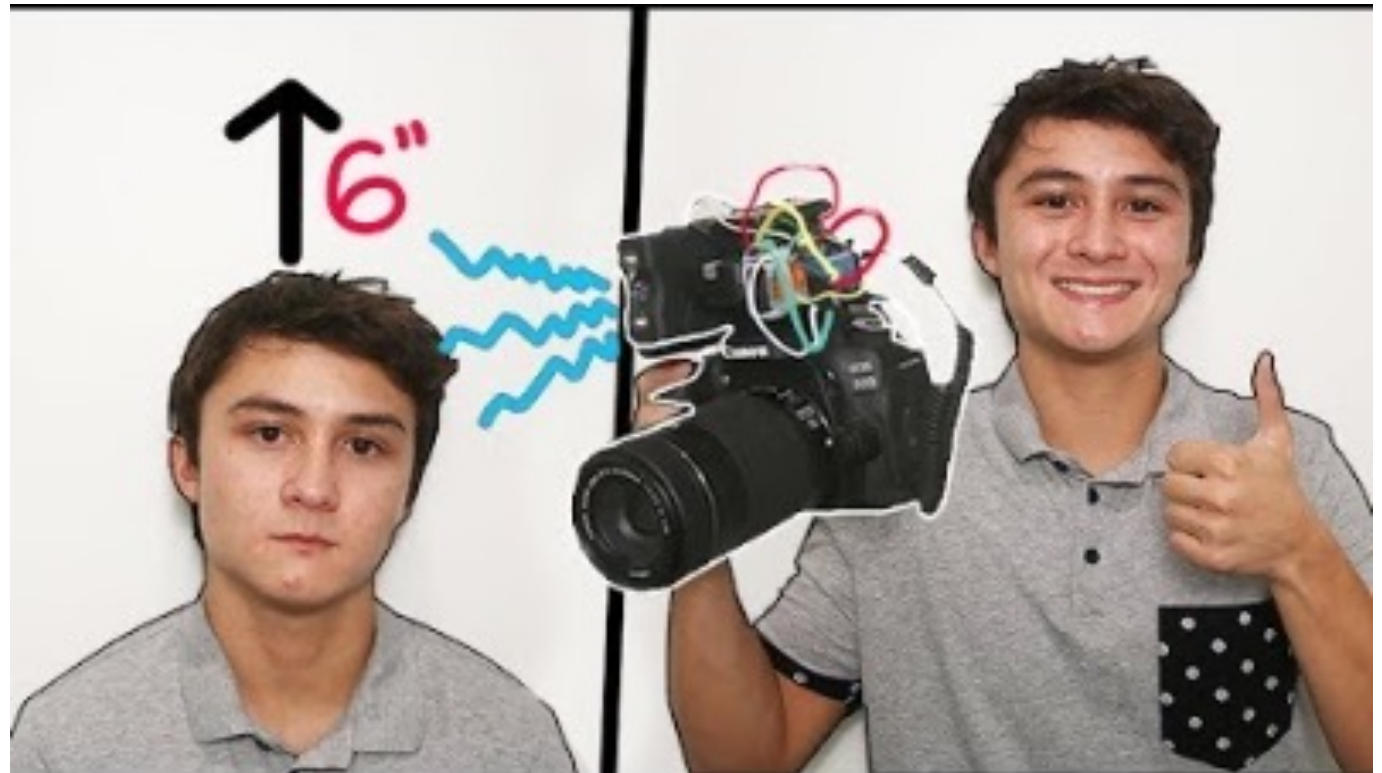
M. Franceschi, L. Seminara, S. Dosen, M. Strbac, M. Valle, D. Farina,
A System for Electrotactile Feedback Using Electronic Skin and Flexible Matrix Electrodes: Experimental Evaluation.
IEEE Transactions on Haptics. **10**, 162–172 (2017).

Electrostimulation

If not careful, TENS (Transcutaneous Electrical Neural Stimulation) can get out of control...



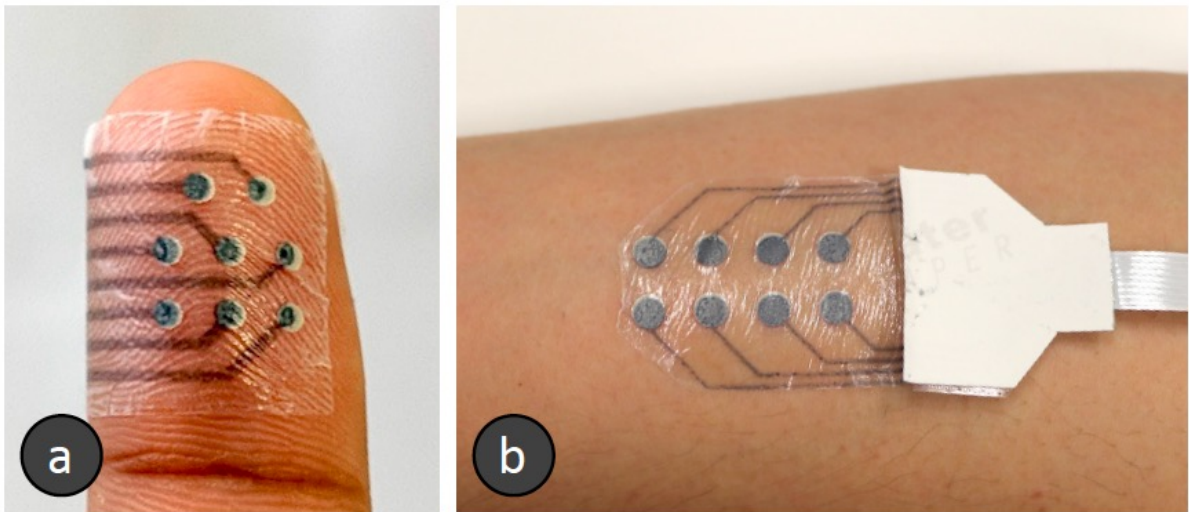
TeslaSuit



<https://www.youtube.com/watch?v=DvrkHAWj1Sk>

Michael Reeves

Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output



35 μm thick

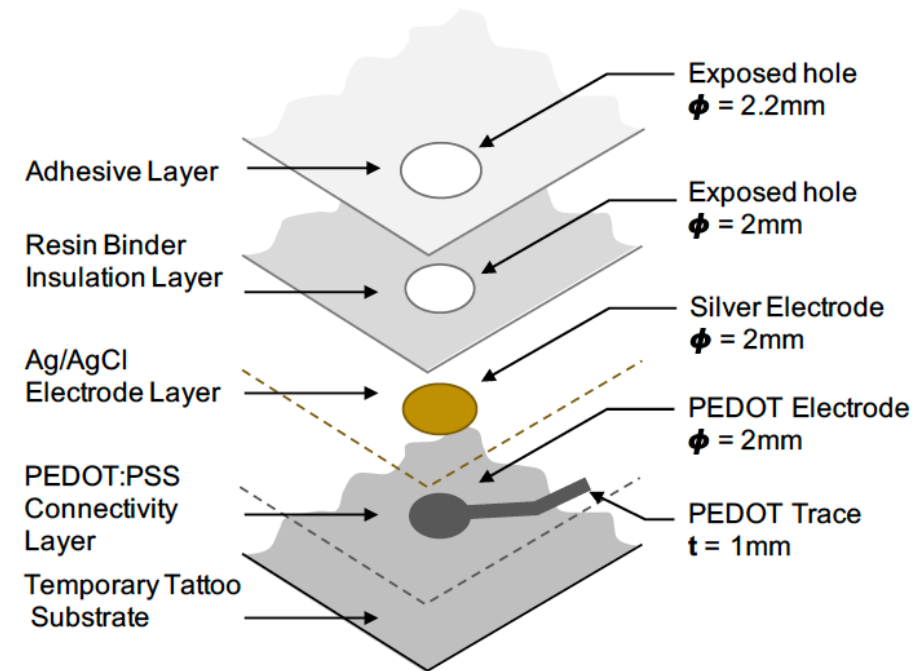


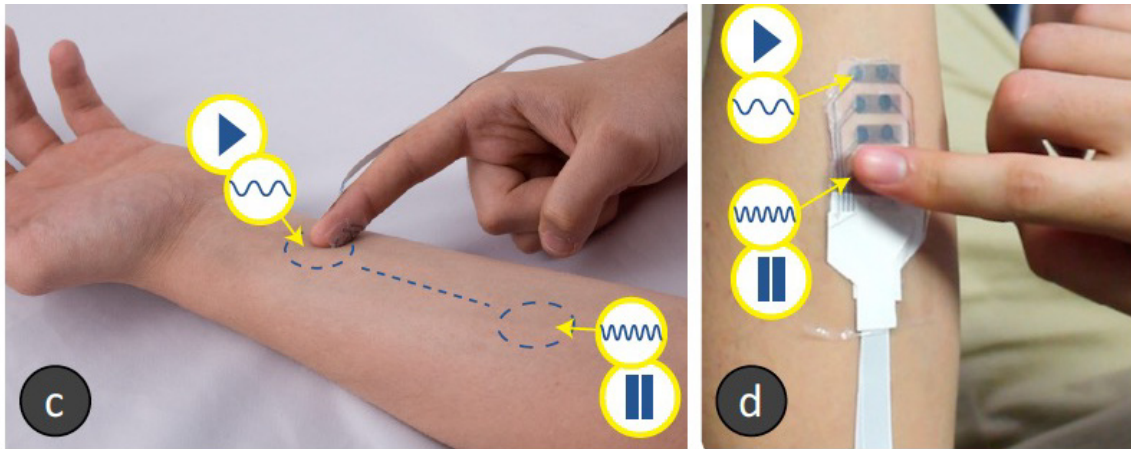
Figure 2. Layered fabrication of Tacttoo

A. Withana, D. Groeger, and J. Steimle, "Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output," in *UIST*, 2018, p. 14. doi: [10.1145/3242587.3242645](https://doi.org/10.1145/3242587.3242645).

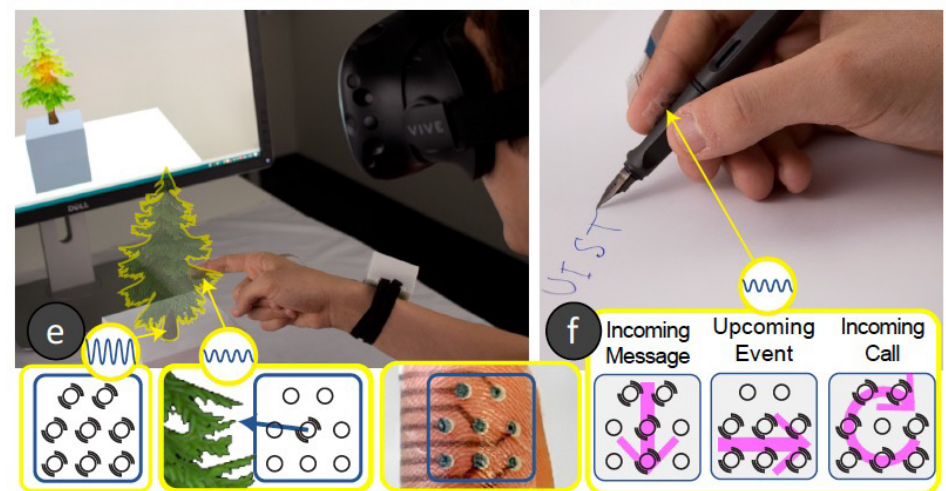


A. Withana et al, "Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output" *UIST* 2018

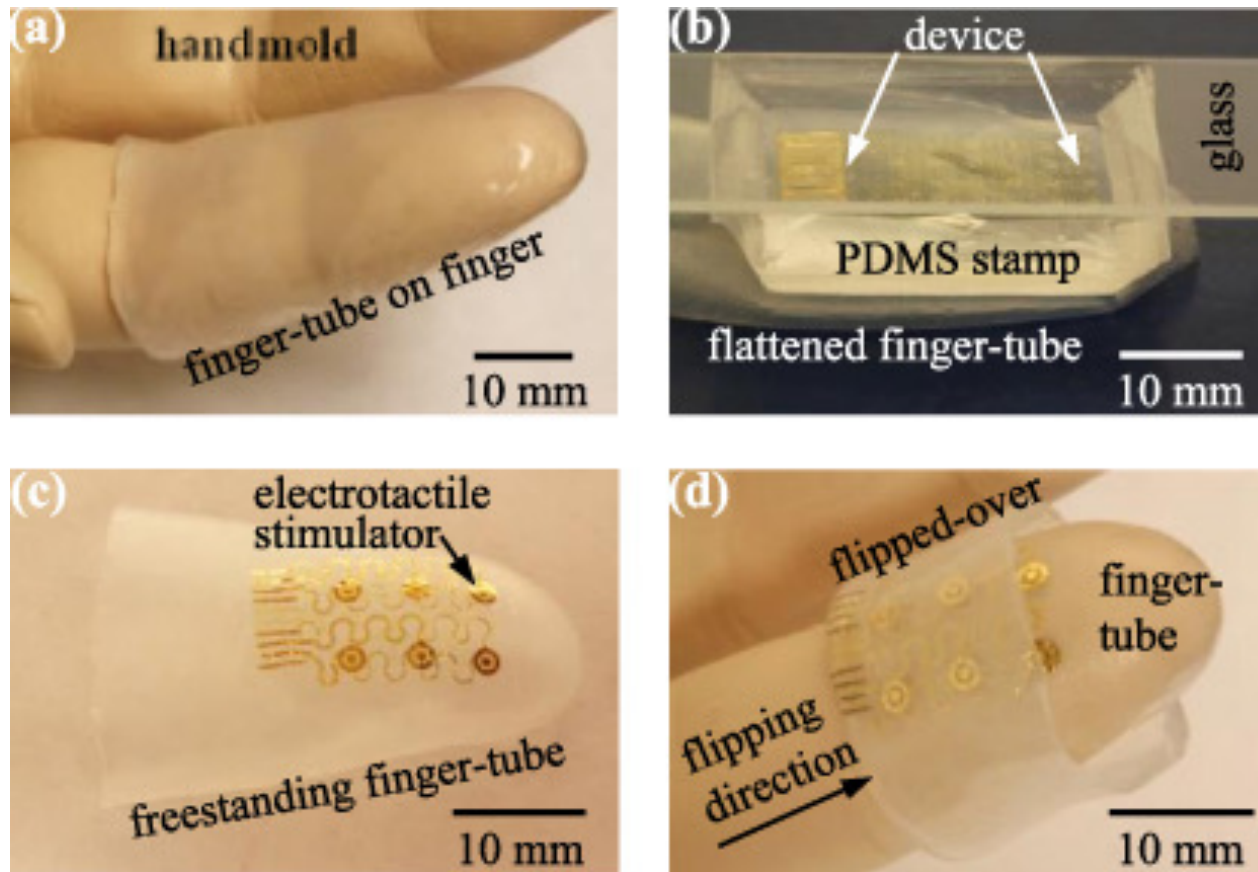
Tactile augmented reality



Dynamic tactile landmarks for on-skin interactions



Private tactile notifications

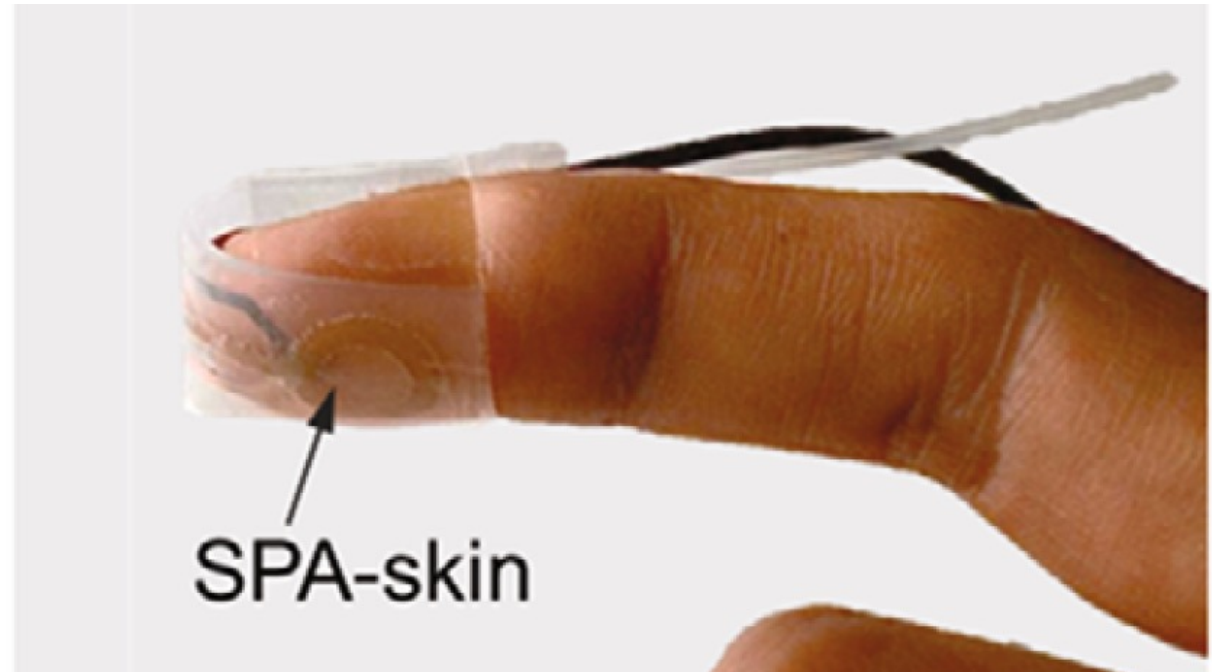


M. Ying, A. P. Bonifas, N. Lu, Y. Su, R. Li, H. Cheng, A. Ameen, Y. Huang, J. A. Rogers, Silicon nanomembranes for fingertip electronics. *Nanotechnology*. **23**, 344004 (2012).

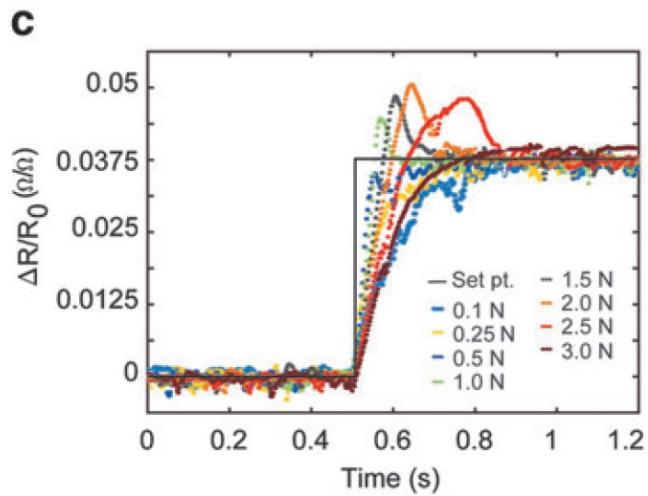
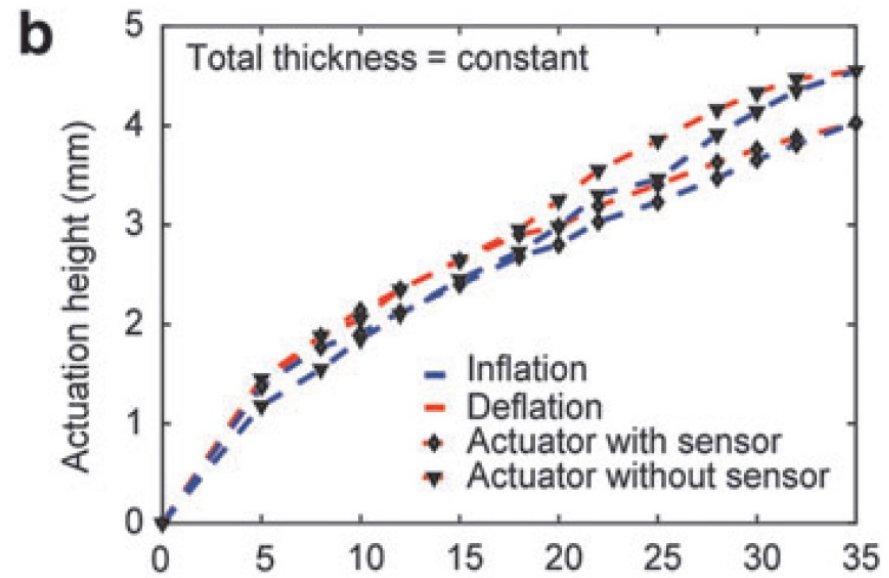
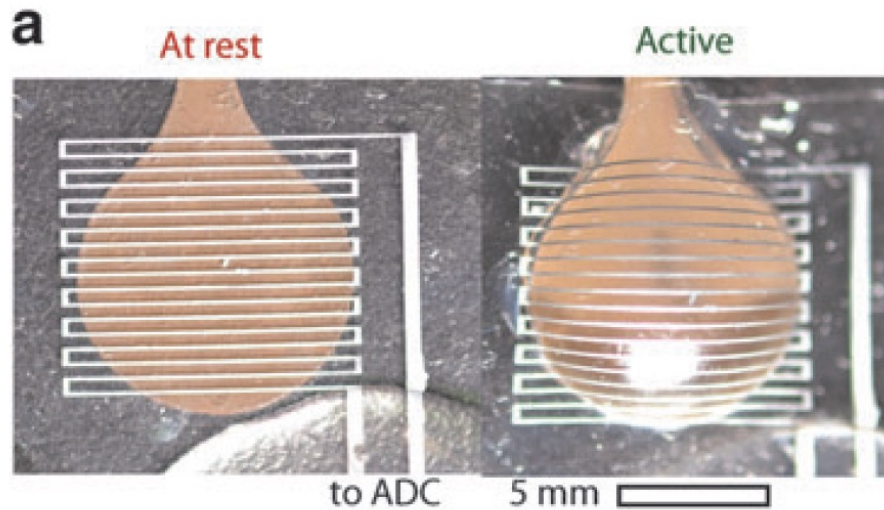
- Can be combined with stick-on muscle stimulation
- Lifetime?

4.2 SOFT PNEUMATIC ACTUATORS (SPA) FOR CUTANEOUS HAPTICS

- “Easy” manufacturing
- 1N
- Max a few Hz,
- 100 Hz shown with special controller
- Often linked to sensing



H. A. Sonar, J.-L. Huang, J. Paik,
Soft Touch using Soft Pneumatic Actuator–Skin as a Wearable Haptic
Feedback Device. *Advanced Intelligent Systems*, 2000168 (2021).



H. A. Sonar, A. P. Gerratt, S. P. Lacour, J. Paik, Closed-Loop Haptic Feedback Control Using a Self-Sensing Soft Pneumatic Actuator Skin. *Soft Robotics*. **7**, 22–29 (2020).

A commercial example

- 150 fluidic channels!
- Effective sensation for cutaneous using fluidics
- Large controller



4.3 ELECTROMAGNETIC

Hard:

- Motors (eccentric rotating mass)
- linear resonance actuators (LRA)
- Voice coil
- Bistable

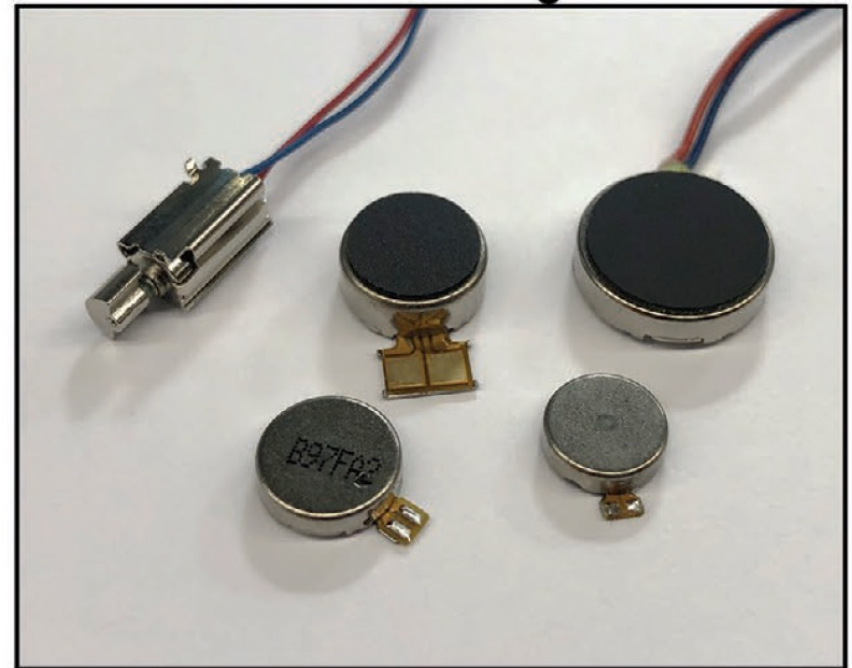
Soft:

- Soft coils (liquid metal)
- Soft magnet (elastomer composite)

Common Issue: high power consumption

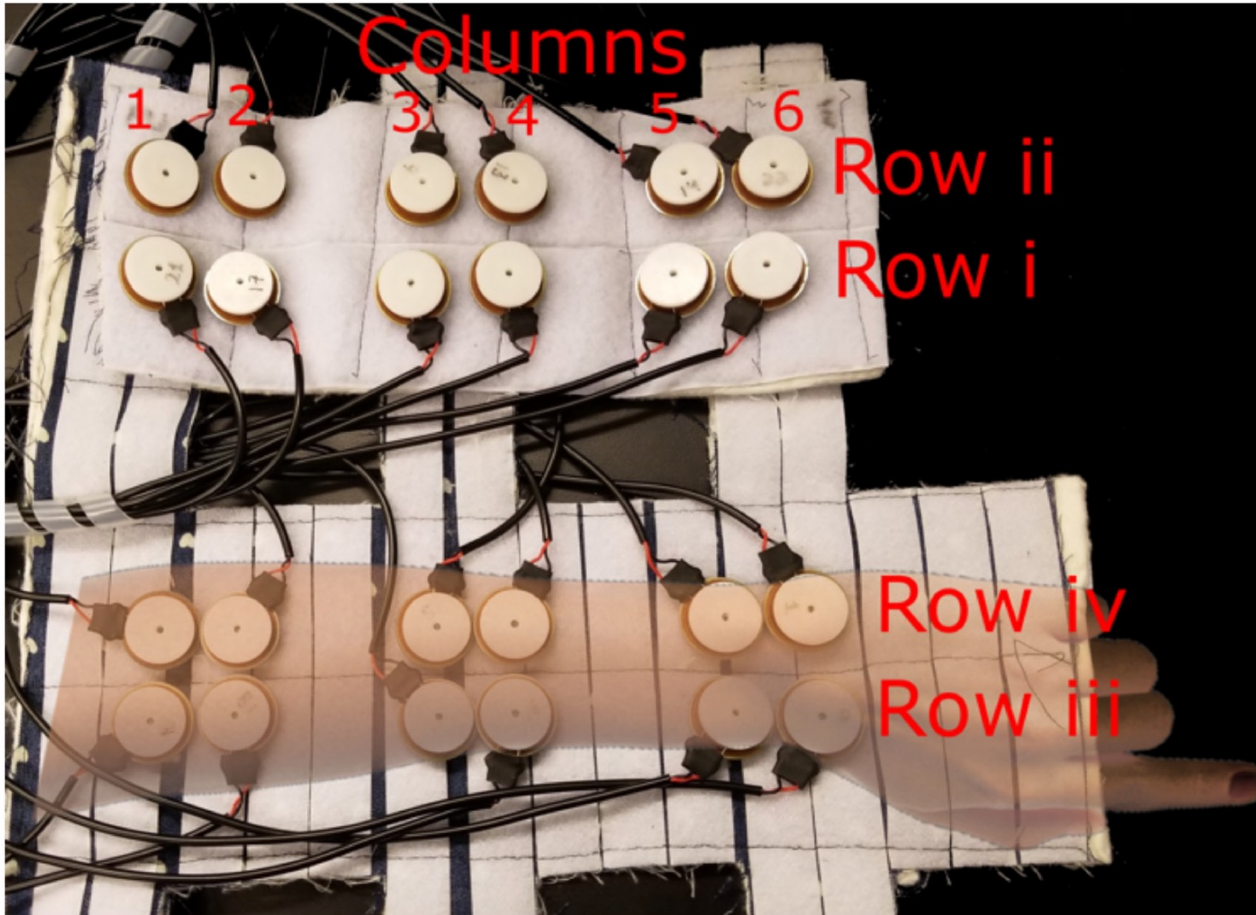
Generally only gives vibration,

Eccentric rotating mass



Y. H. Jung, J.-H. Kim, J. A. Rogers,
Skin-Integrated Vibrotactile Interfaces for Virtual and Augmented Reality.
Advanced Functional Materials, 2008805 (2020).

Voice coil array on forearm



4x6 array of voicecoils, worn on forearm (top and bottom)

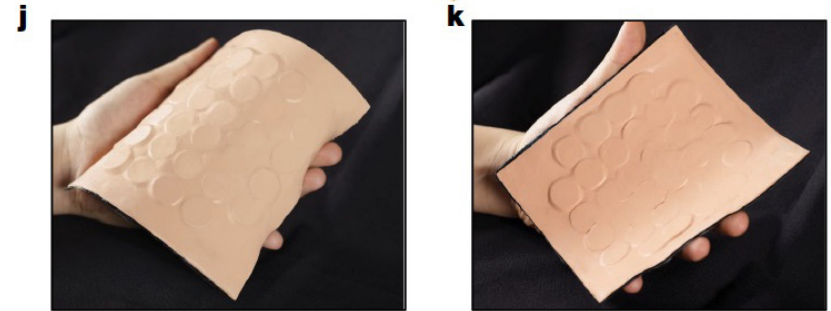
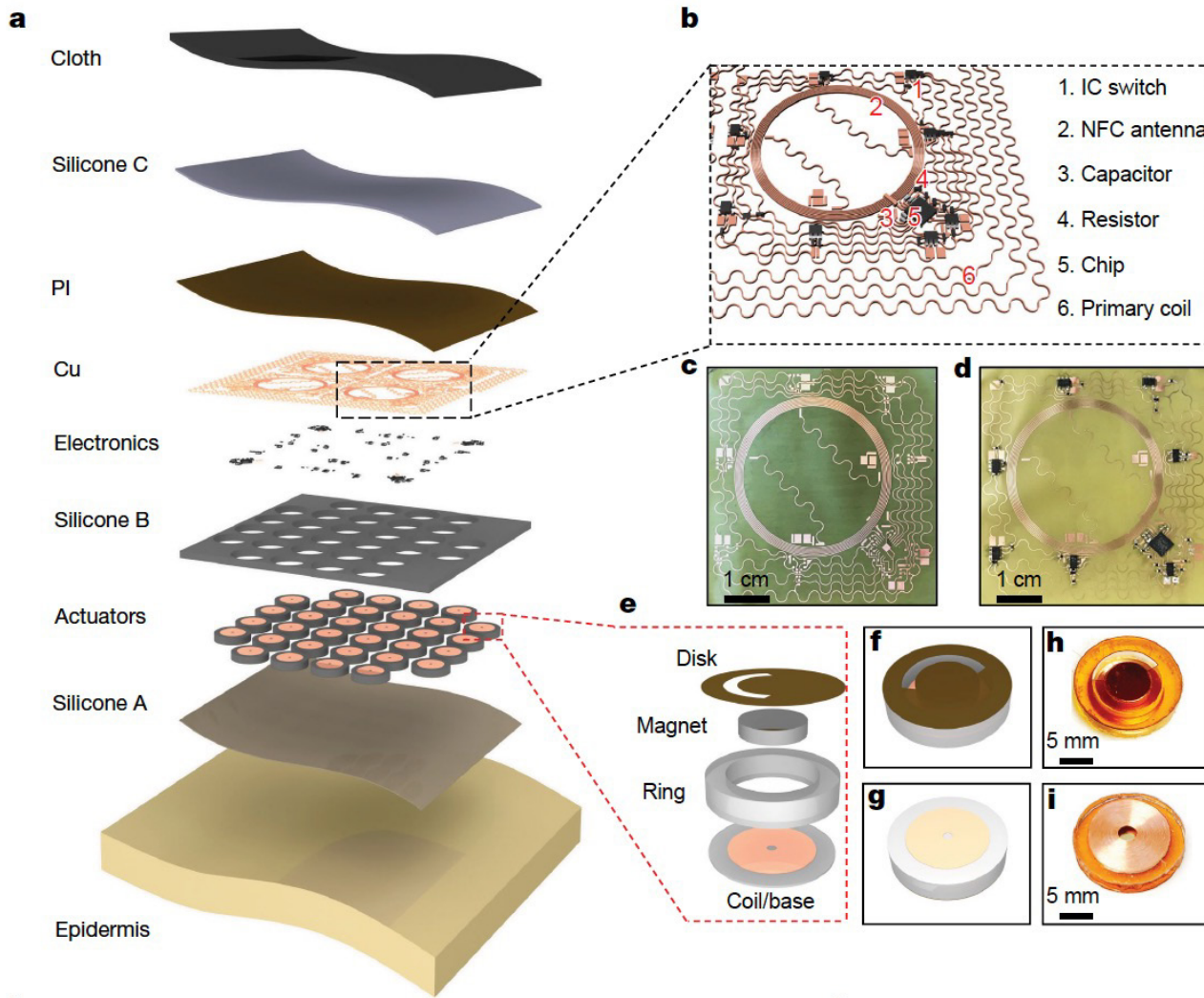
Some users could learn to recognize 500 words in 6 hours



About 2 W / coil

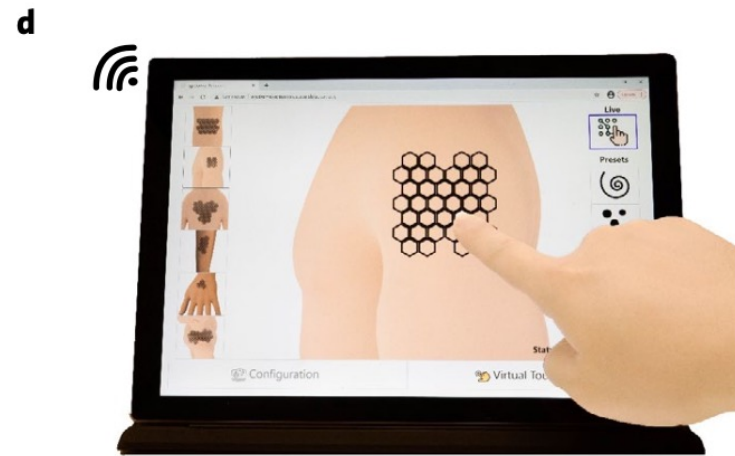
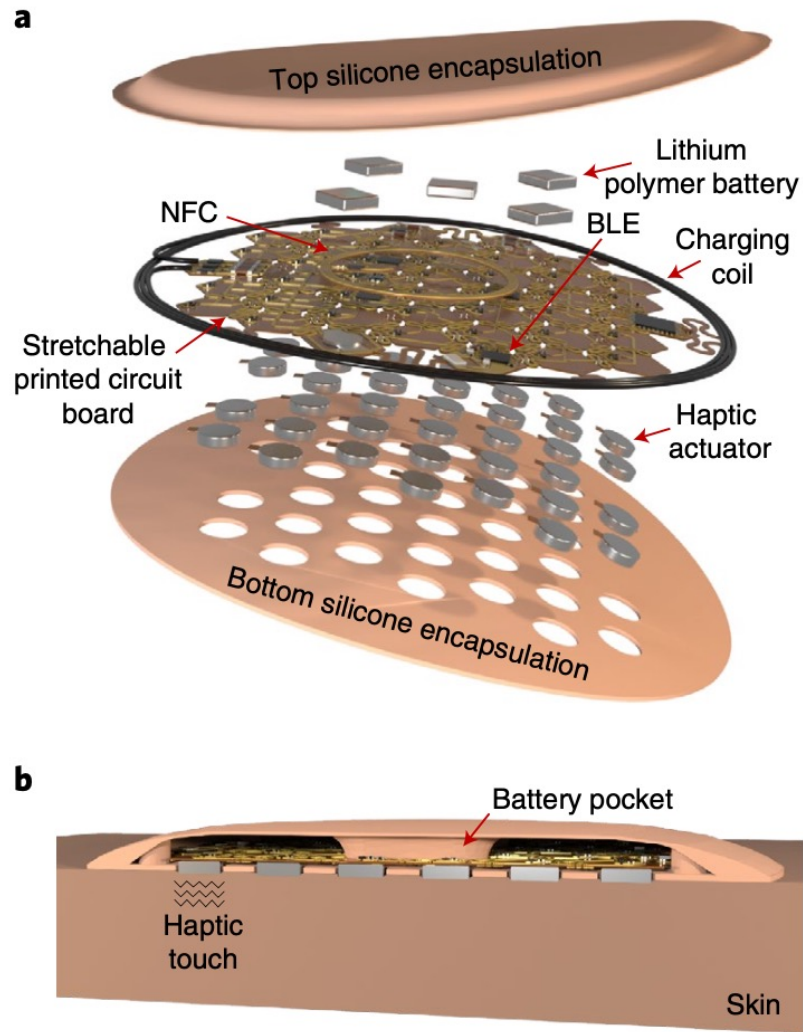
H. Z. Tan et al, Acquisition of 500 English Words through a TActile Phonemic Sleeve (TAPS).
IEEE Transactions on Haptics. **13**, 745–760 (2020).

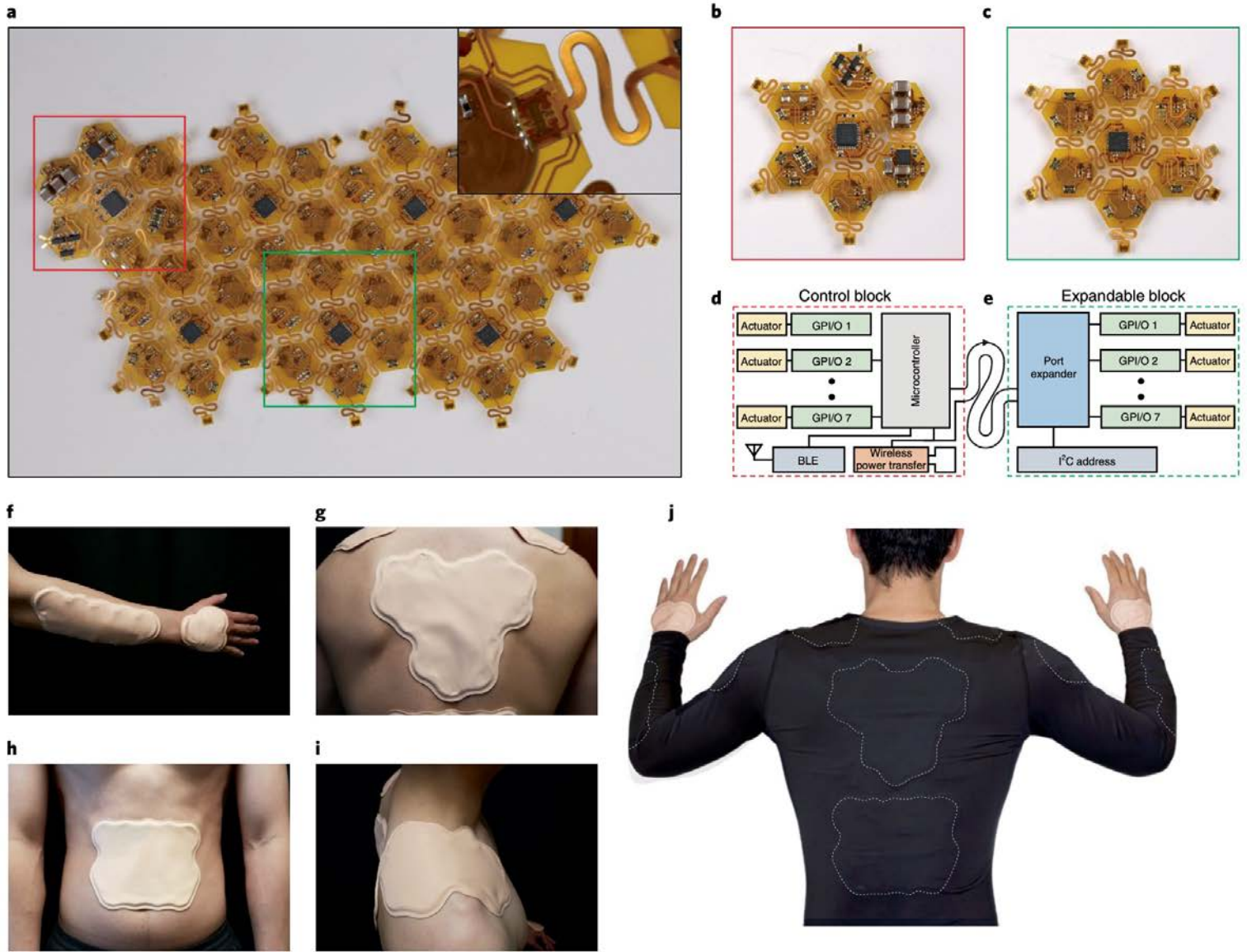
Highly integrated EM vibro-tactile solution: hard device in soft skin



- Wireless platform of electronic systems and haptic
- Remote power + control (need coil)

X. Yu, et al (J. Rogers), Skin-integrated wireless haptic interfaces for virtual and augmented reality. *Nature*. **575**, 473–479 (2019).





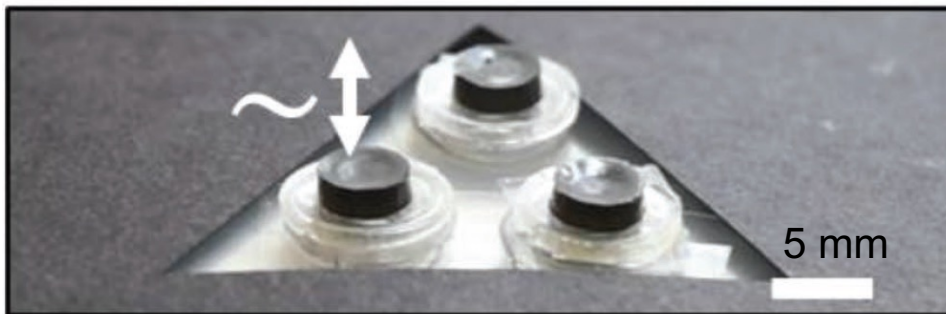
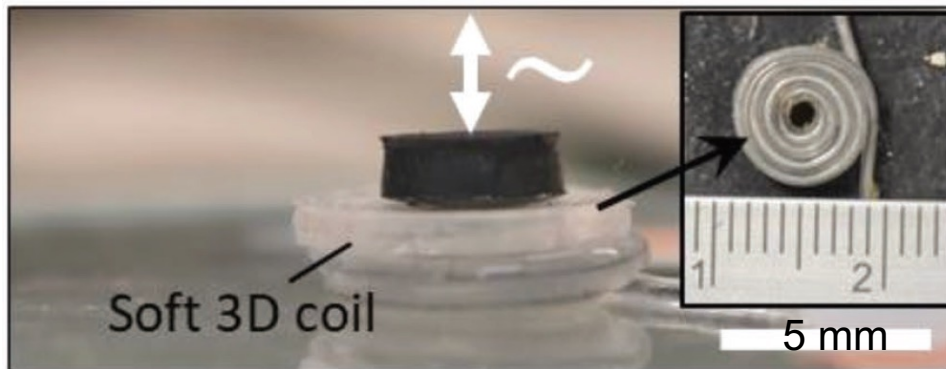
- Density remains low
- OK for on-body
- Not suitable for on hand or face

- Only vibration

- EM actuators do not scale down well to mm-size

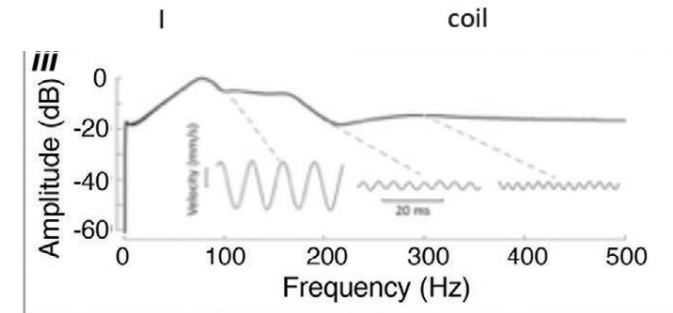
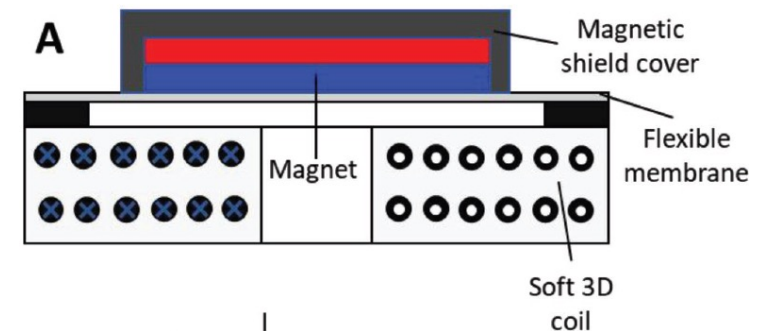
Soft electromagnetic actuators

1W per device



Soft materials:

- silicone polymer,
- liquid metal (LM) alloy (eutectic gallium indium, EGaln), and
- magnetic (NdFeB) powder



T. N. Do, H. Phan, T.-Q. Nguyen, Y. Visell
 Miniature Soft Electromagnetic Actuators for Robotic Applications.
Advanced Functional Materials. **28**, 1800244 (2018).

- DC force (not vibration)
- 130 mW to switch state
- 0 mW to hold state (bistable)

2019

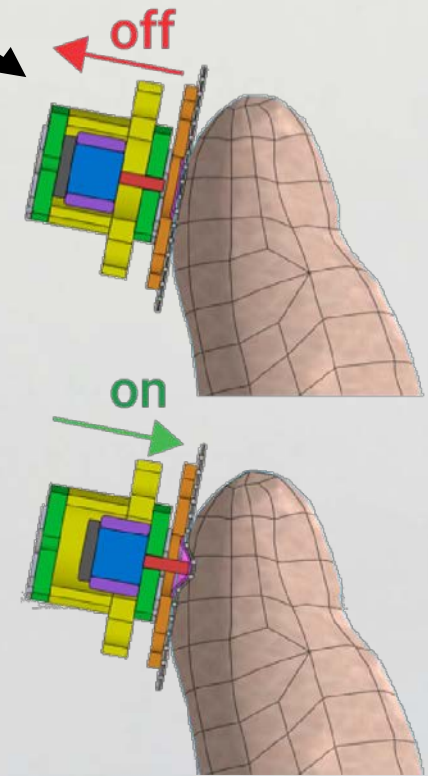
EPFL

ETH zürich

94



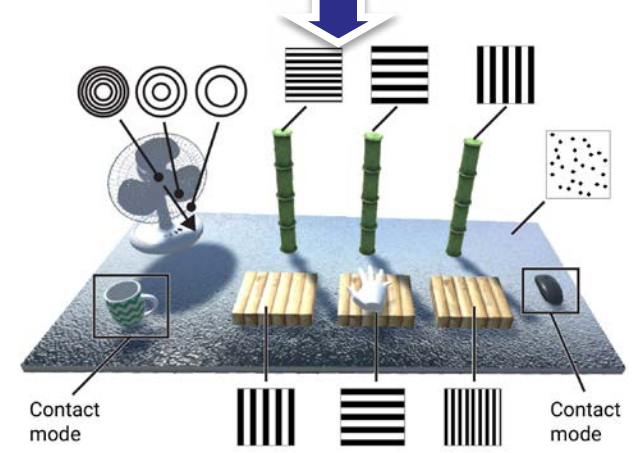
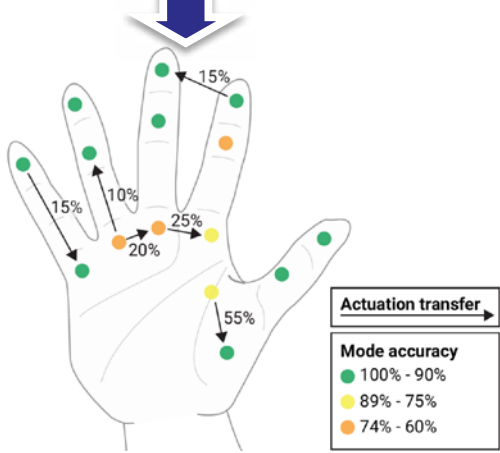
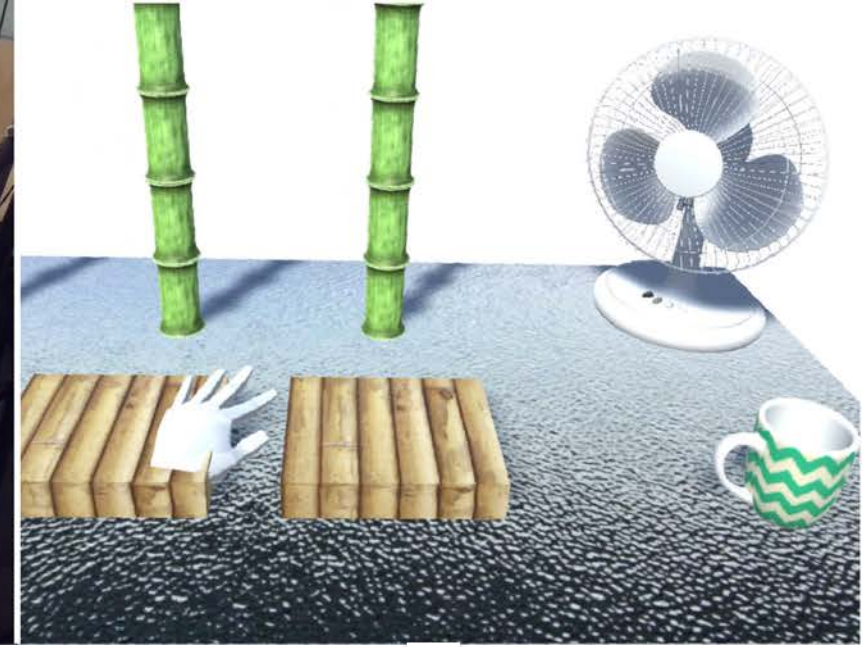
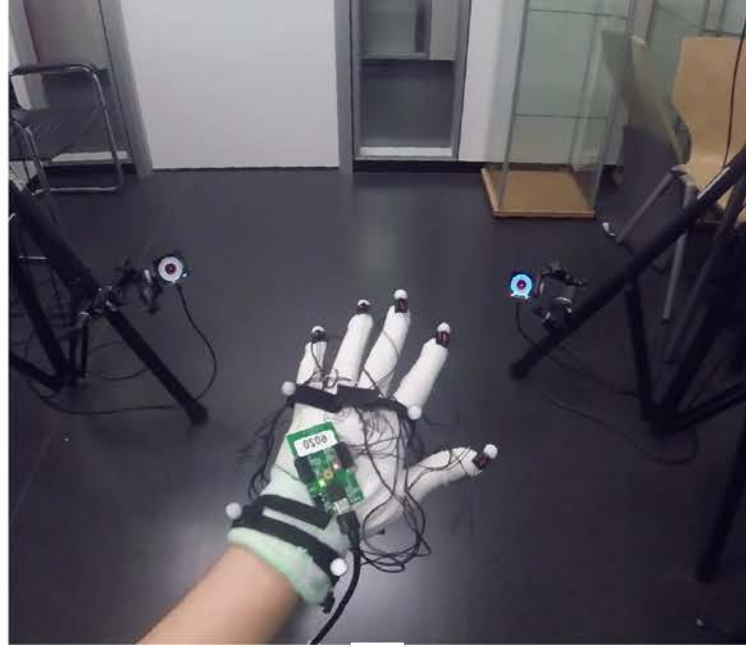
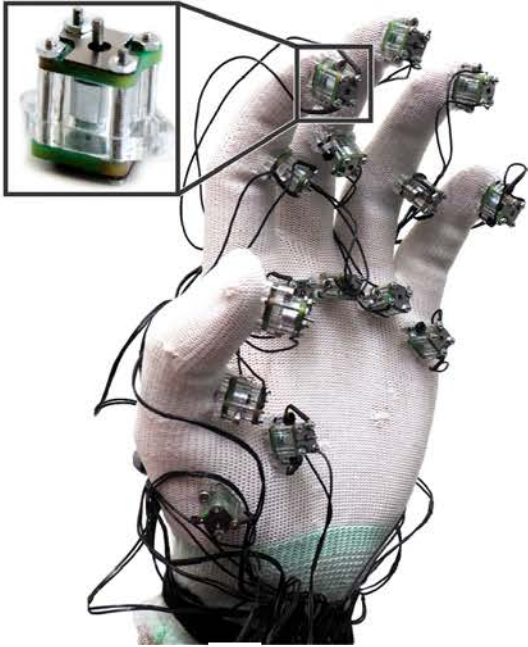
14 TacTiles



TacTiles push
on fingers' skin

V. Vechev, J. Zarate, D. Lindlbauer, R. Hinchet, H. Shea, O. Hilliges,
2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)

Where to provide cutaneous haptic feedback?



A white fabric hand is shown with various sensors and actuators attached to it. The hand is positioned with fingers slightly spread. The sensors are small, rectangular devices with wires extending from them. The actuators are small, cylindrical devices with a white ball on top. The background is a light, neutral color.

TacTiles

Contact and Texture Rendering in VR via Re-configurable Arrays
of Fast Switching Electromagnetic Actuators

Submission for IEEE VR 2019

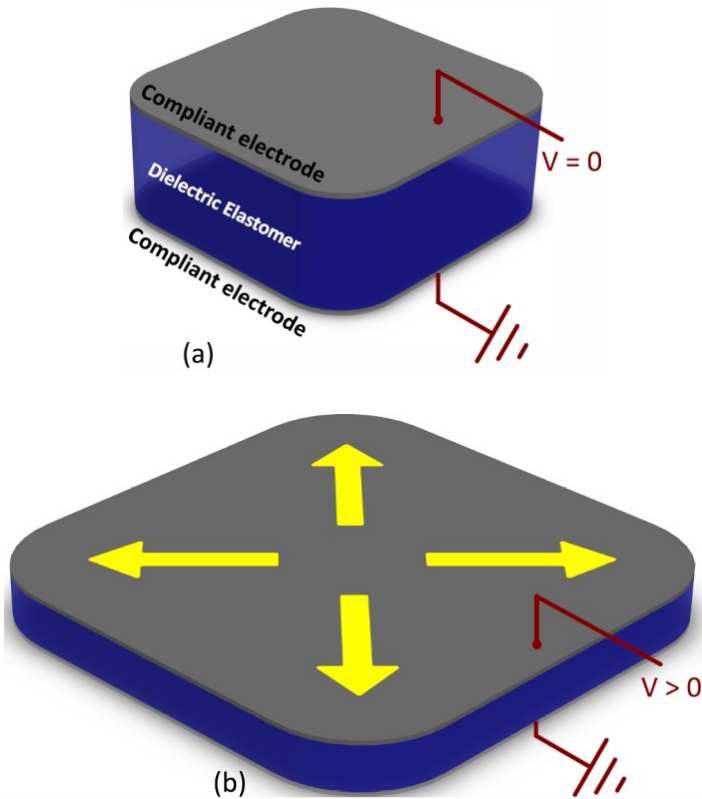
video contains narration

4.4

Dielectric Elastomer Actuators (DEAs) :

E. Hajiesmaili, D. R. Clarke, Dielectric elastomer actuators.
Journal of Applied Physics. **129**, 151102 (2021).

Dielectric Elastomer Actuators (DEAs) are electrostatically-driven elastomer actuators



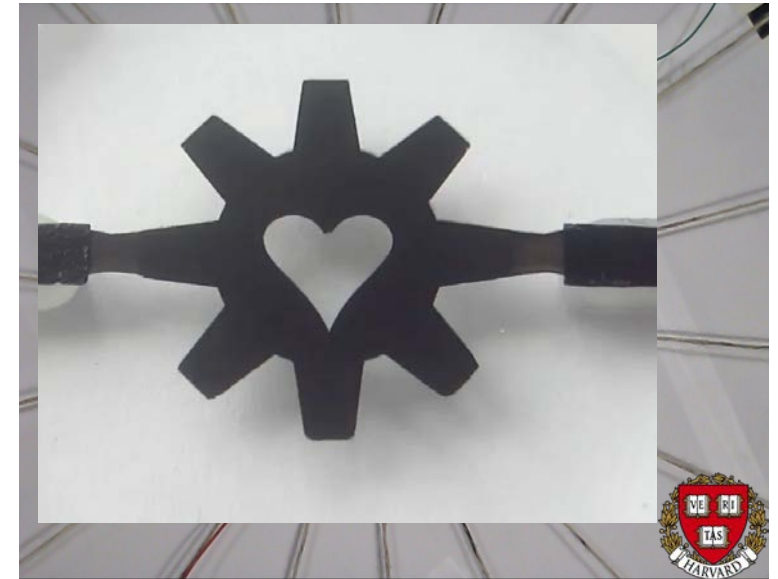
Simple structure

Compliant materials
(~1 MPa)

Large strain
(> 100%)

Fast actuation
(>kHz)

Self-Sensing



Huang et al.. APL 100, 041911 (2012)
>400% area strain

$$F_{ES} = \epsilon_0 \epsilon_r A (V/t)^2$$

Pelrine, *Science* 2000

Typical elastomer thickness t 20 to 50 μm
Typical voltages V 1 – 5 kV

Pioneering DEA work was done at SRI, 25 years ago



High-Speed Electrically Actuated Elastomers with Strain Greater Than 100%

Ron Pelrine,* Roy Kornbluh, Qibing Pei, Jose Joseph

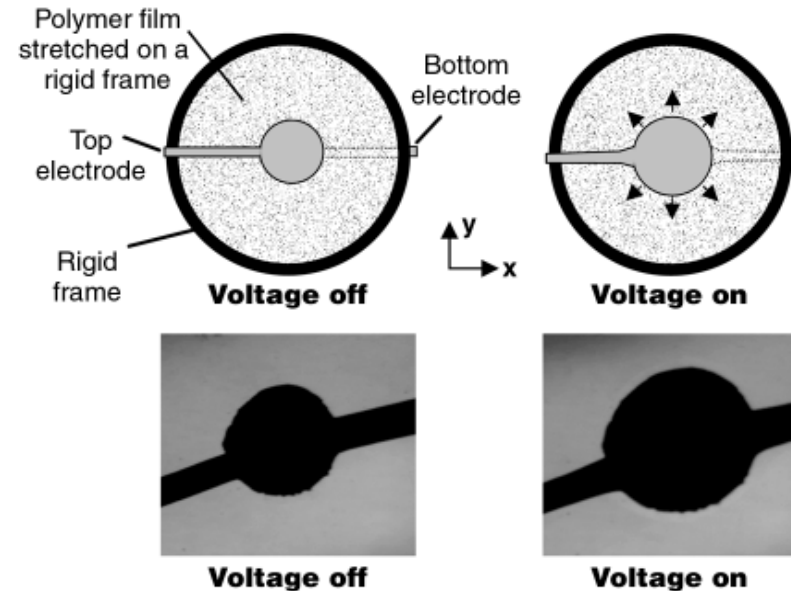
Electrical actuators were made from films of dielectric elastomers (such as silicones) coated on both sides with compliant electrode material. When voltage was applied, the resulting electrostatic forces compressed the film in thickness and expanded it in area, producing strains up to 30 to 40%. It is now shown that prestraining the film further improves the performance of these devices. Actuated strains up to 117% were demonstrated with silicone elastomers, and up to 215% with acrylic elastomers using biaxially and uniaxially prestrained films. The strain, pressure, and response time of silicone exceeded those of natural muscle; specific energy densities greatly exceeded those of other field-actuated materials. Because the actuation mechanism is faster than in other high-strain electroactive polymers, this technology may be suitable for diverse applications.

New high-performance actuator materials capable of converting electrical energy to mechanical energy are needed for a wide range of

demanding applications, such as mini- and microrobots, micro air vehicles, disk drives, flat-panel loudspeakers, and prosthetic devices. Many types of candidate materials are under investigation, including single-crystal piezoelectric ceramics (1) and carbon nanotubes (2). Electroactive polymers are of particular interest because of the low cost of materials and the

SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025, USA.

*To whom correspondence should be addressed. E-mail: pelrine@erg.sri.com



R. Astron.

$\kappa_j + \rho g z_i =$
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ations con-
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tion to the
ions at the
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ce-balance
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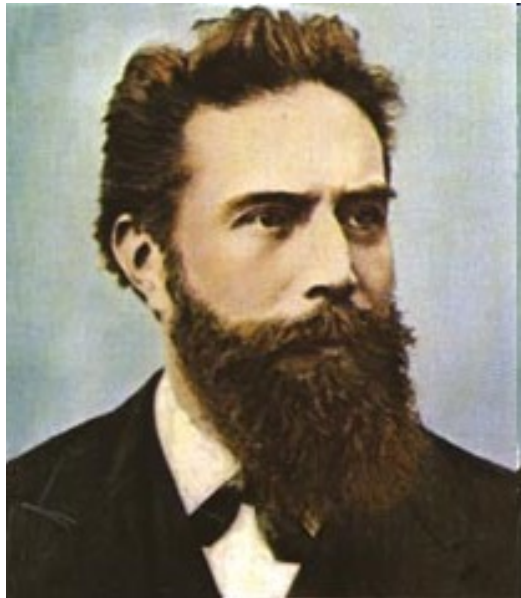
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imization

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$\int_V 2 \tau_{xy}^2 dS$

But effect first reported by W. C. Röntgen in 1880!
Ann. Phys. Chem. 247, 771 (1880)

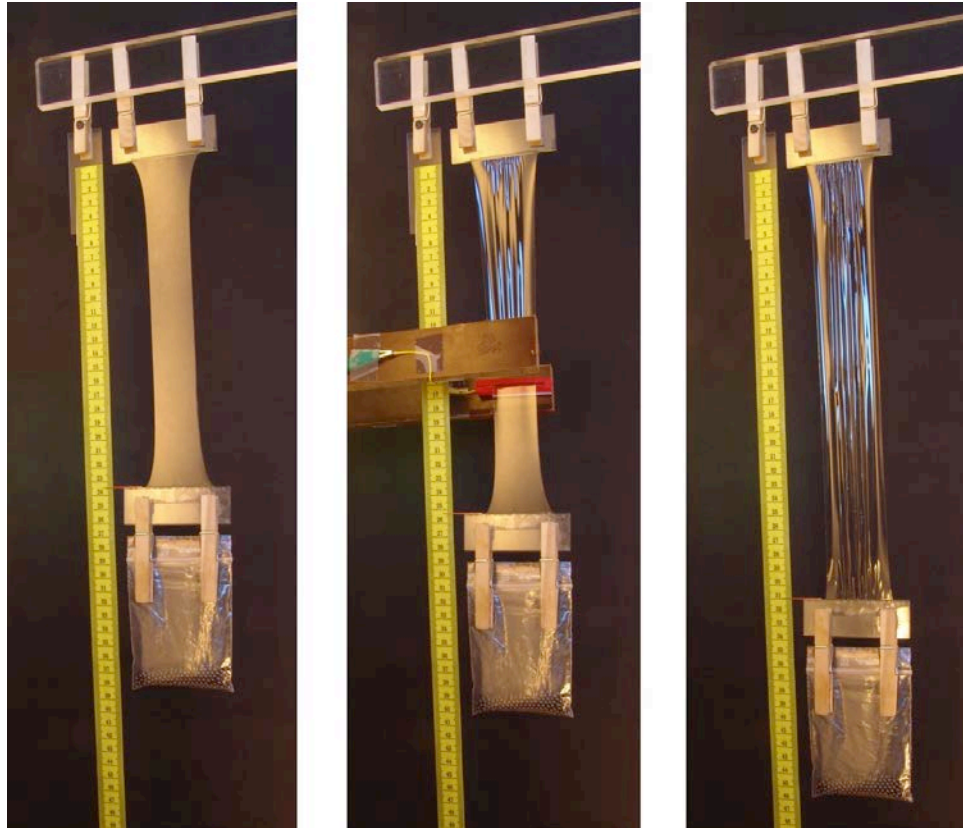
Wilhelm Conrad Röntgen (1845-1923) – “rubber muscles”



*III. Ueber die durch Electricität bewirkten Form-
und Volumenänderungen von dielectrischen
Körpern; von W. C. Röntgen;*

(Aus den Ber. d. Oberhess. Gesellsch. f. Natur- u. Heilk. 20.
mitgetheilt vom Herrn Verfasser.)

Röntgen's experiment with today's materials



Keplinger, C., Kaltenbrunner, M., Arnold, N., & Bauer, S. (2010).
Röntgen's electrode-free elastomer actuators without electromechanical pull-in instability.
Proceedings of the National Academy of Sciences of the United States of America, 107(10), 4505–
10. doi:10.1073/pnas.0913461107

(nice) Features of Dielectric Elastomer Actuators (DEAs)

- **Large strain:**
 - over 1400% area strain demonstrated,
 - 15% to 40% strain for long-term operation today
- Power density (record is 1kW/kg, typical 50 W/kg)
- Soft: Young's modulus \approx 1 MPa
- Capacitive: no power to hold a position
- Can add intelligence through self-sensing
- Scales well from μm to m



EMPA's (Zurich) 7 m long blimp: "swims" through the air using 4 artificial muscles

DEAs: single layer example

Taking advantage of the flexibility to enable new concepts:
e.g., 7m long blimp at EMPA (Dübendorf): shape of entire system changes



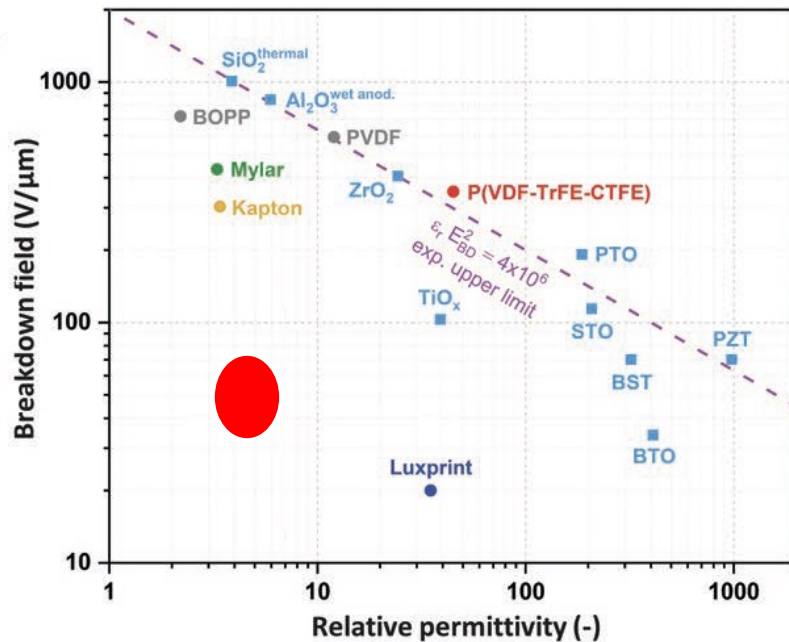
Dielectric Elastomer Actuators (DEAs)



$$Pressure_{Maxwell} = \epsilon_0 \epsilon_r \left(\frac{V}{t} \right)^2$$

$$energy\ density_{es,DEA} = \epsilon_r \epsilon_0 E^2$$

E = electric field,
 Y = Young's modulus
 ϵ_r = relative permittivity
 ϵ_0 = permittivity of free space



When including the stored mechanical energy:

$$W_{DEA} = \frac{1}{2Y} \epsilon_0 \epsilon_r E^4$$

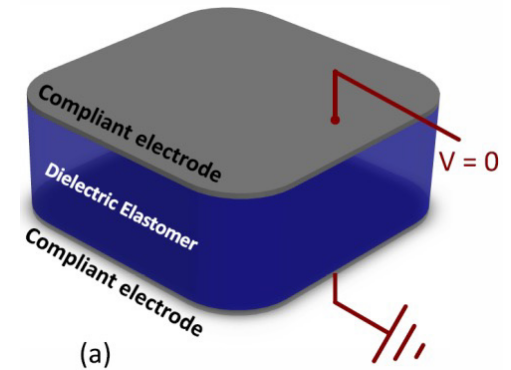
Duduta et al., *PNAS* 201815053 (2019)

DEA large deformation modeling

- DEA is simply a stretchable capacitor
- So, why challenging to model?

Because materials and forces are non-linear

- What limits actuation?
 - Dielectric breakdown (max E-field)
 - Rupture at excessive strain
 - ... but in a non-trivial highly-coupled manner



Two forces with different scaling : ES + elastic

- Initial thickness d . motion x . actuated thickness = $d-x$

- Normal electrostatic Force for an applied voltage V :

$$F_{ES} = \epsilon_0 \epsilon_R \frac{V^2}{2d^2} = \epsilon_0 \epsilon_R \frac{E^2}{2}$$

$$F_{ES} = \epsilon_0 \epsilon_R \frac{V^2}{2(d-x)^2} \quad \text{Diverges to infinity when } x \rightarrow d$$

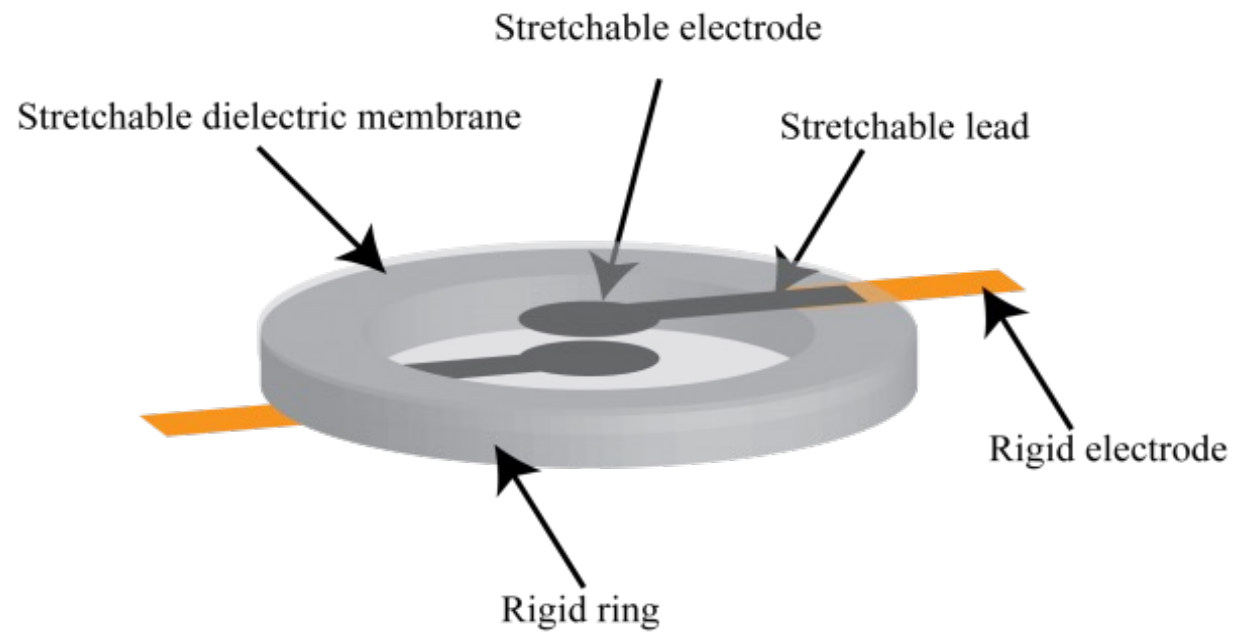
- Restoring force of the elastomer spring $k \cdot x$

$$F_{elastic} = -kx \quad \text{Does not diverge when } x \rightarrow d$$



Single layer with VHB and carbon grease, 2 minutes

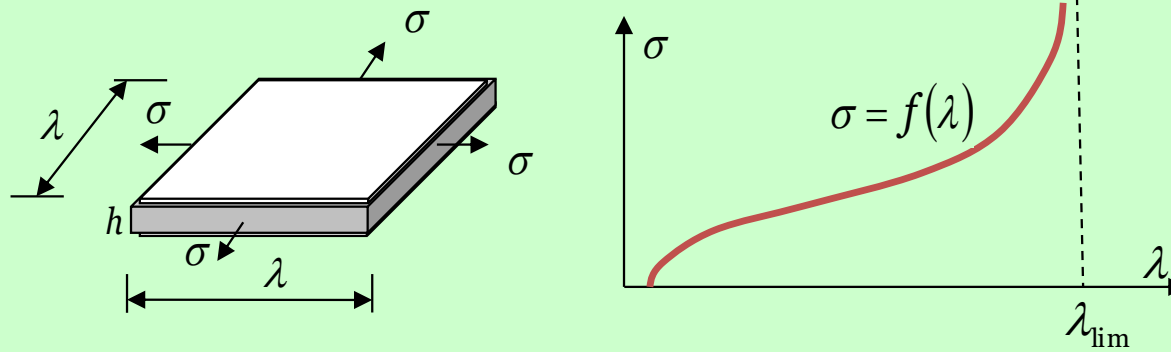
<https://softroboticstoolkit.com/book/dielectric-elastomer-actuators>



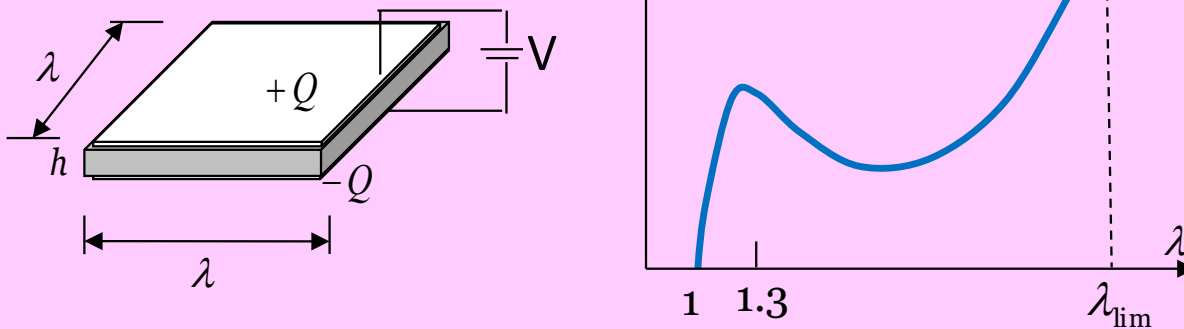
Easily get 20% are straiu

Electromechanical instability (EMI)

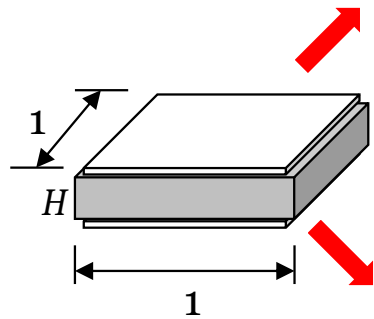
Stretch by force



Stretch by voltage



Zhao, Hong, Suo. *Physical Review B* **76**, 134113 (2007)



Reference state

DEA actuation at in-plane strains >26%

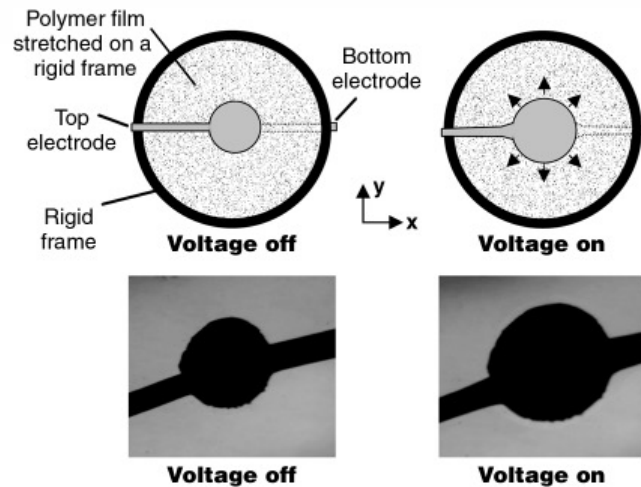
- See Zhigang Suo *et al*'s key papers for insightful and extensive analysis
- Pull-in instability (electromechanical instability or snap-through) can be pushed to higher actuation strain than 26% if one understands and controls elastomer stress-strain curve
- Strains of 500% have been achieved with elastomer that have suitable stress-strain characteristics (but usually very slow)

Suo, Z. Theory of dielectric elastomers. *Acta Mechanica Sinica* **23**, 549–578 (2010).

T. Li, C. Keplinger, R. Baumgartner, S. Bauer, W. Yang, Z. Suo, Giant voltage-induced deformation in dielectric elastomers near the verge of snap-through instability. *Journal of the Mechanics and Physics of Solids*. **61**, 611–628 (2013).

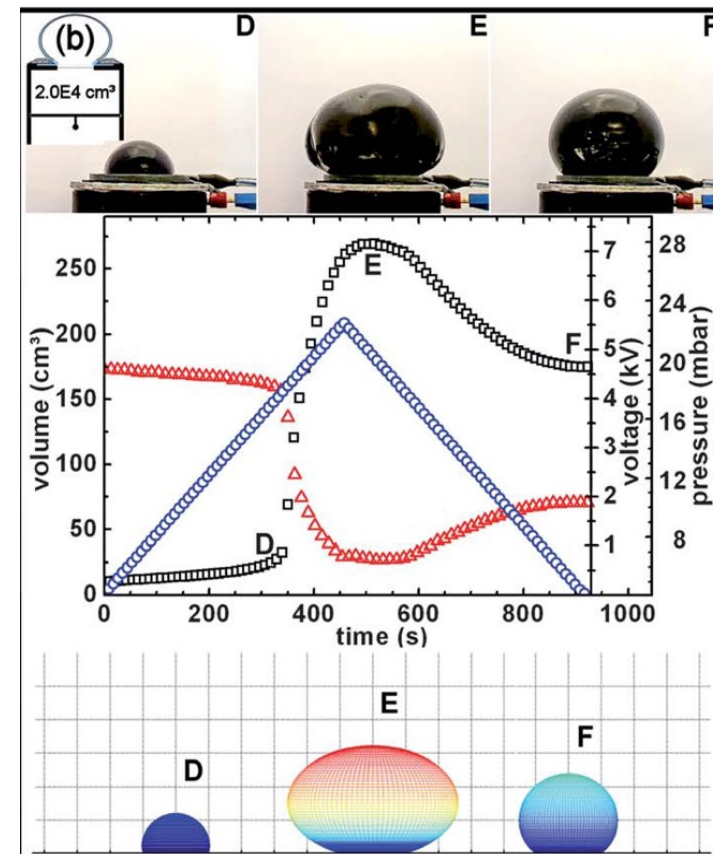
S. J. A. Koh, T. Li, J. Zhou, X. Zhao, W. Hong, J. Zhu, Z. Suo, Mechanisms of large actuation strain in dielectric elastomers. *Journal of Polymer Science Part B: Polymer Physics*. **49**, 504–515 (2011).

With the right elastomer, can get huge in-plane strain



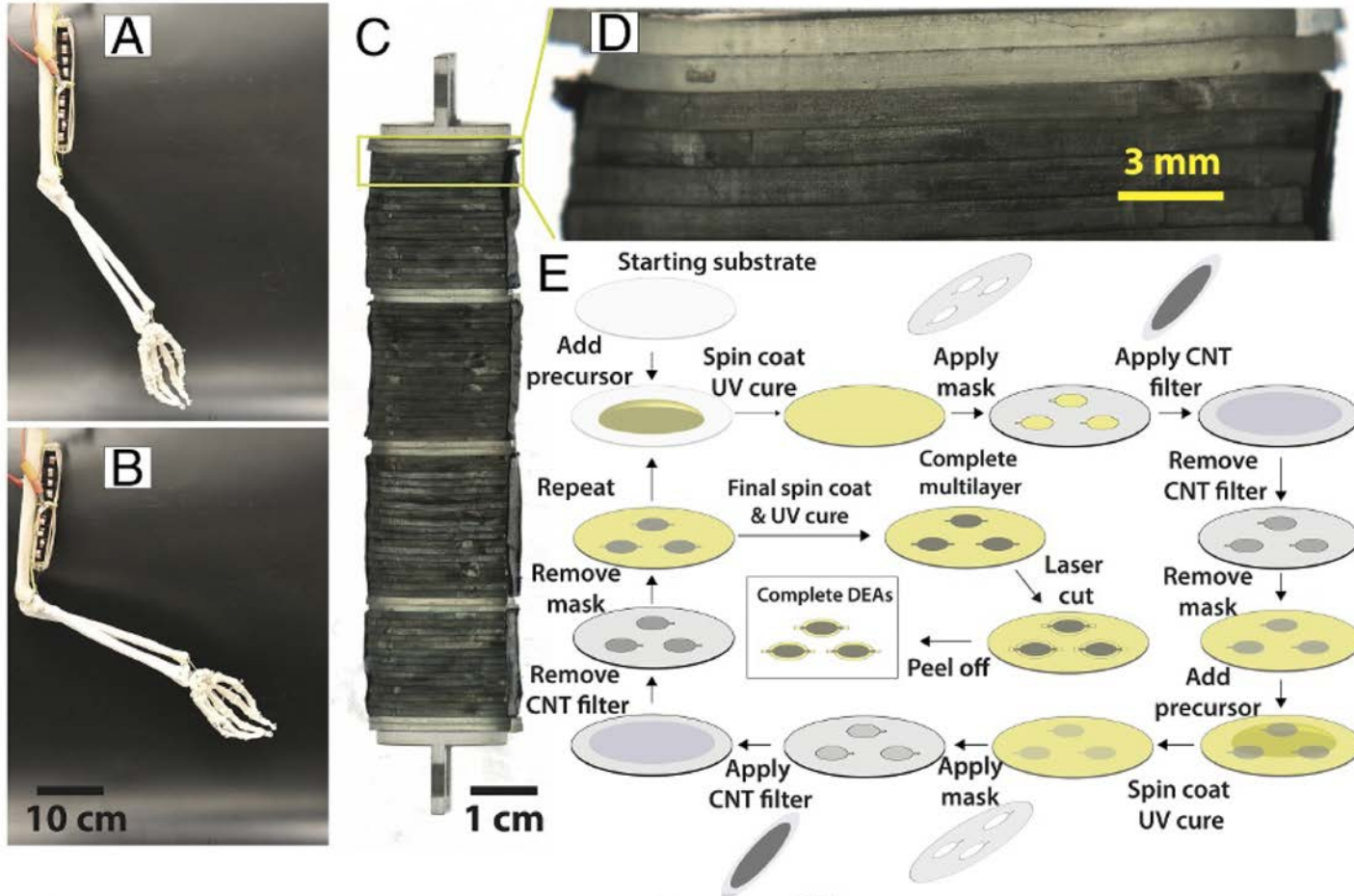
Material	Prestrain (x,y) (%)	Actuated relative thickness strain (%)	Actuated relative area strain (%)
<i>Circular strain</i>			
HS3 silicone	(68,68)	48	93
	(14,14)	41	69
CF19-2186 silicone	(45,45)	39	64
	(15,15)	25	33
VHB 4910 acrylic	(300,300)	61	158
	(15,15)	29	40
<i>Linear strain</i>			
HS3	(280,0)	54	117
CF19-2186	(100,0)	39	63
VHB 4910	(540,75)	68	215

Pelrine, R. et al. *High-speed electrically actuated elastomers with strain greater than 100%* Science, 2000, 287, 836-839



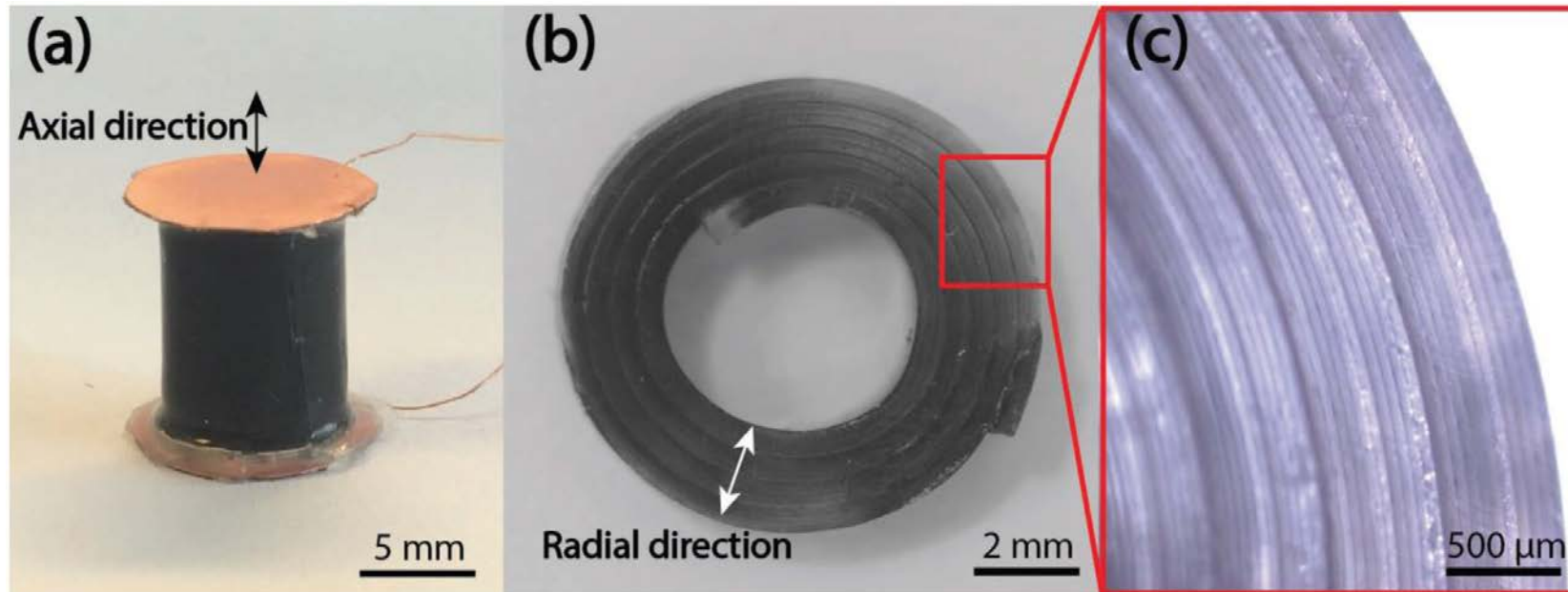
Keplinger, C. et al. *Harnessing snap-through instability in soft dielectrics to achieve giant voltage-triggered deformation* Soft Matter, The Royal Society of Chemistry, 2012, 8, 285-288

To get larges force, need many layers, and low strain, high E_{BD}



$$W_{DEA} = \frac{1}{2Y} \epsilon_0 \epsilon_r E^4$$

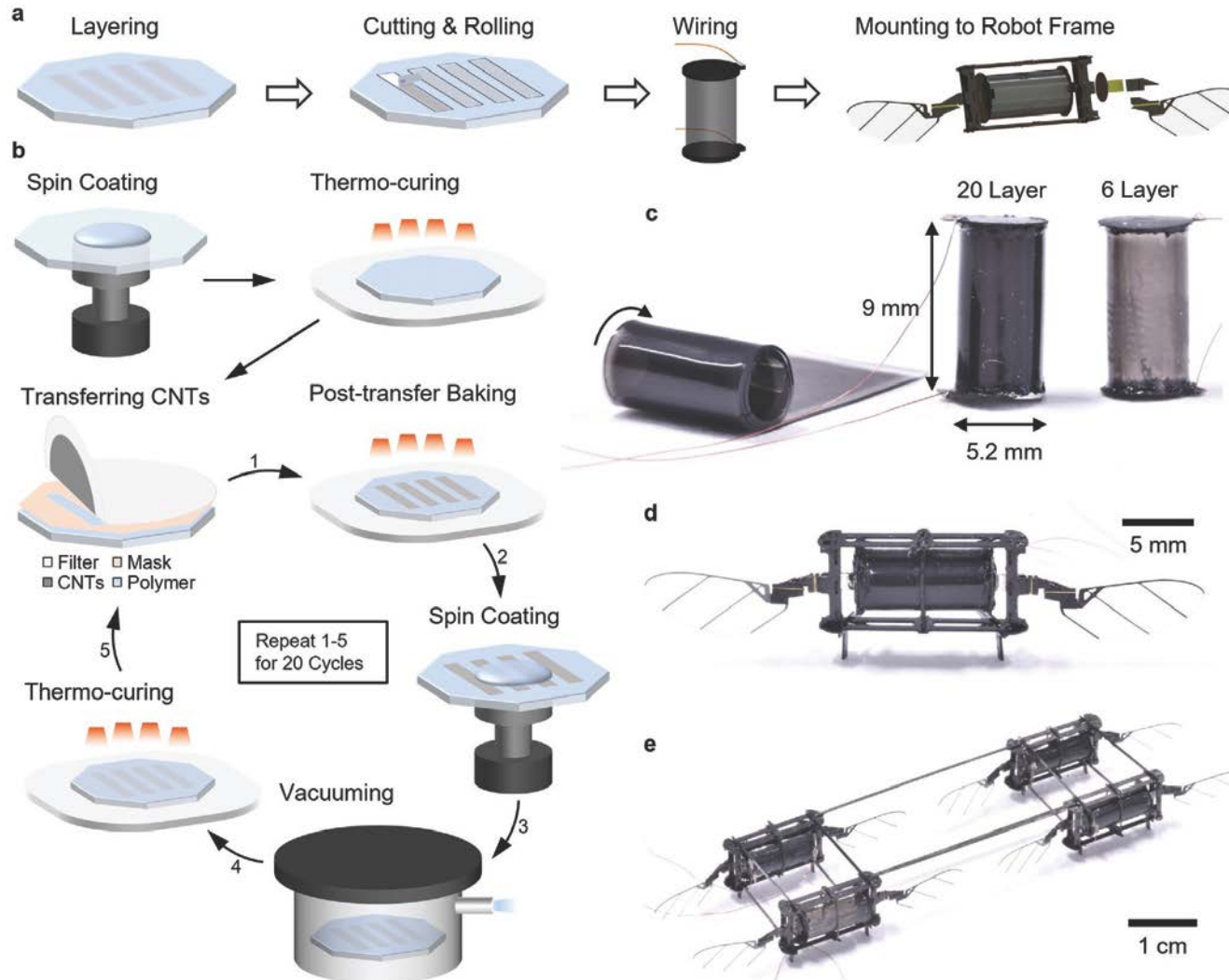
Duduta, et al. *Proceedings of the National Academy of Sciences* 201815053 (2019).



- 1 N blocked force and free displacement of 1 mm, within a volume of less than 1 cm³
- Up to 200 Hz
- Effectively 50 layers

Zhao, H. *et al.* Compact Dielectric Elastomer Linear Actuators. *Advanced Functional Materials* 1804328 (2018).

High energy density DEA (1 kW / kg) with hundreds of layers



Z. Ren *et al.*, "A High-Lift Micro-Aerial-Robot Powered by Low-Voltage and Long-Endurance Dielectric Elastomer Actuators," *Advanced Materials*, vol. 34, no. 7, p. 2106757, 2022, doi: [10.1002/adma.202106757](https://doi.org/10.1002/adma.202106757).

When DEA operated at 400 Hz, the 143 mg device generates forces of 0.36 N and displacements of 1.15 mm

SV1: robot flapping simulation and experiment

Z. Ren *et al.*, "A High-Lift Micro-Aerial-Robot Powered by Low-Voltage and Long-Endurance Dielectric Elastomer Actuators," *Advanced Materials*, vol. 34, no. 7, p. 2106757, 2022, doi: [10.1002/adma.202106757](https://doi.org/10.1002/adma.202106757).

Y. Chen, et al, "Collision Resilient Insect-Scale Soft-Actuated Aerial Robots With High Agility," *IEEE Transactions on Robotics*, pp. 1–13, 2021, doi: [10.1109/TRO.2021.3053647](https://doi.org/10.1109/TRO.2021.3053647).

Much improved control of flying DEA insects



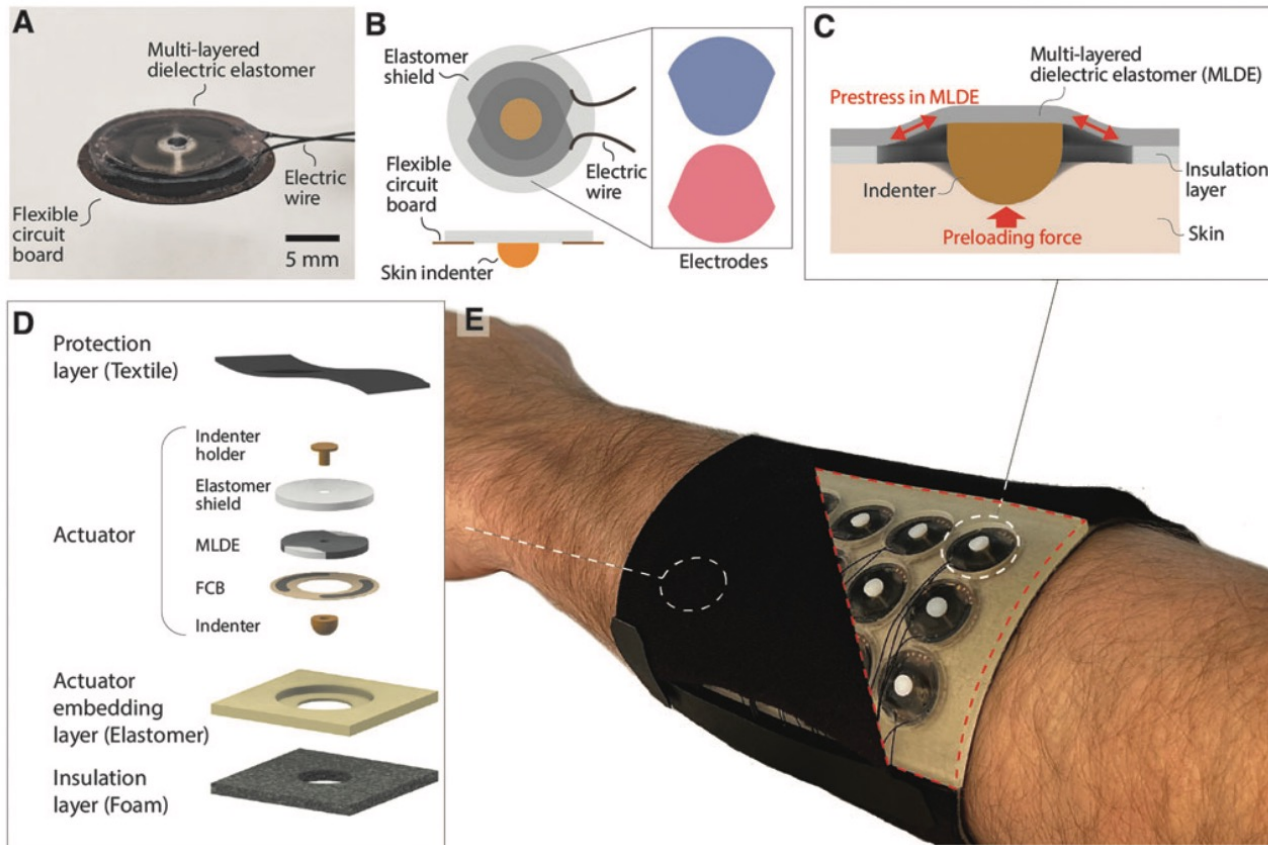
SV3: robot hovering demonstration

665 mg aerial robot that is powered DEA achieves high power density (1.2 kW/kg) and high transduction efficiency (37%).

Careful choice of Silicone

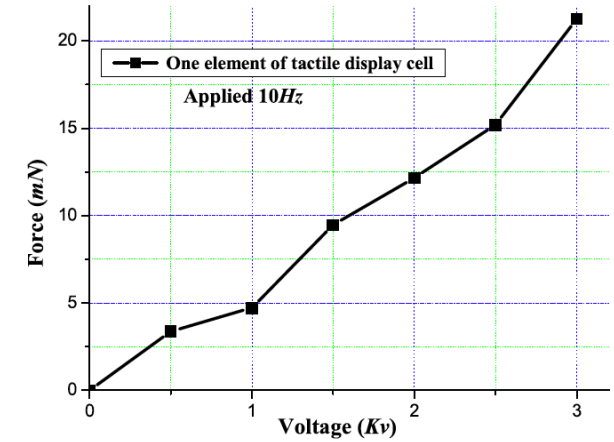
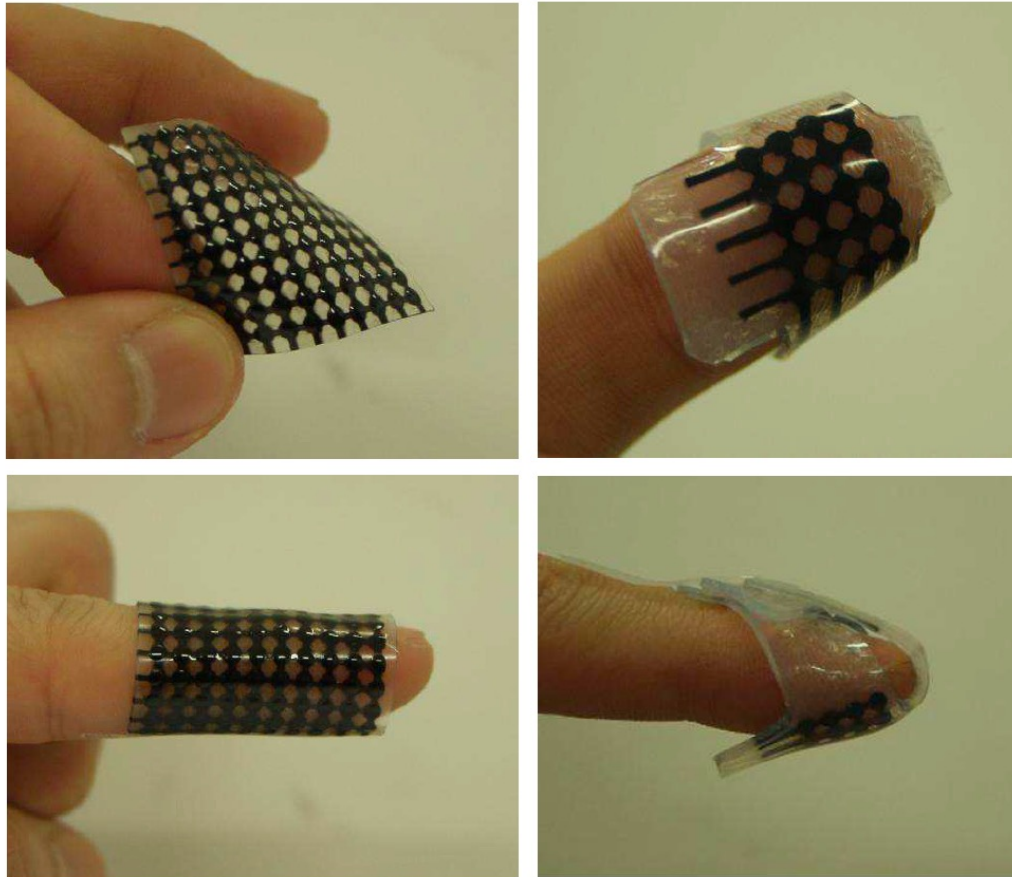
Y. Chen, S. Xu, Z. Ren, P. Chirarattananon,
Collision Resilient Insect-Scale Soft-Actuated Aerial Robots With High Agility.
IEEE Transactions on Robotics, 1–13 (2021).

One example of wearable DEAs for haptics



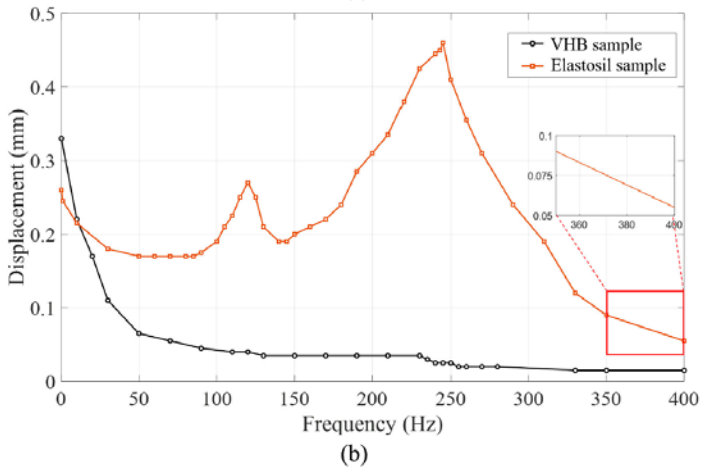
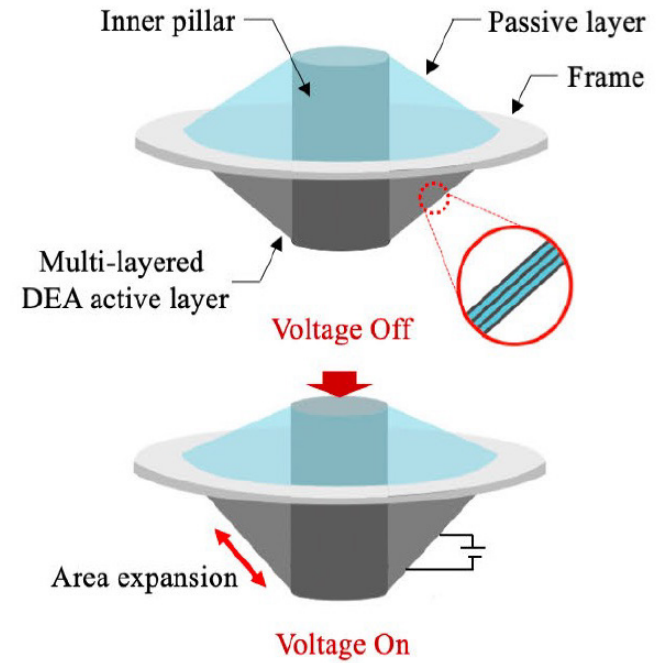
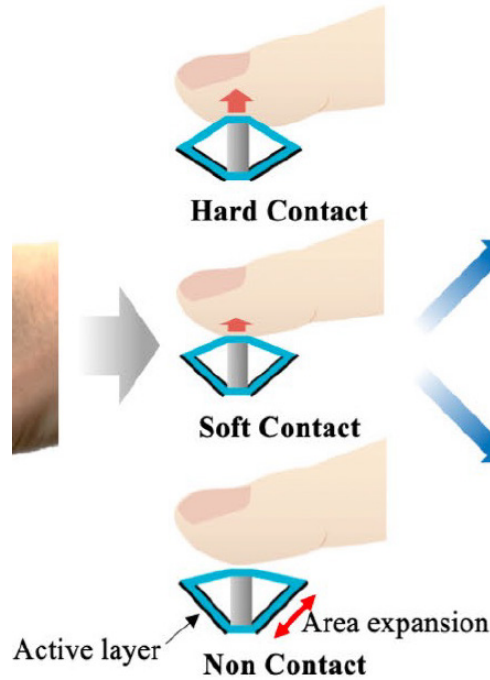
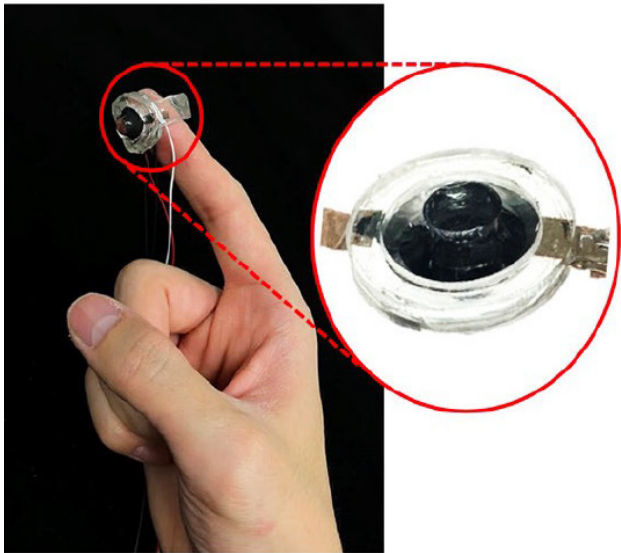
D.-Y. Lee *et al.*, "A Wearable Textile-Embedded Dielectric Elastomer Actuator Haptic Display," *Soft Robotics*, 2022
doi: [10.1089/soro.2021.0098](https://doi.org/10.1089/soro.2021.0098).

Compliant DEA arrays



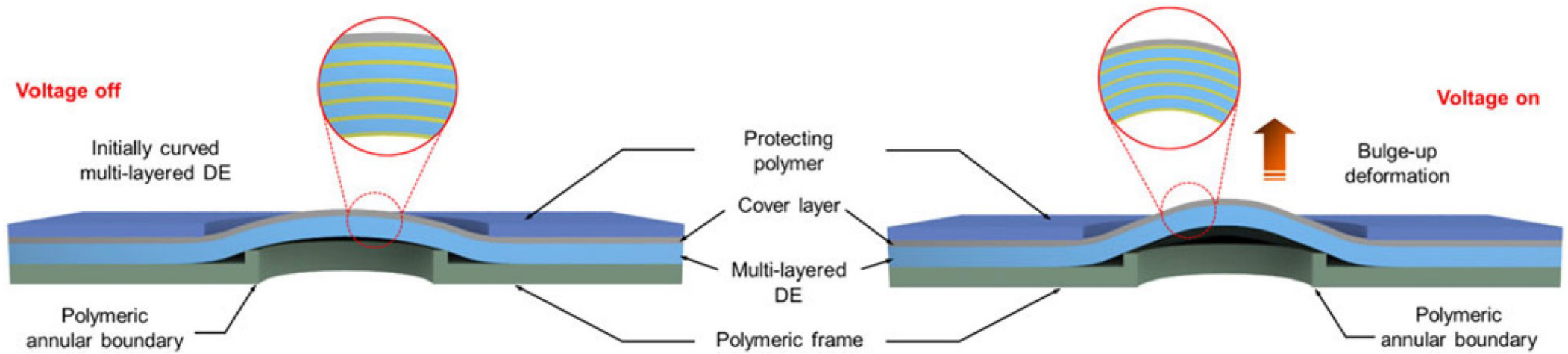
No user tests...

I. Koo, K. Jung, J. Koo, J. Nam, Y. Lee, H. R. Choi, Wearable tactile display based on soft actuator. *ICRA 2006*.



Claim 8 N force at resonance...

J.-H. Youn, H. Mun, K.-U. Kyung, A Wearable Soft Tactile Actuator With High Output Force for Fingertip Interaction. *IEEE Access*. **9**, 30206–30215 (2021).

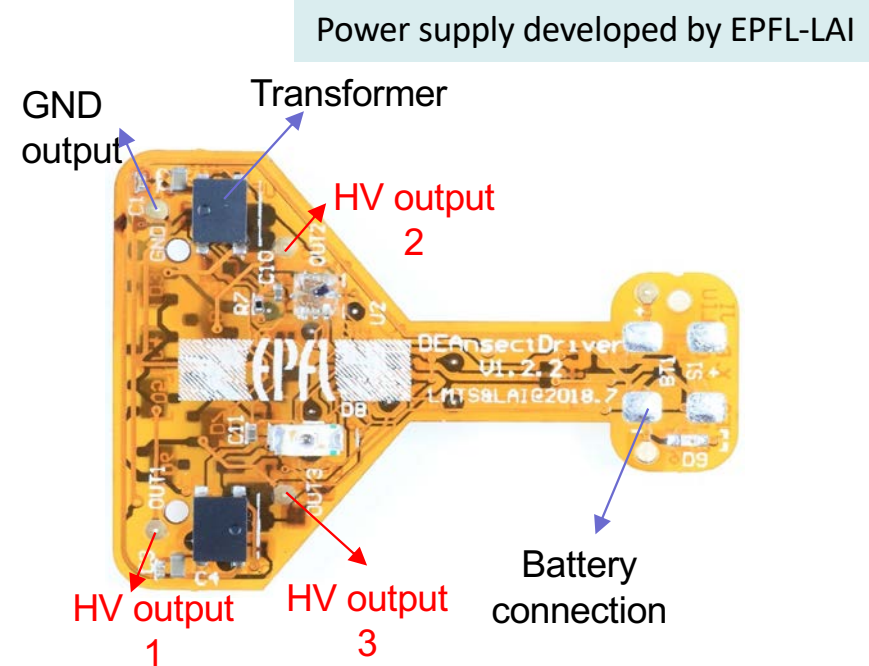


S. Mun, et al
Electro-Active Polymer Based Soft Tactile Interface for Wearable Devices.
IEEE Transactions on Haptics. **11**, 15–21 (2018).

If reduce voltage to below 500V, can use very compact electronics
...and thus a path to complex intelligent machines



Miniature 1 channel 5 kV 1 Hz
 power supply:
 16.0 g

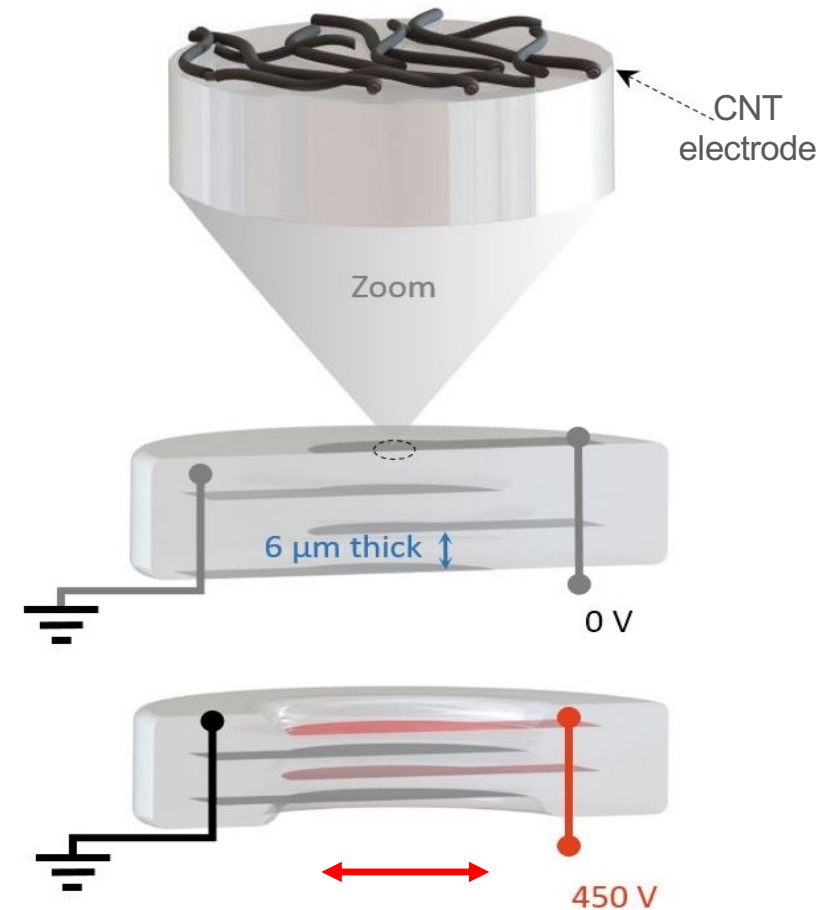


Miniature 2 channel 500 V 1 kHz
 power supply:
 0.35 g

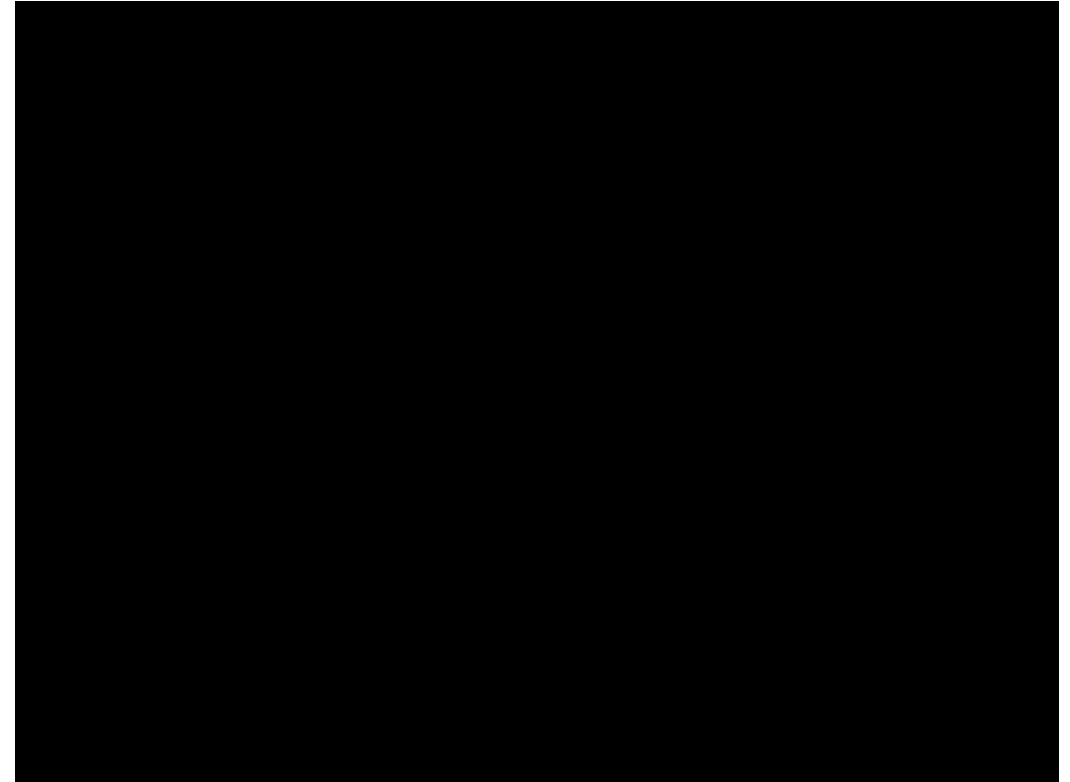
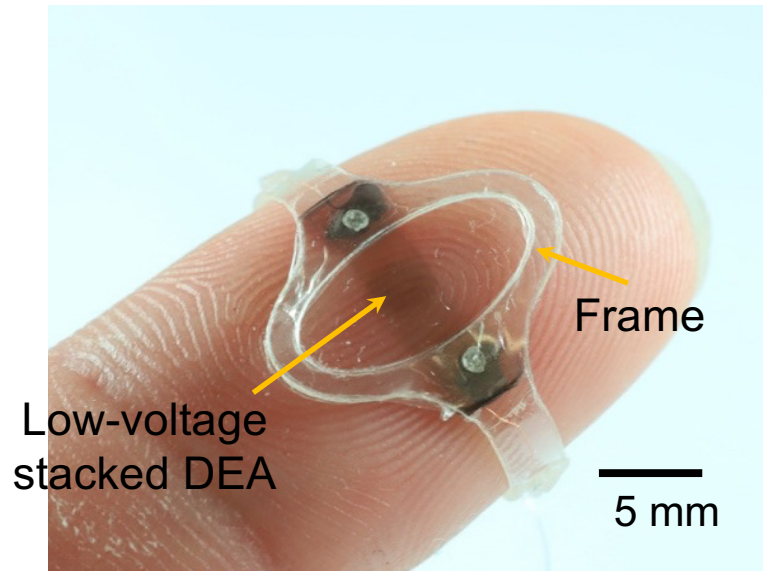
Low-voltage stacked DEAs with aligned carbon nanotube electrodes

Full DEA strain at 450V, up to 500 Hz

- 6 μm thick silicone layers
- Aligned CNT electrodes (Langmuir-Schaefer process)
- Power density $>10^6 \text{ W/m}^3$ at 580 Hz
- Specific power density of nearly 1000 W/kg



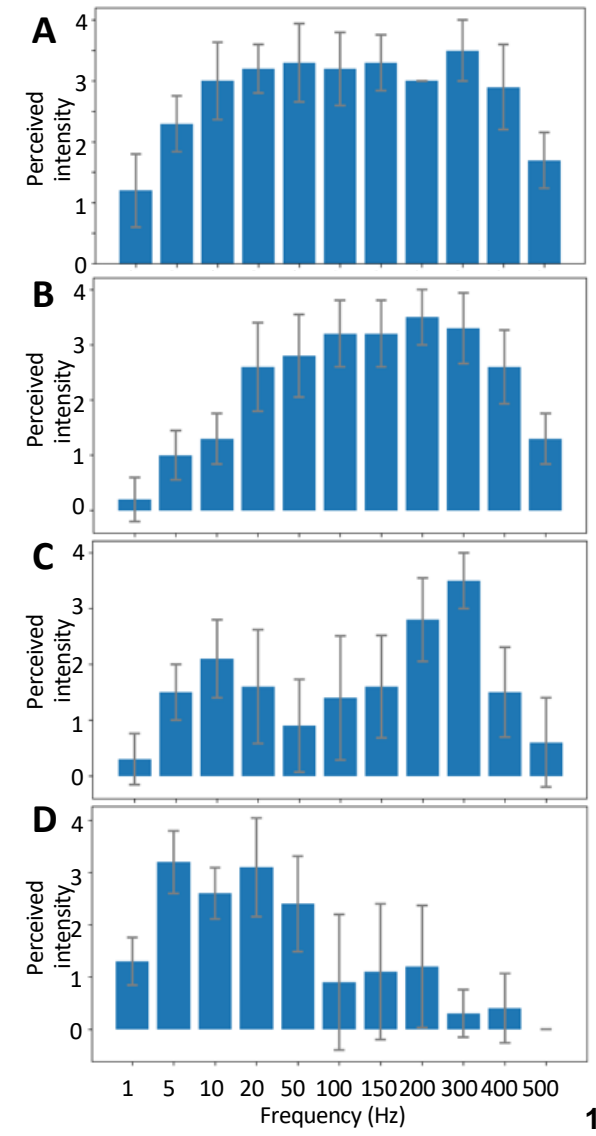
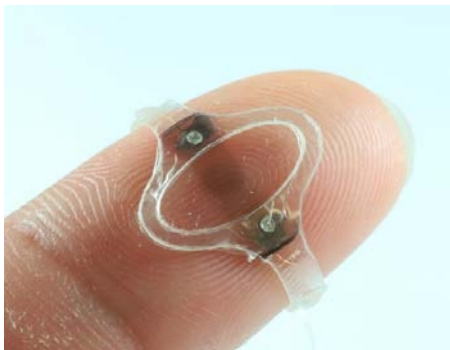
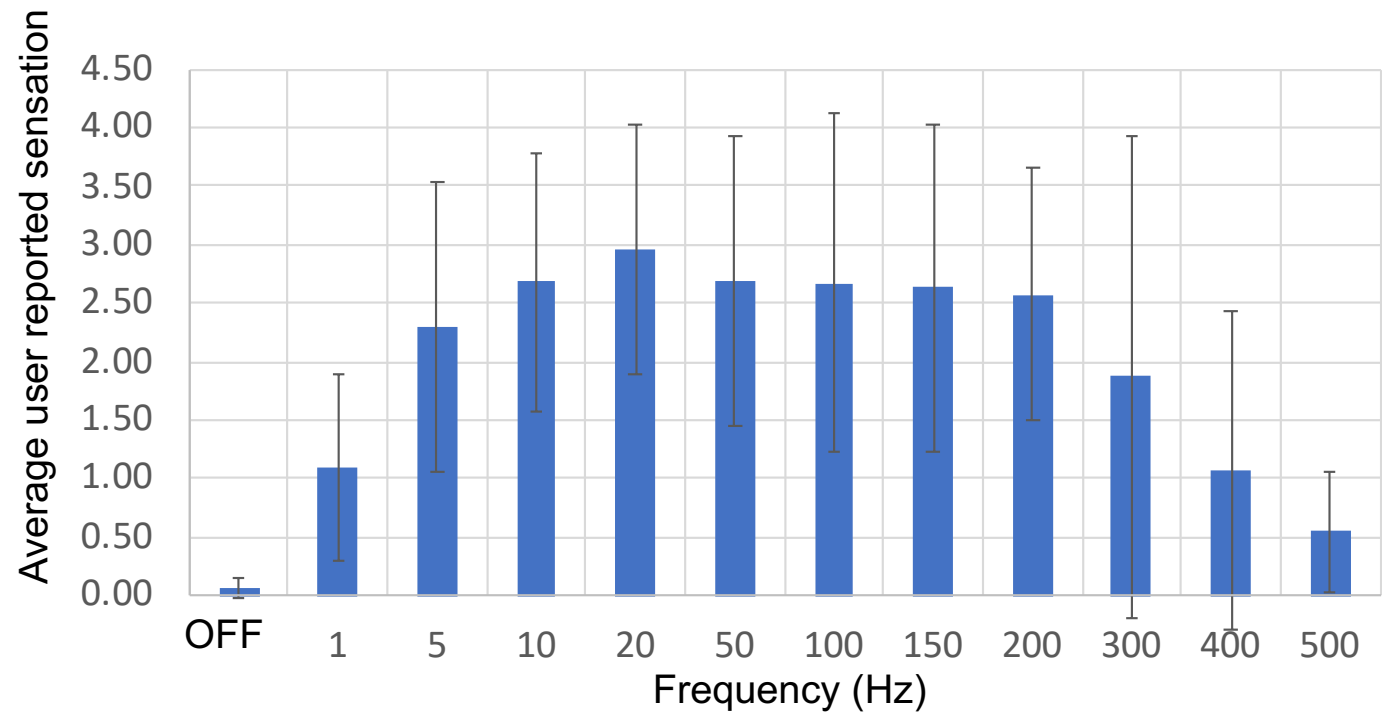
“feel-through” haptics driven by “Low”-voltage DEA



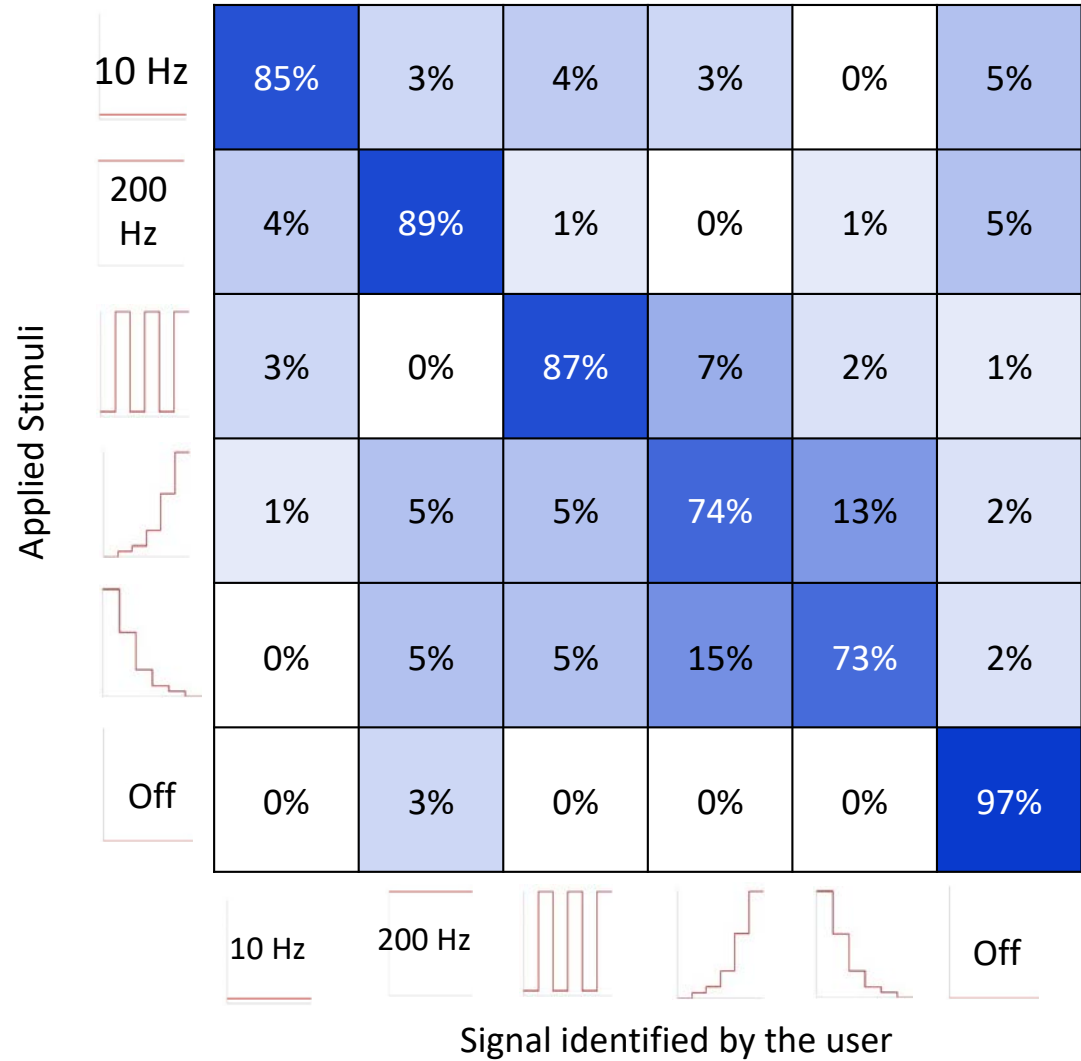
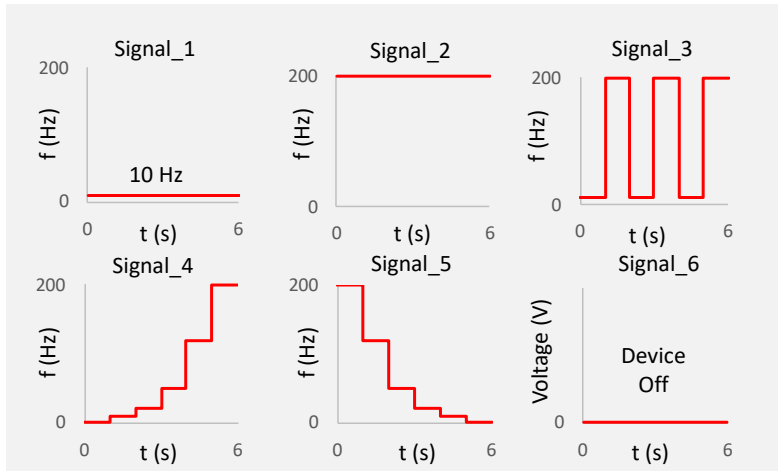
Key features:

- “Low” operating voltage: below 450 V
- Soft: adapts to body shape
- Generates rich notification signals: 1-500 Hz
- Only 18 μm -thick: unperceivable when off; finger remain free to use

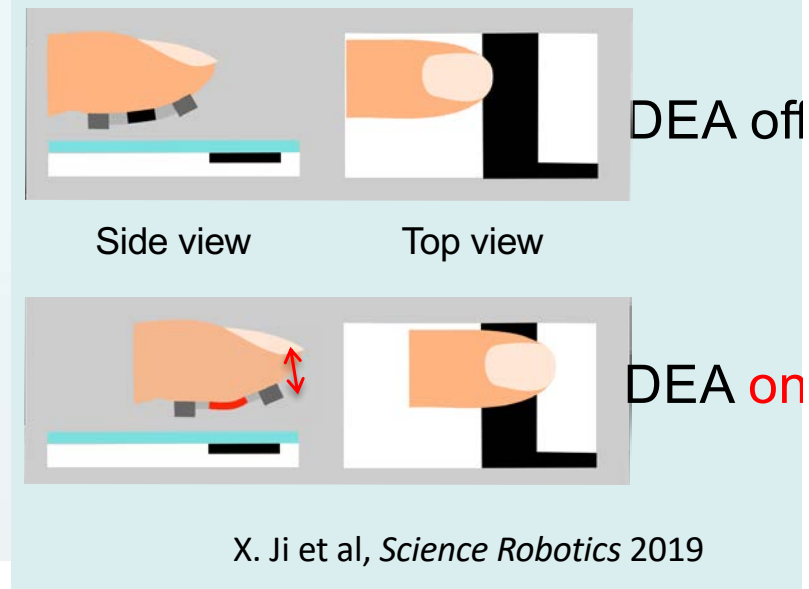
Users can feel a broad range of frequencies



Users can accurately distinguish different haptic signals



Control: with "low-V" electronics: can have some processing power



Electronics made by EPFL-LAI

<https://www.youtube.com/watch?v=S8g8CU7yp3E>

**Use a finger to
“see” letters!**

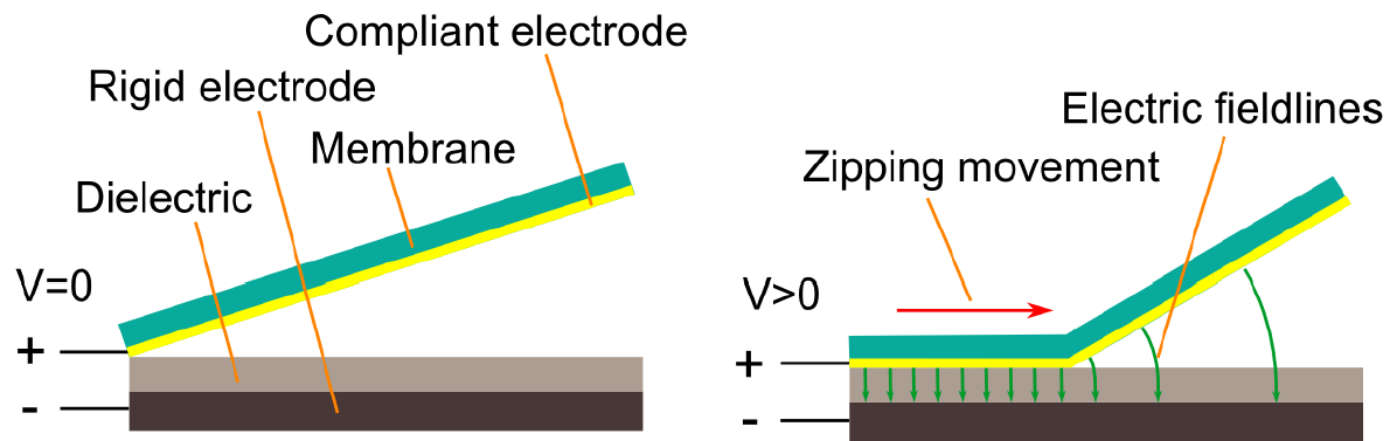
Limitations of thin DEA cutaneous devices

- Typically only one finger
- Few user studies
- Low forces, low displacement

Why?

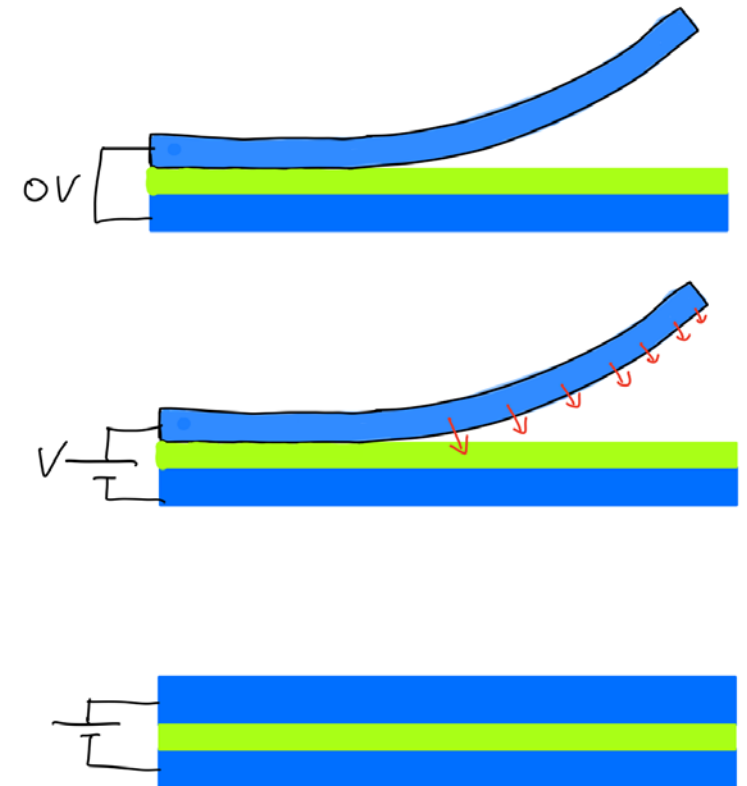
- Low maturity devices: low yield, low lifetime
- Challenging fabrication
- On-body integration to ensure good force transmission

4.5 ZIPPING ELECTROSTATICS



Zipping electrostatic actuators:

- reduce voltage of electrostatic actuators
- large displacement and higher power density
- Use flexible (but not stretchable!) materials with higher E_{BD} and higher permittivity.
- Metal electrodes: easy fab, low resistance

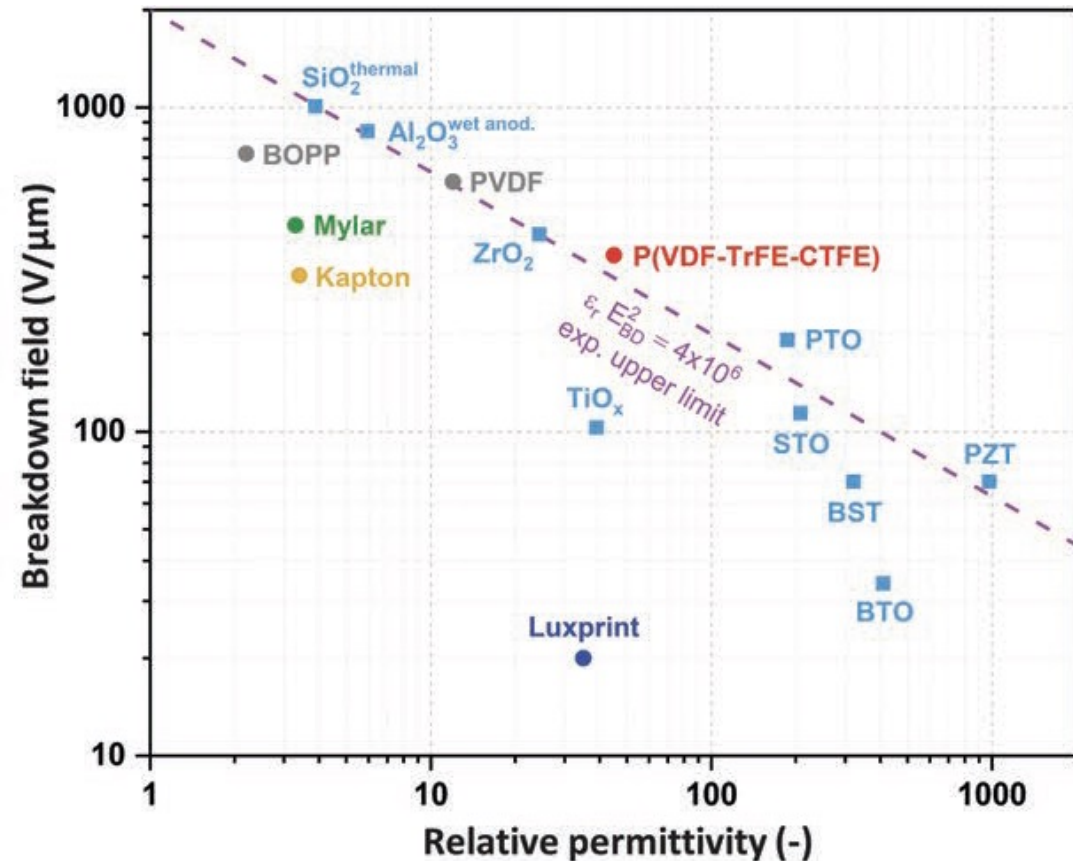


“old” concept used in MEMS since the 90s

Zipping electrostatic actuators allow using materials with excellent electrical properties (eg good dielectrics, metal electrodes), yet get large motion

- On paper, ES zipping has up to 100x higher energy density than DEAs
- eg compare PDMS vs PVDF co-terpolymer with permittivity of 40, E_{BD} of 250 V/ μm

$$energy_density_{ES} = \frac{1}{2} \epsilon_0 \epsilon_r E^2$$



Many groups develop compliant Electrostatic zipping devices !

- Peano-HASEL (C. Keplinger group)

N. Kellaris et al., *Science Robotics*, 2018

P. Rothmund et al, *PNAS* 2020

...

- Electro-ribbon actuators (J. Rossiter group)

M. Taghavi, et al. , *Science Robotics*, 2018

T. Helps et al, *Science Robotics*, 2022

- Tunable Lenses (M Kaltenbrunner group)

F. Hartmann et al, *Advanced Science* 2020

- Bellow Muscle actuators (M. Fontana group)

I. Sîrbu et al, *Science Robotics*, 2021

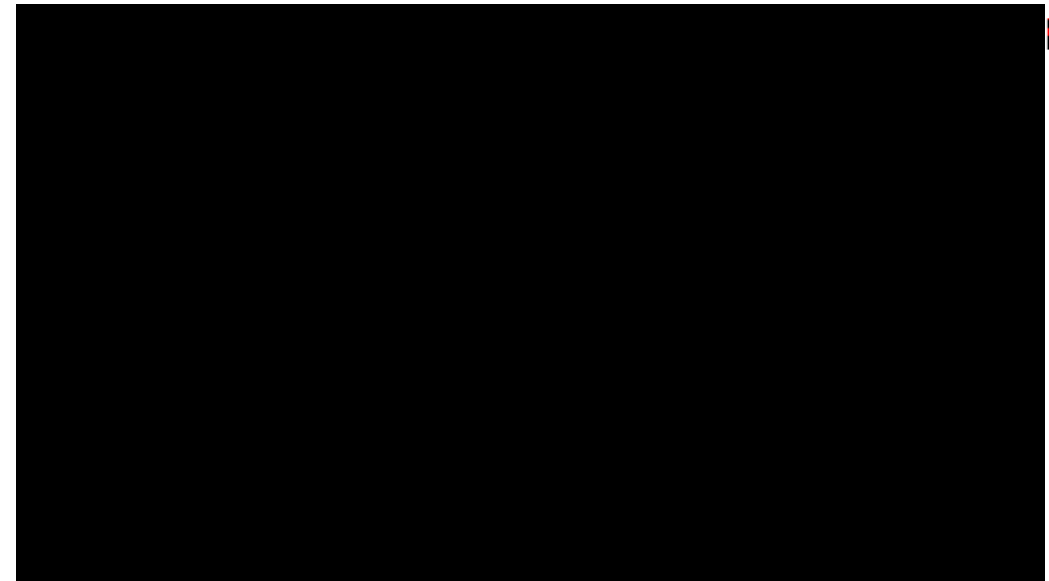


Zippering electrostatic actuators

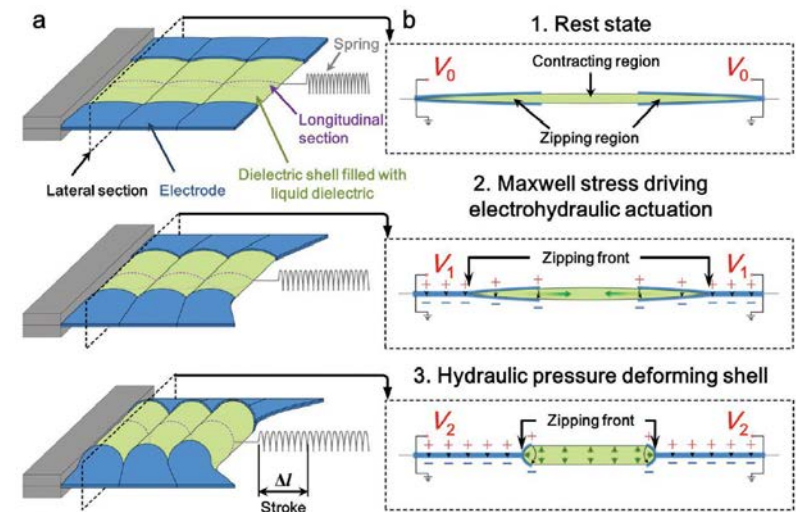
Very active research area! for instance

- Electro-ribbon actuators (Rossiter group)
- **Peano Hasel (Keplinger group)**
- Tunable lenses (Kaltenbrunner group)
- EBM (Fontana group)

- Can be accurately modeled
- Does not use higher permittivity insulator

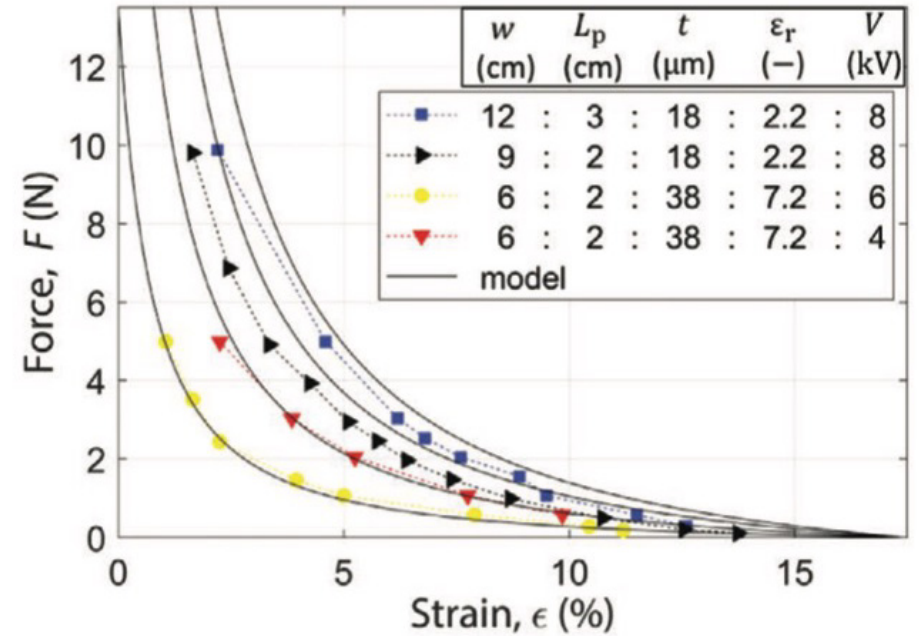
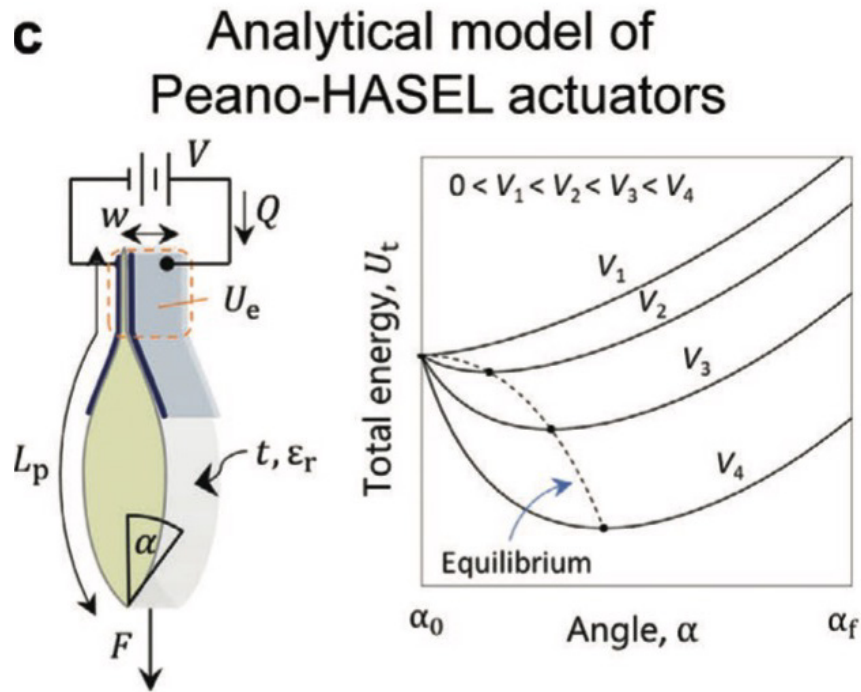


N. Kellaris et al, *Science Robotics*. **3**, eaar3276 (2018).



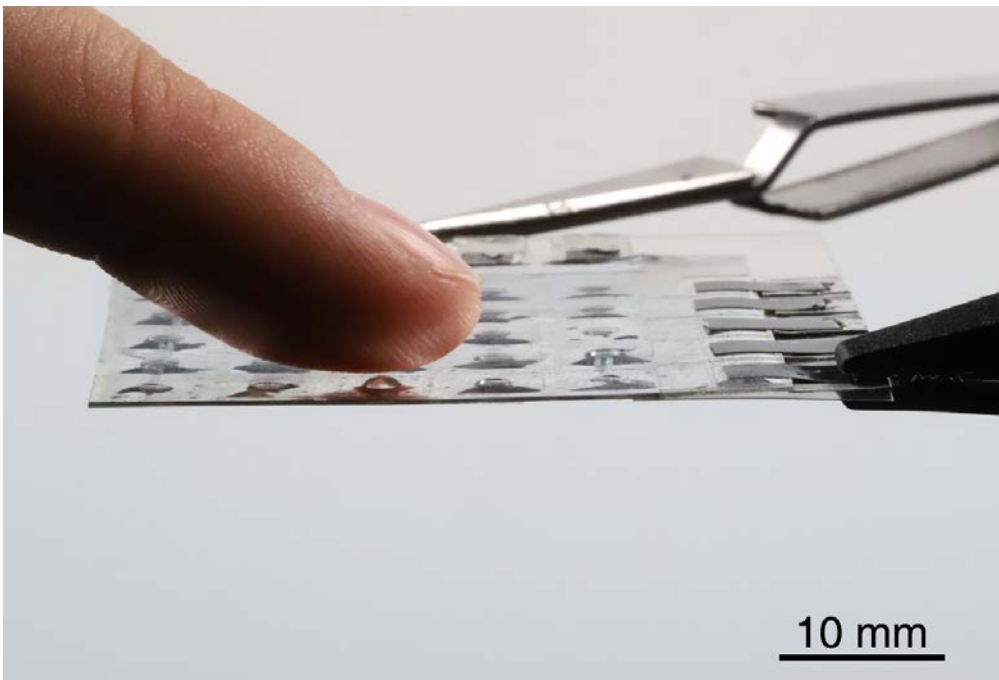
Wang ... Keplinger, *Adv. Func Mat* 2019

HASEL scaling + force



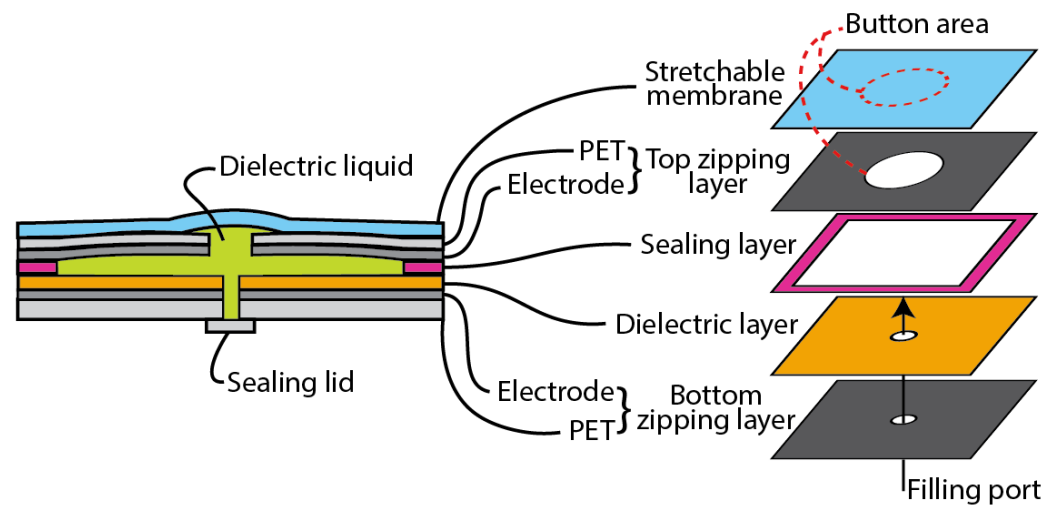
P. Rothemund et al, HASEL Artificial Muscles for a New Generation of Lifelike Robots—Recent Progress and Future Opportunities. *Advanced Materials* 2020

Can combine zipping with stretchable elements so
can use on the body:
high energy density and yet use elastomers?

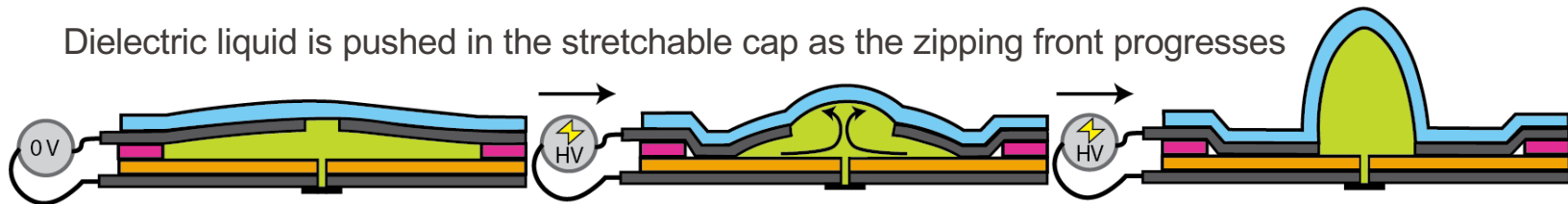


E. Leroy, R. Hinchet, H. Shea,
Multimode Hydraulically Amplified Electrostatic
Actuators for Wearable Haptics.
Advanced Materials. **32**, 2002564 (2020).

- Hydraulically **A**mplified Ta**X**ELs (HAXELs) family of zipping actuators.
- HAXELs consist of two metallic electrodes that are separated by a layer of solid dielectric and a liquid dielectric
- Applying a high voltage (1-2 kV), applies an electrostatic force to the electrode causing them to zip
- Zipping of the electrodes pushes the liquid into a stretchable membrane that pops up / generates mechanical work



Dielectric liquid is pushed in the stretchable cap as the zipping front progresses

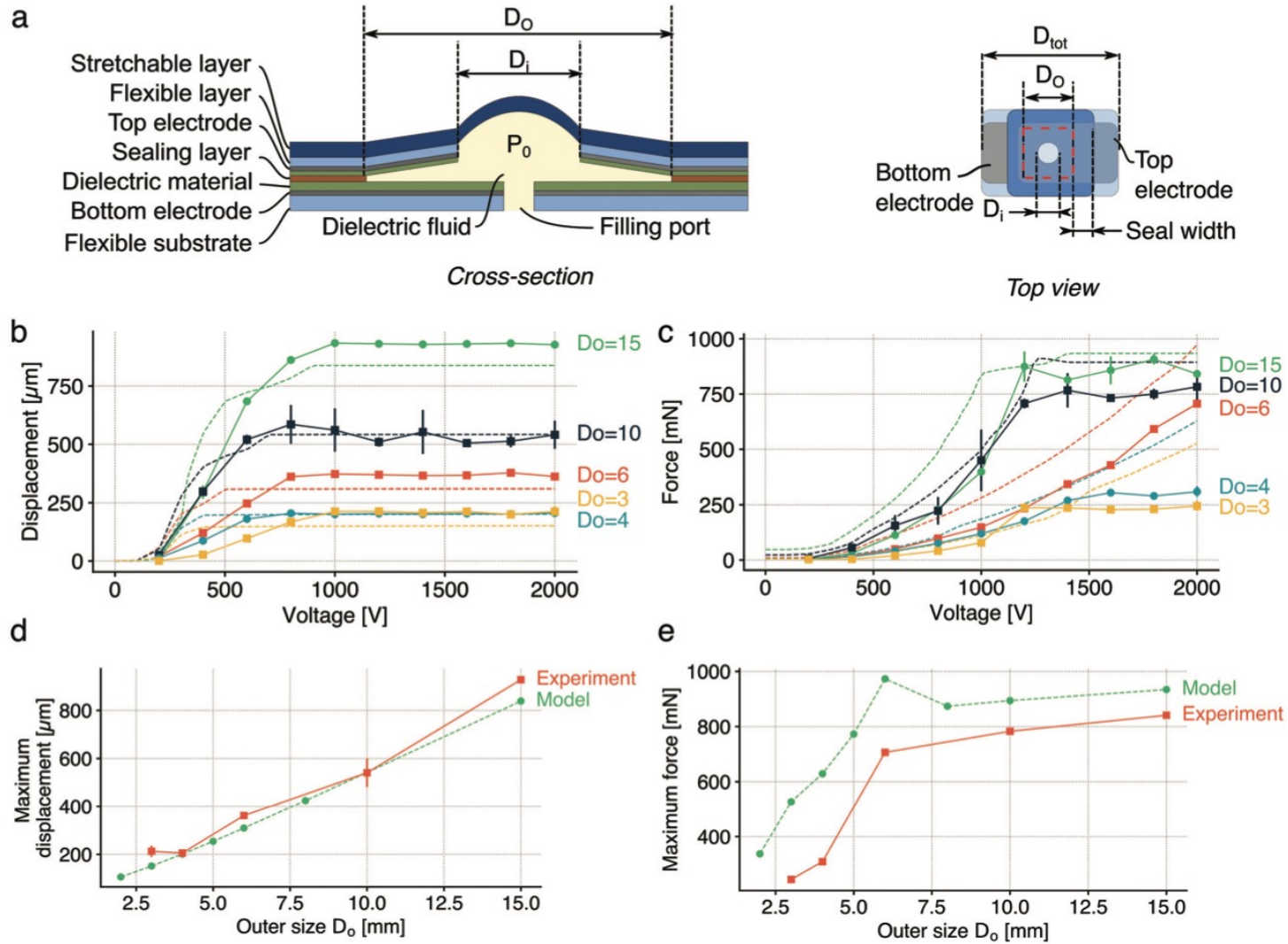


Hydraulically amplified mm-scale actuators for wearable haptics

Edouard Leroy and Herbert Shea

Ecole Polytechnique Fédérale de Lausanne
Neuchatel, Switzerland

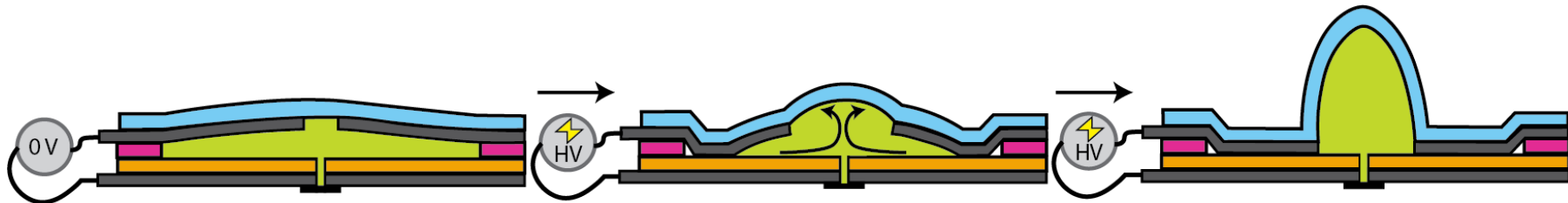
How much force can one get?



Leroy et al, Adv. Mat. Tech 2023

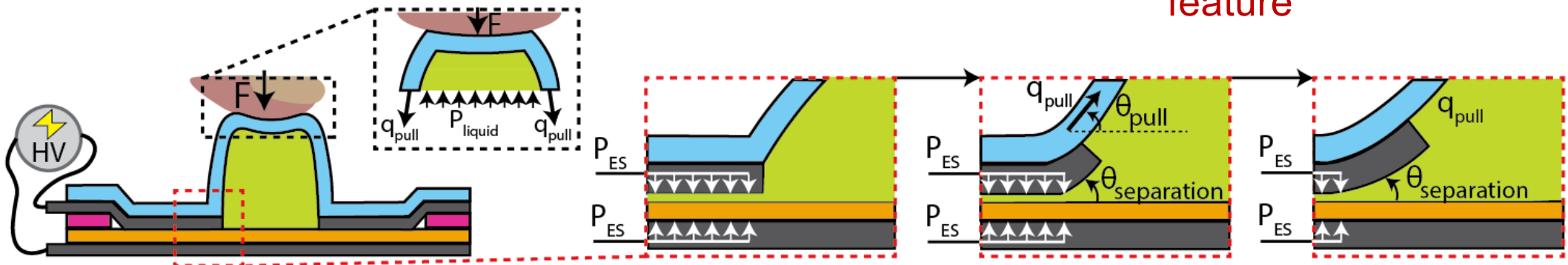
- Flexible zipping layers allow the gradual progression of the zipping front
- Gradual zipping is key for i) large volume displacement and ii) large force

Gradual zipping is a desirable feature



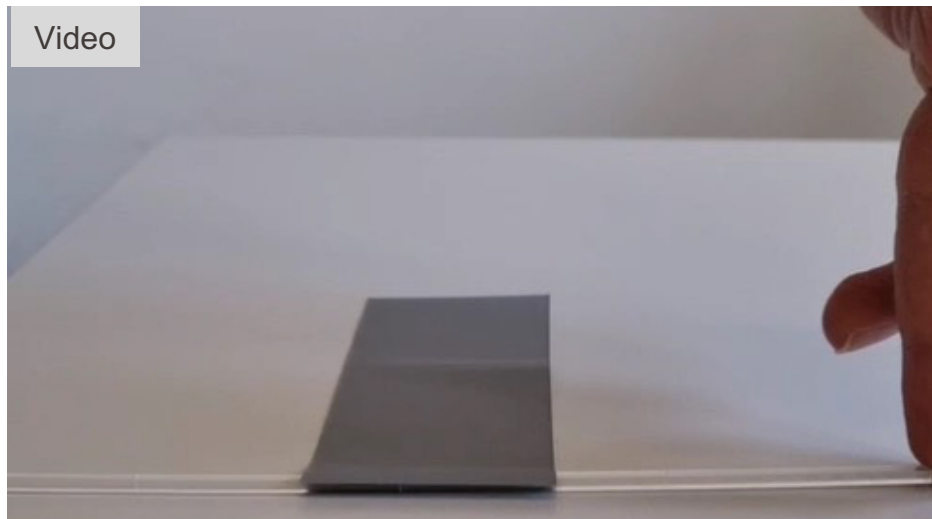
- After zipping, the flexibility become a disadvantage leading to gradual unpeeling when an external force is applied
- Peeling mechanics limits the maximum loading capacity of the actuator

Gradual unpeeling is an undesirable feature

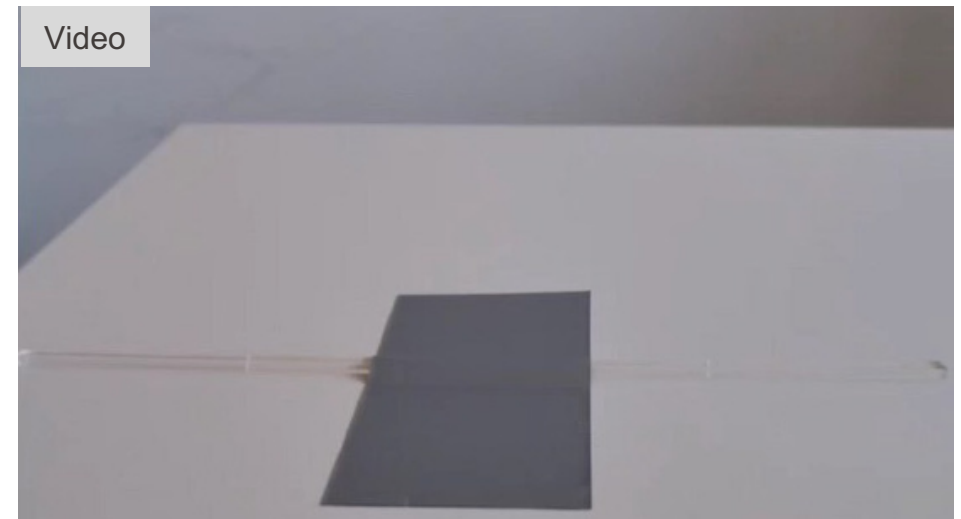


- Double-sided peeling threshold is 10x-100x larger than that of the single-sided peeling
 - Force applied to one end results in single-sided peeling
 - Force applied to a mid point results in double-sided peeling

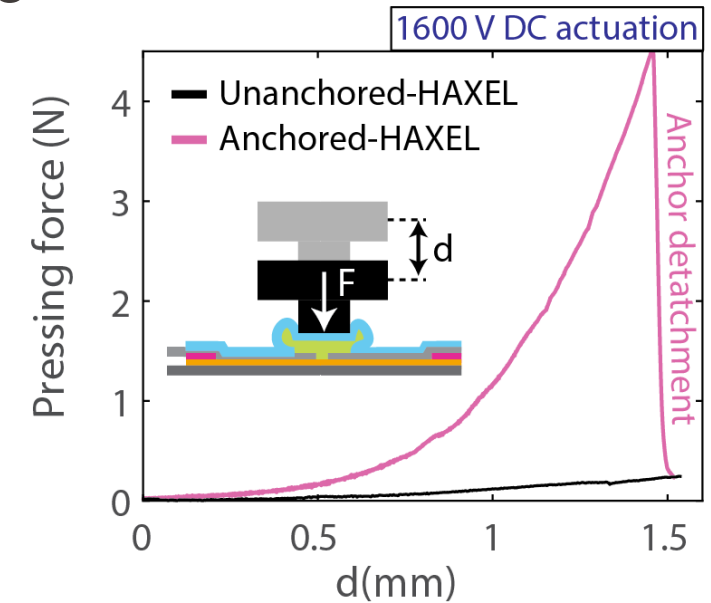
Single-sided peeling



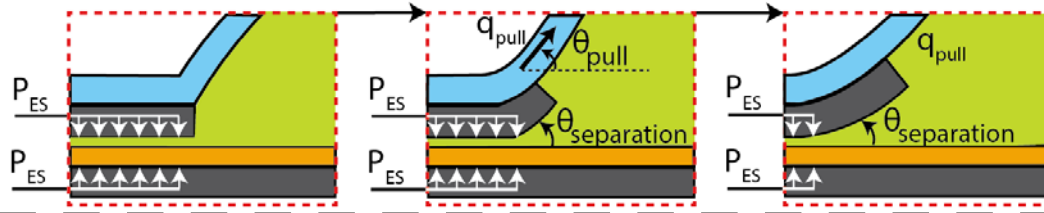
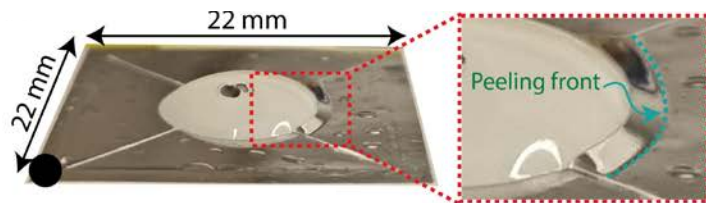
Double-sided peeling



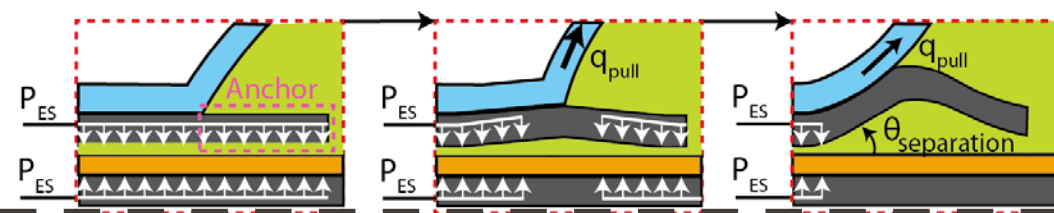
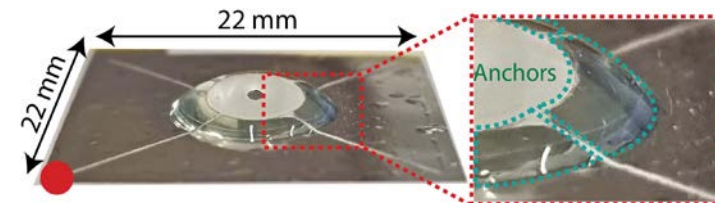
- Extending the zipping layer beyond the application point of the force alters the peeling mechanics of HAXELS from single-sided to double-sided
- These extensions (anchors) have a negligible effect on the zipping
- Anchors significantly increase the peeling threshold of the zipped layers
- HAXELS with anchors are characterized by
 - An order of magnitude larger holding force under indentation
 - A snap through feature



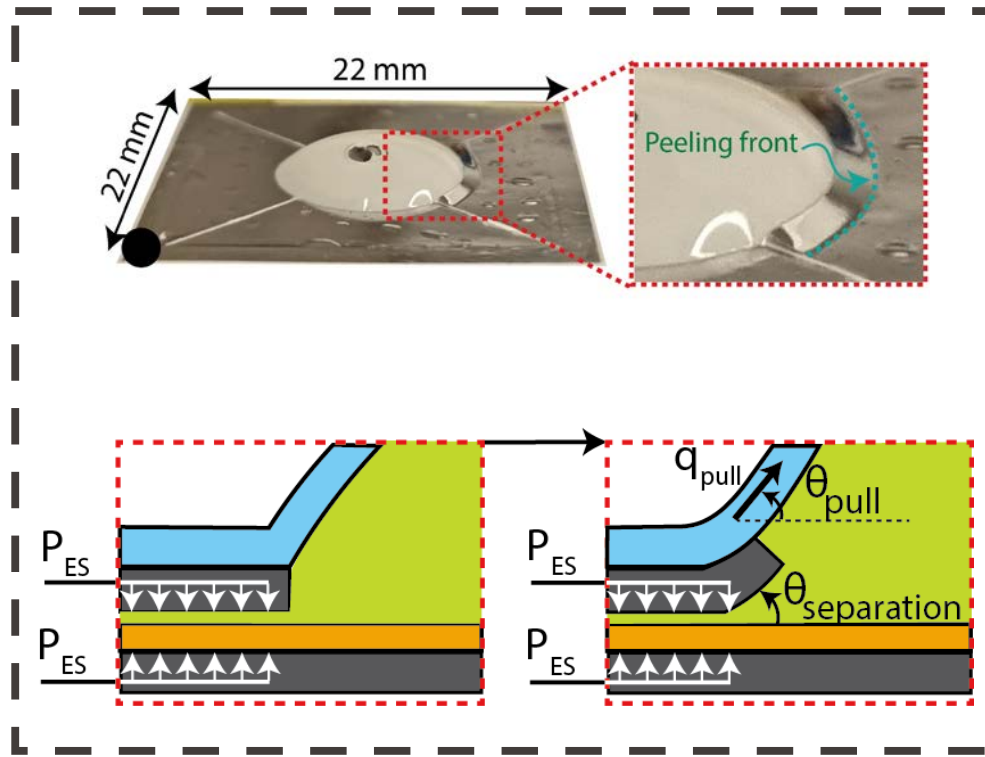
Unanchored HAXEL with single-sided peeling



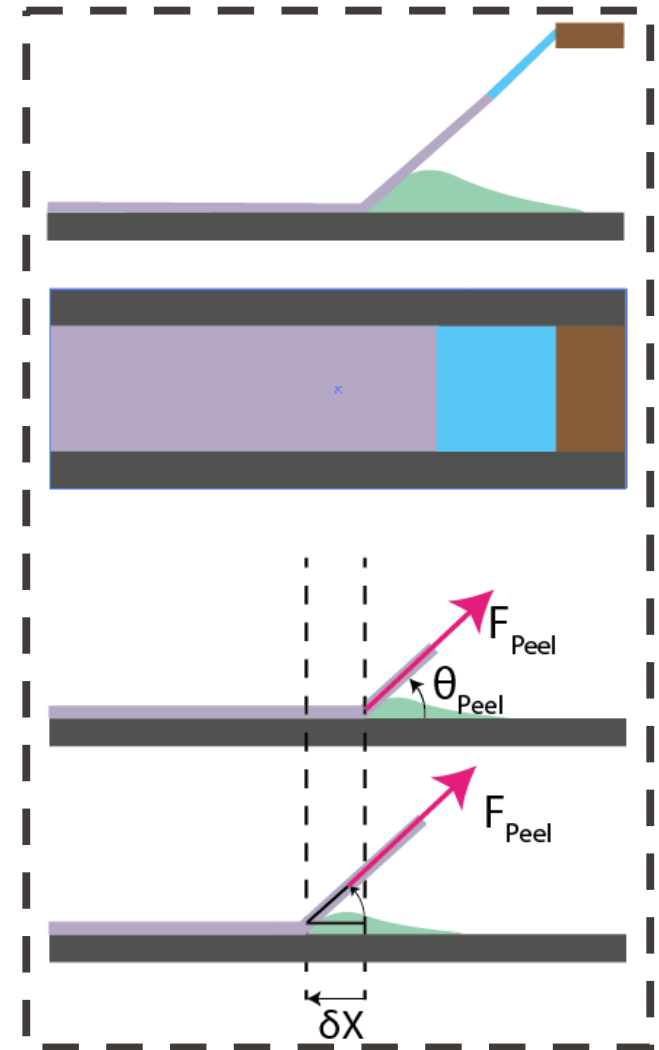
Anchored HAXEL with double-sided peeling



Single-sided Peeling in Unanchored-HAXELs



~



EPFL Single-sided Peeling Threshold

Mechanical work done by the peeling force:

$$W_{Peel} = F_{Peel} \sin(\theta_{Peel}) \cdot \delta x \sin(\theta_{Peel}) - F_{Peel} \cos(\theta_{Peel}) \cdot \delta x (1 - \cos(\theta_{Peel}))$$

$$W_{Peel} = F_{Peel} \cdot \delta x (1 - \cos(\theta_{Peel}))$$

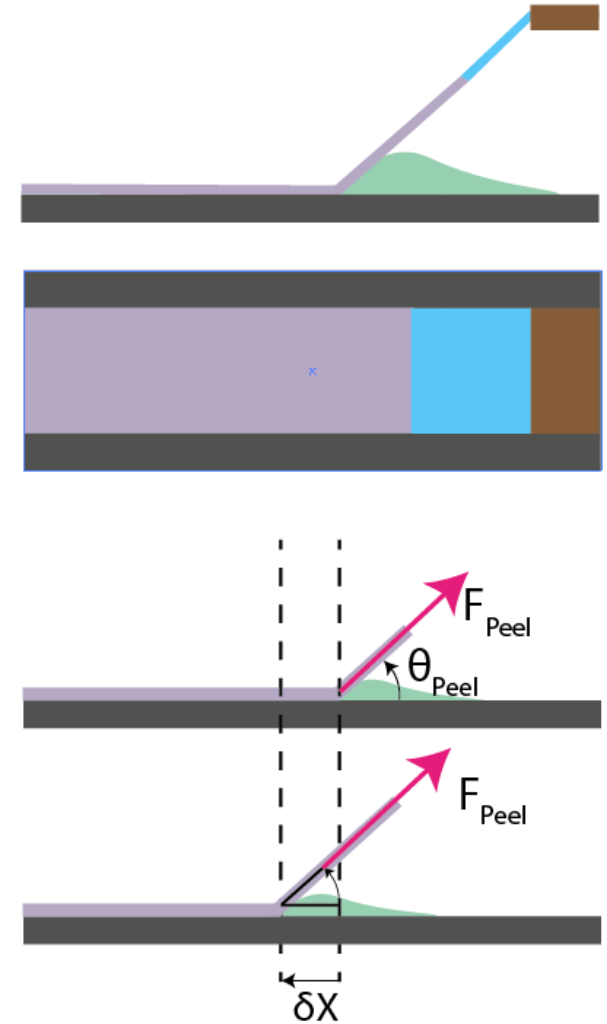
Energy required to create new surface by detaching the layers:

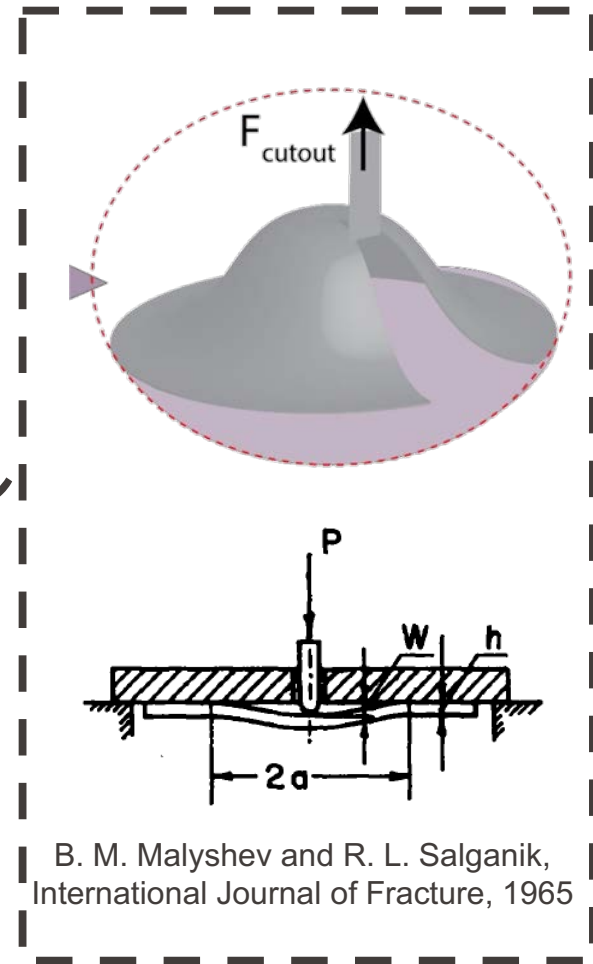
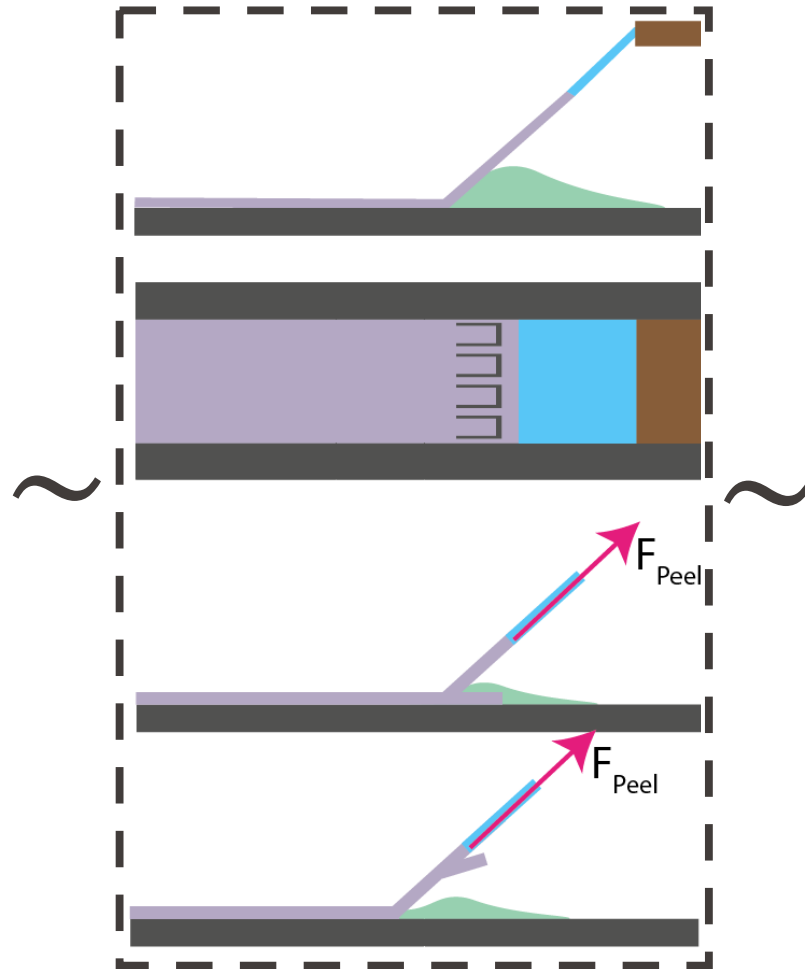
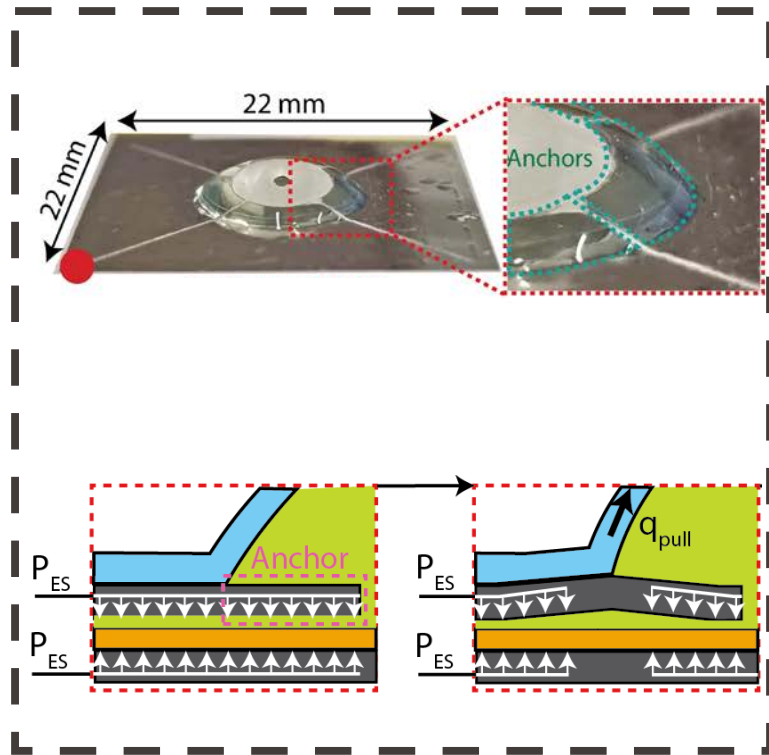
$$E_{\Delta A} = R_{ES} \delta x b, \quad R_{ES} = \frac{1}{2} \frac{(C_{zipped} - C_{peeled}) V^2}{A}$$

Energy Conservation:

$$W_{Peel} = E_{\Delta A} \rightarrow F_{Peel} = \frac{R_{ES} b}{1 - \cos(\theta_{Peel})}$$

$$F_{Peel} = 1.1 \text{ N per cm length of the peeling front (for } R_{ES} = 15 \frac{\text{N}}{\text{m}}, m, \theta_{Peel} = 30^\circ)$$





B. M. Malyshev and R. L. Salganik, International Journal of Fracture, 1965

EPFL Double-sided Peeling Threshold

Peeling mechanics in Anchored-HAXEL is similar to that of the well-studied shaft-loaded blister formation.

$$w = \frac{P a^2}{16 \pi D}, \quad D = \frac{E h^3}{12(1 - \nu^2)}, \quad E_{pot} = 1/2 P w = \frac{P^2 a^2}{32 \pi D}$$

Rate of mechanical energy release due to expansion of peeling force:

$$\frac{\partial E_{pot}}{\partial a} = \frac{P^2 2a}{32 \pi D}, \quad P = F_{Peel} \sin \theta_{Peel}$$

Rate of energy required to create new surface:

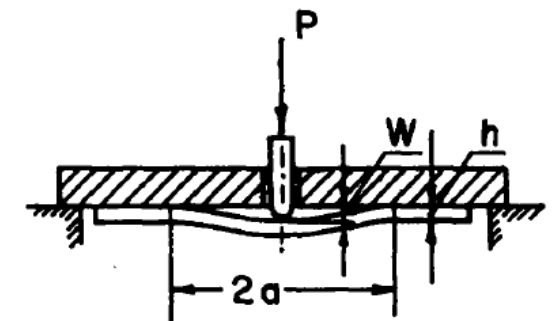
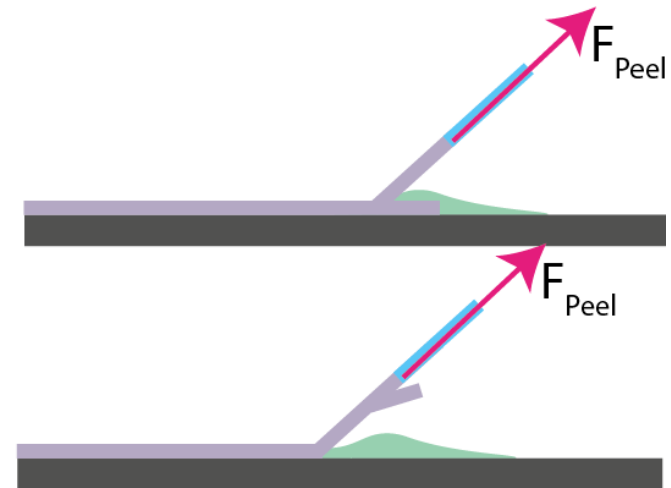
$$\frac{\partial E_{\Delta A}}{\partial a} = \frac{\partial (R_{ES} \pi a^2)}{\partial a} = 2\pi a R_{ES}, \quad R_{ES} = \frac{1}{2} \frac{(C_{zipped} - C_{peeled}) V^2}{A}$$

Energy Conservation:

$$\frac{\partial E_{pot}}{\partial a} = \frac{\partial E_{\Delta A}}{\partial a} \rightarrow P = 4\pi \sqrt{2DR_{ES}}, \quad F_{Peel} = 3N \text{ per anchor (for } R_{ES} = 15 \frac{N}{m})$$

Peeling threshold is independent of the diameter of the peeling front. So once peeling (crack) starts, it propagates till complete delamination. This explains the snapping feature of Anchored-HAXELs.

Firouzeh, Mizutani, et al, Adv. Mat 2023

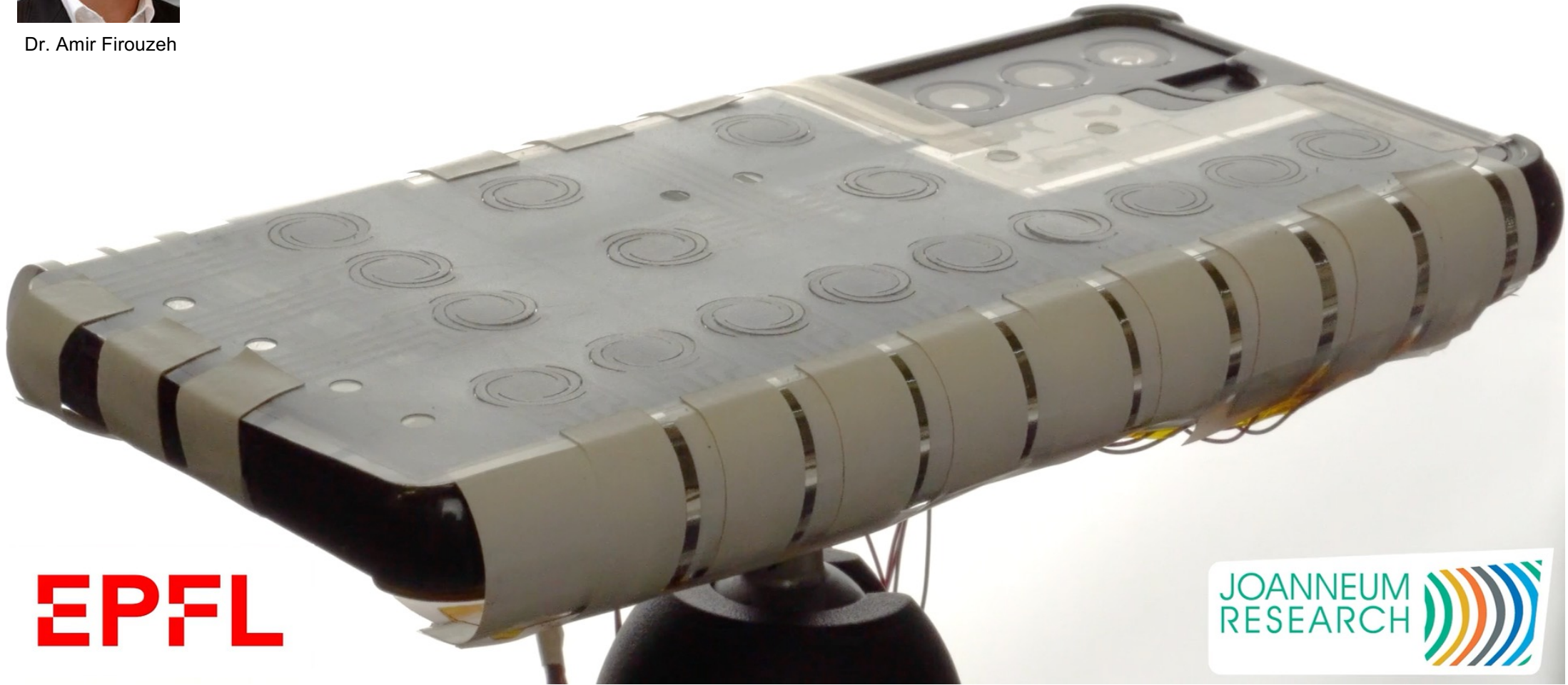


Add touch sensors: sense finger proximity and detect button push.
Now any surface can have pop-up buttons!

Firouzeh, Mizutani, et al, Adv. Mat 2023



Dr. Amir Firouzeh



EPFL

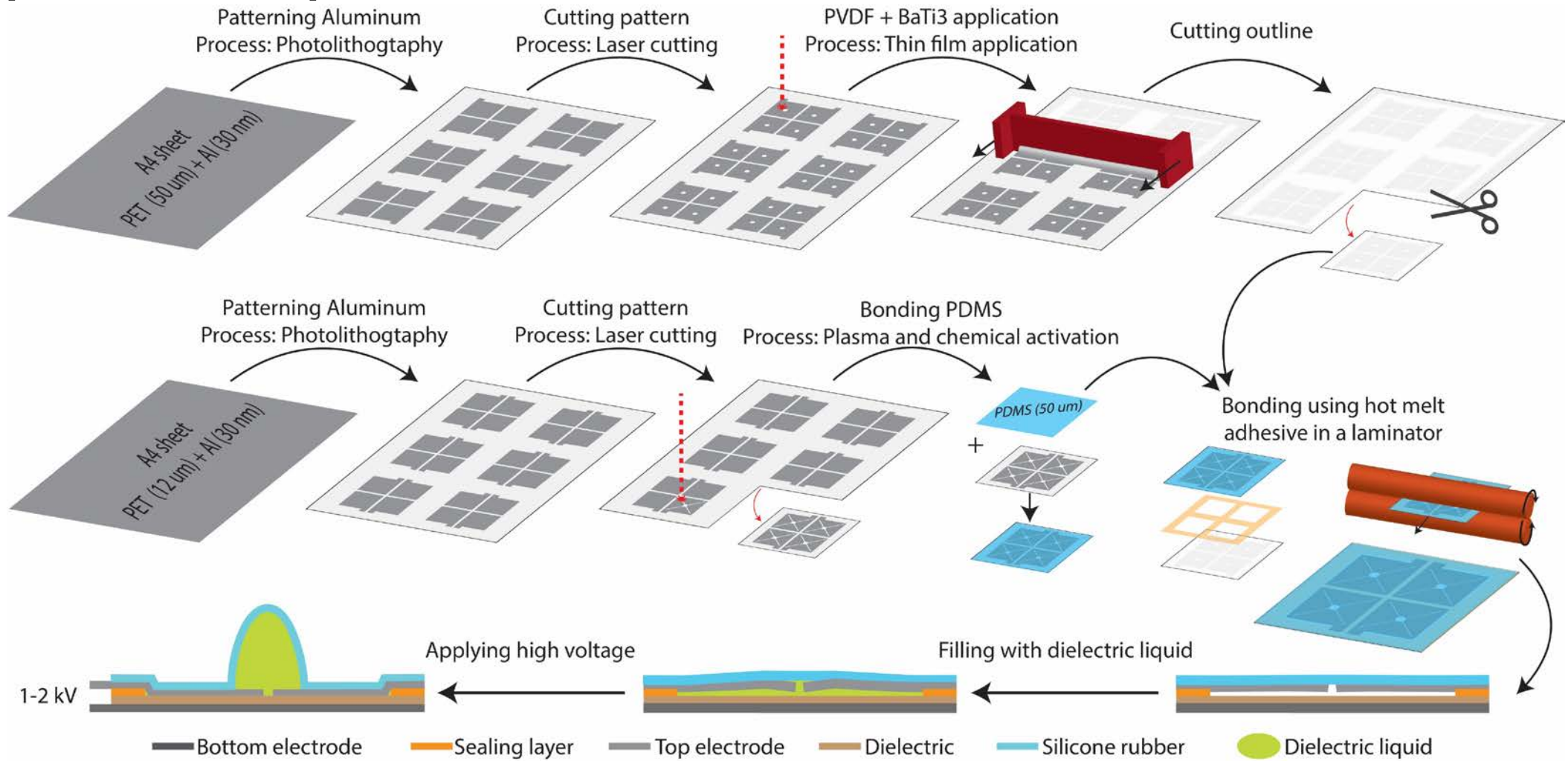


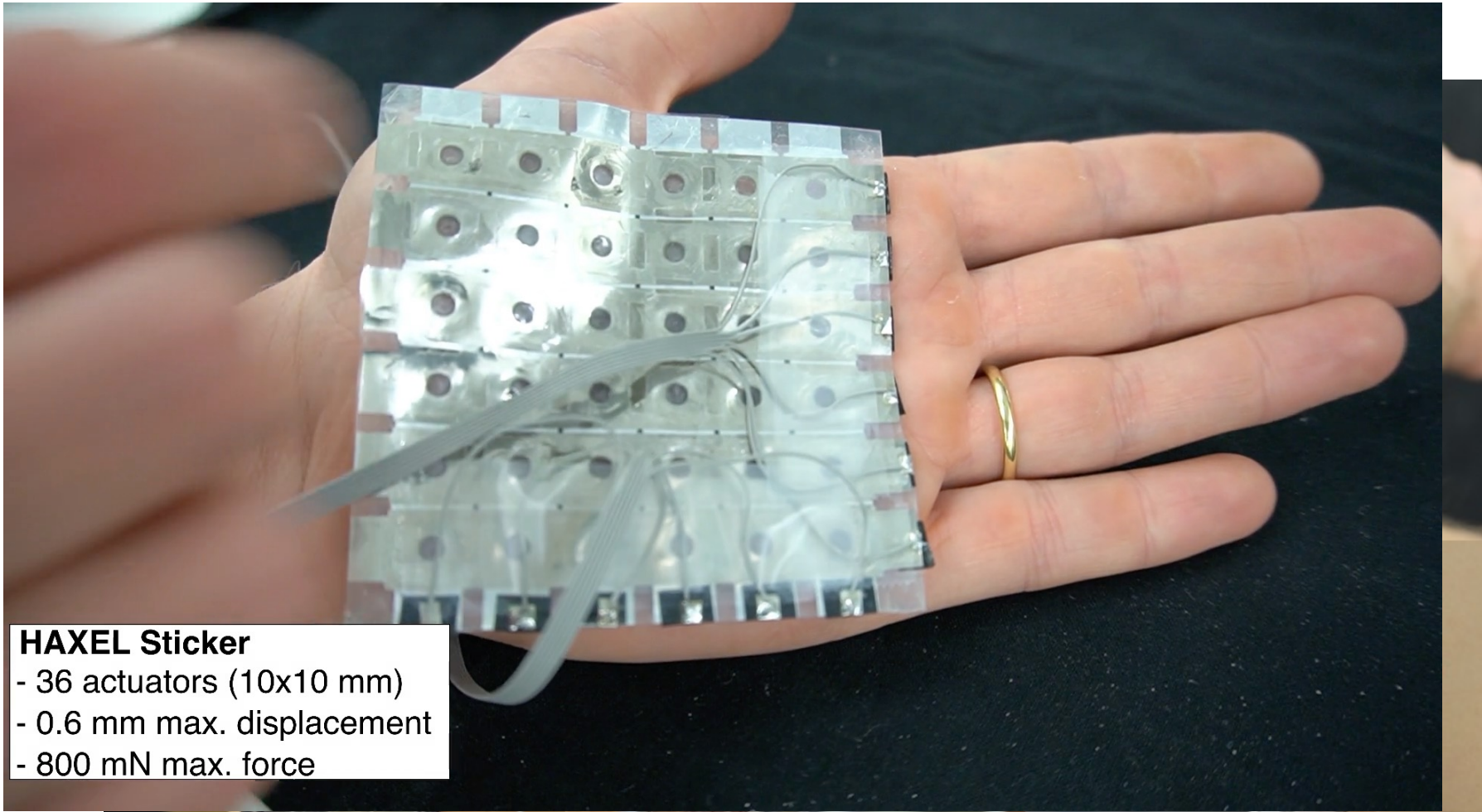
Transparent HAXELS: buttons pop up on touchscreens!



Ayana
Mizutani

HAXEL fabrication process by lamination (overview)





HAXEL Sticker
- 36 actuators (10x10 mm)
- 0.6 mm max. displacement
- 800 mN max. force

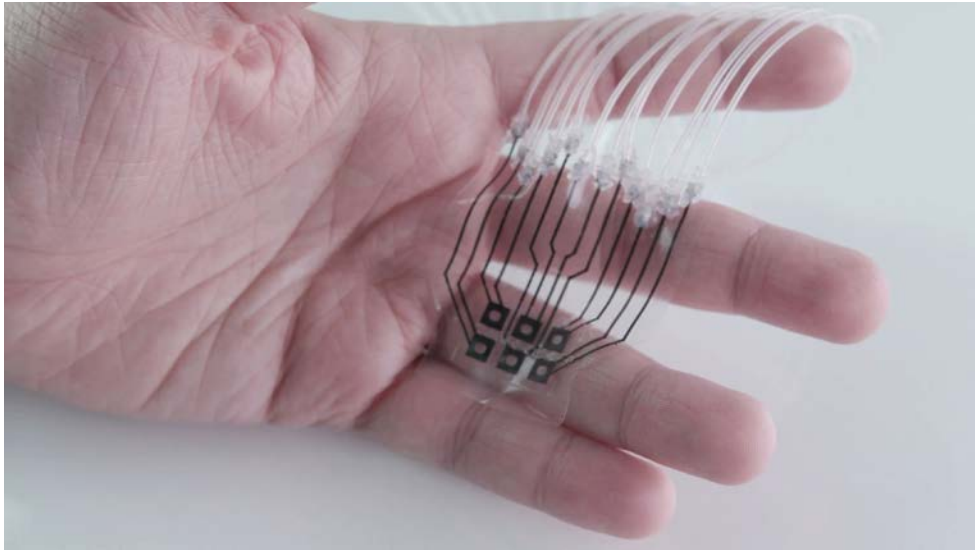


Dr. Edouard Leroy

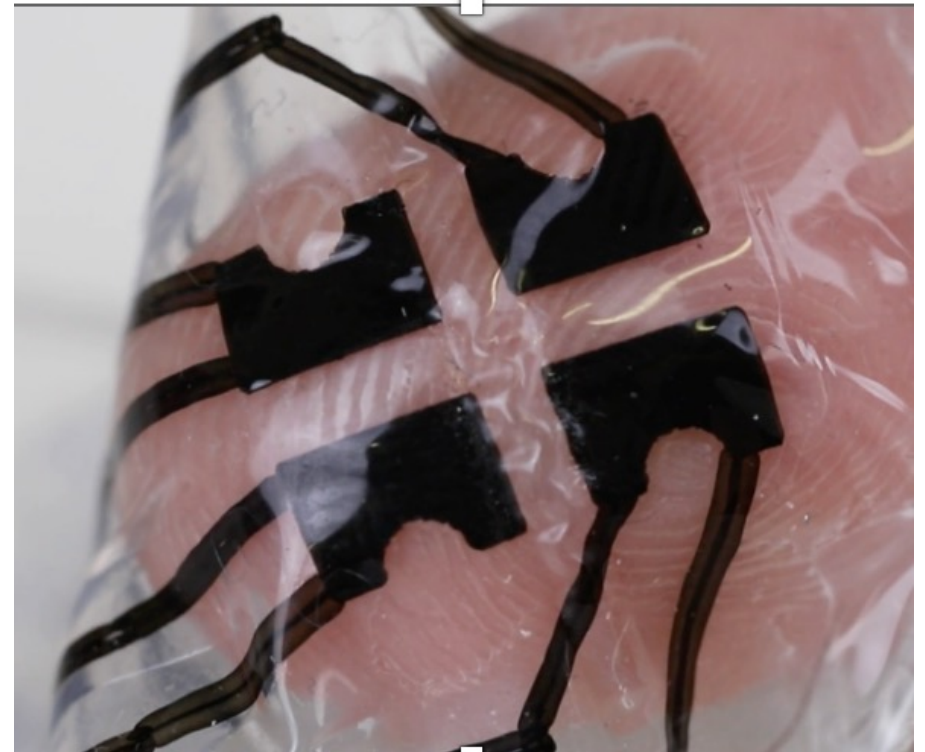


E. Leroy *et al*, iAdv.
Mat tech 2023

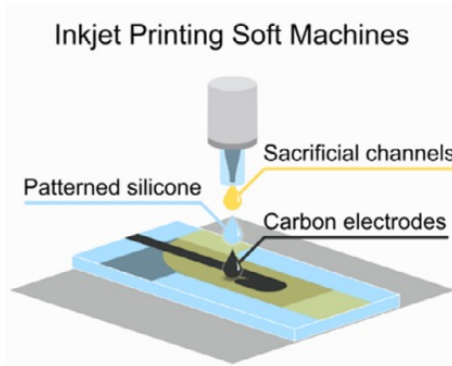
To make it stretchable: all-printed for “feel-through” haptics on fingertips



All elastomer + fluid solution: directly on skin



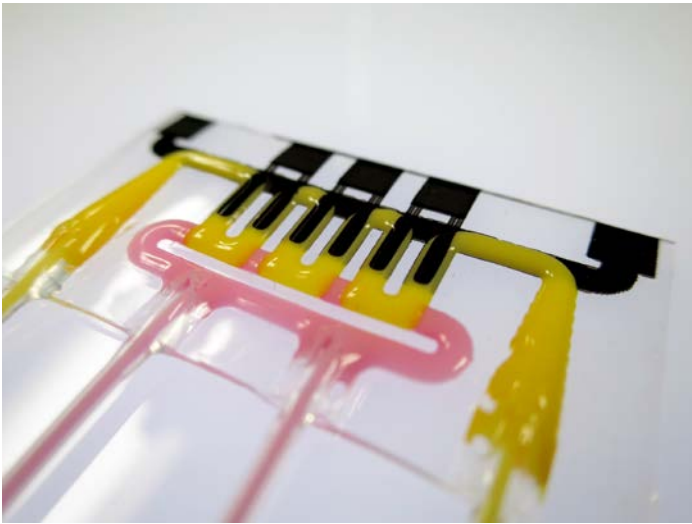
Giulio Grasso



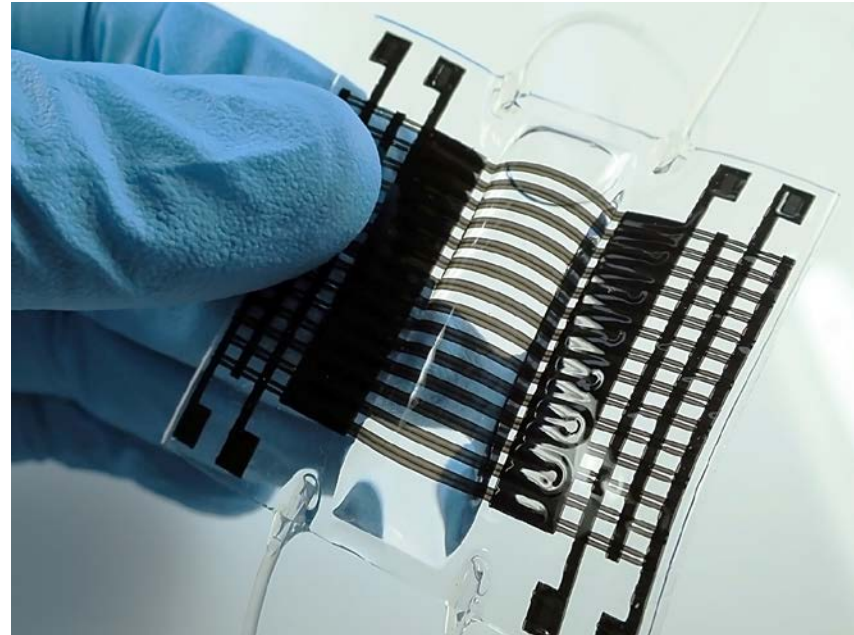
Inkjet-printing densely integrated zipping actuators

Exploit benefits of inkjet printing for DEA + HASEL + zipping

- Multi-layer, no wires!
- Many actuators
- More than 3 materials

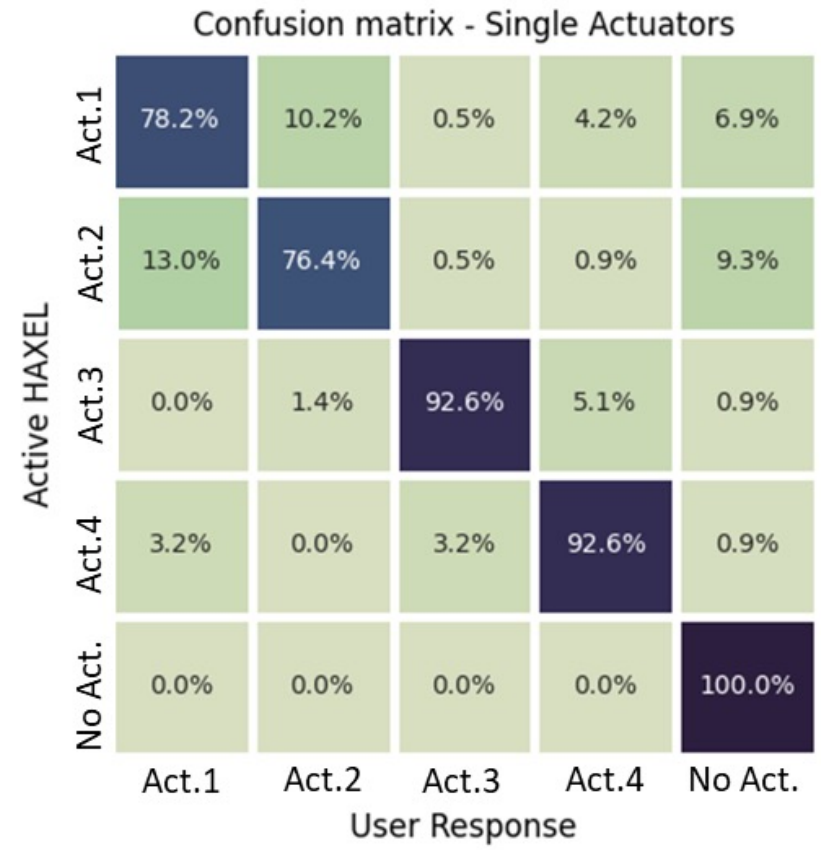


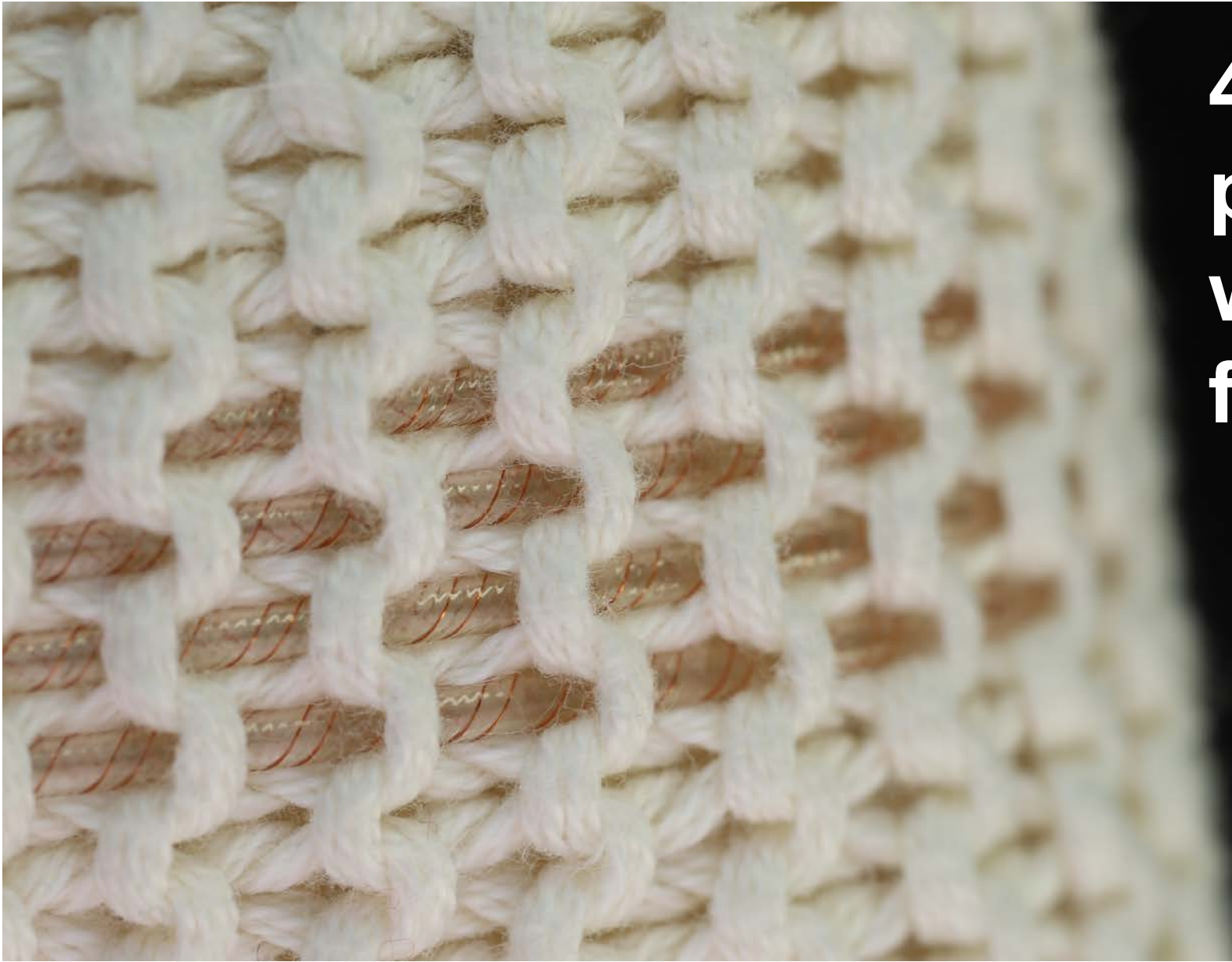
7 printed layers
6 actuators



7 printed layers
28 actuator pairs

Schlatter, et al. "Ink-jet printing of complex soft machines with densely integrated electrostatic actuators." *Advanced Intelligent Systems* (2020) doi:[10.1002/aisy.202000136](https://doi.org/10.1002/aisy.202000136).





4.6. Fiber pumps for wearable fluidics



Dr. Mike Smith

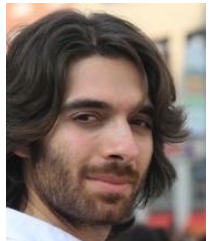
Pneumatics are great, but they are tethered



Meta / Facebook reality labs

Stretchable EHD pump, 2019 edition

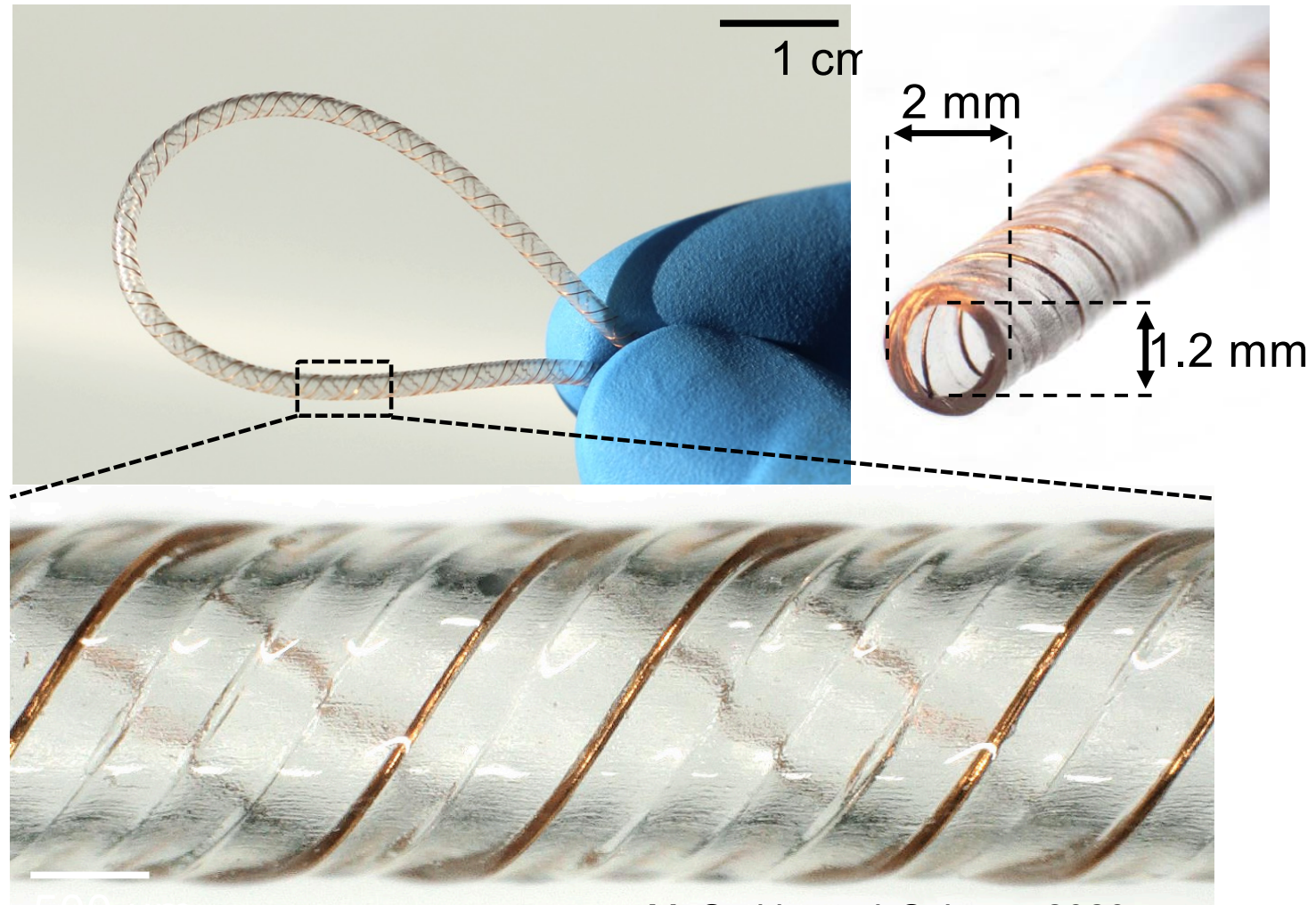
- 2019, we reported a flexible pump with no moving parts, based on Charge injection electrohydrodynamics (EHD)
 - Pressure 0.1 Bar for 10 cm
 - Flow rate 6 ml/min
 - Stretchable
- Challenging to integrate in textile or on body
- Limited length (few cm)
- Limited lifetime
- Low energy density. (0.5 W/kg)



V. Cacucciolo *et al*, Nature 2019

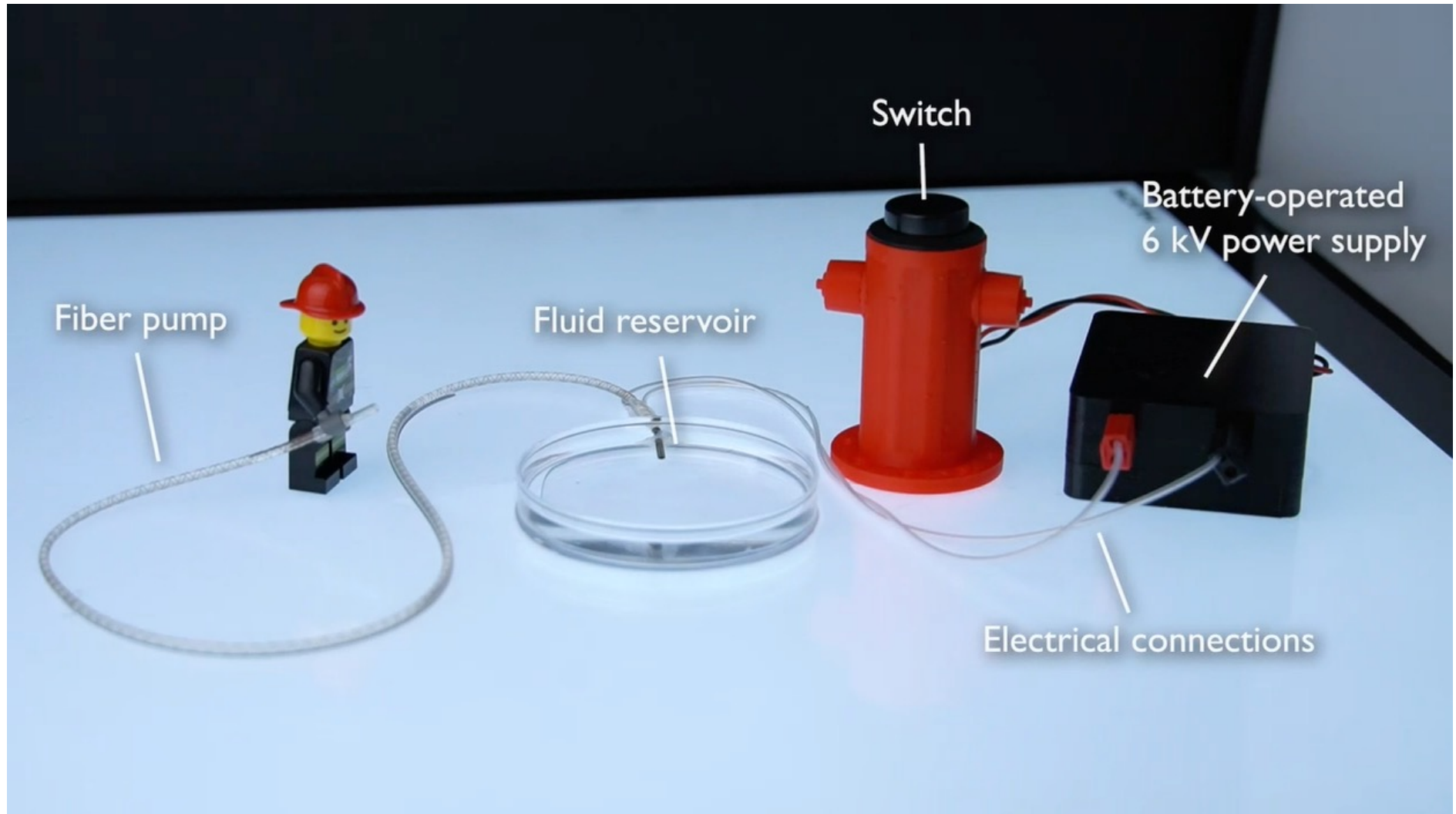
Fiber pumps for wearable fluidic systems

- Operates silently without any moving parts (EHD)
- Soft, flexible & stretchable
- Fiber format
- **Simple, scalable production method**
- **High performance pumps for truly wearable and untethered fluidic systems**
- **Power density: 13 W/kg**



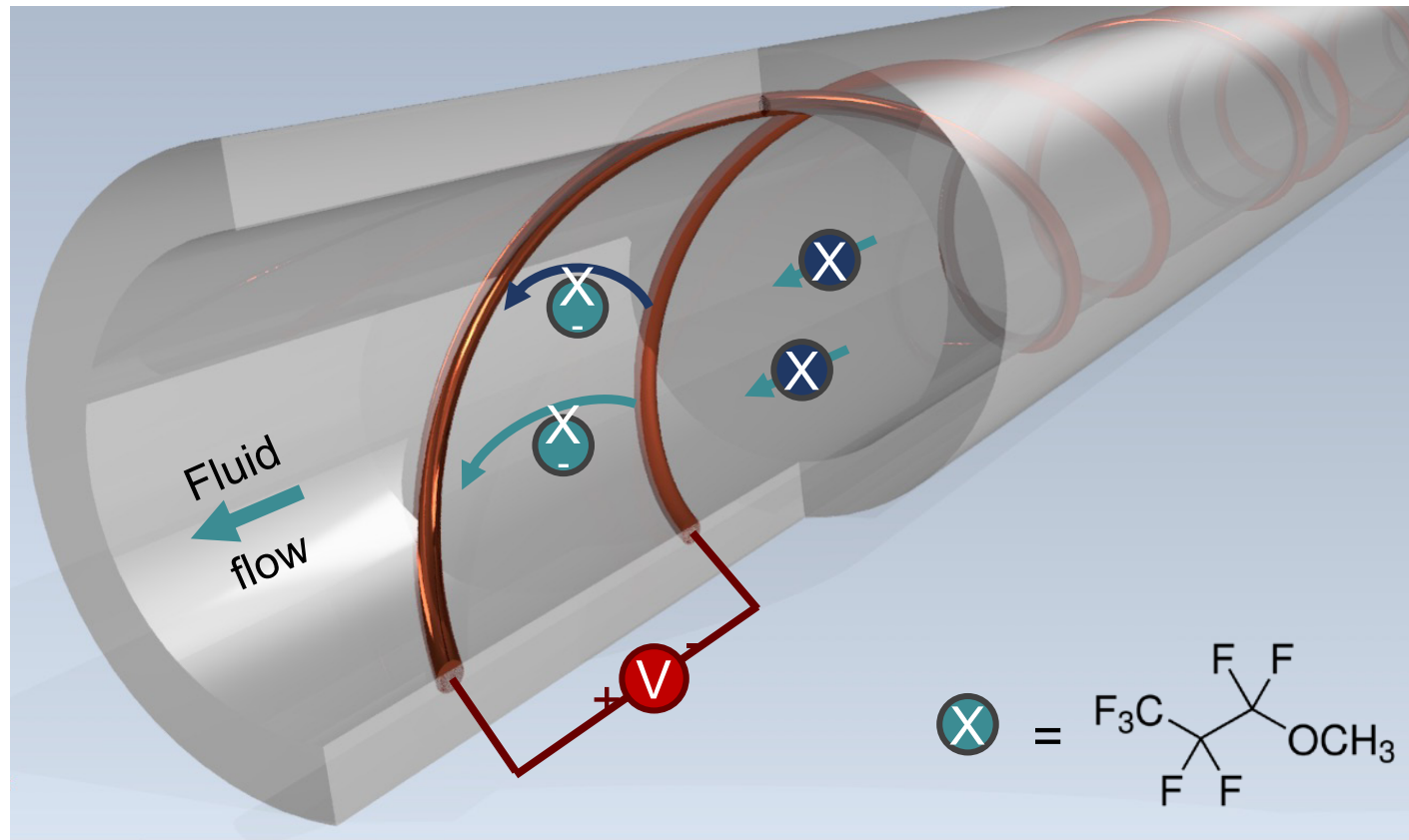
M. Smith *et al*, Science 2023

Fiber pumps for wearable fluidic systems



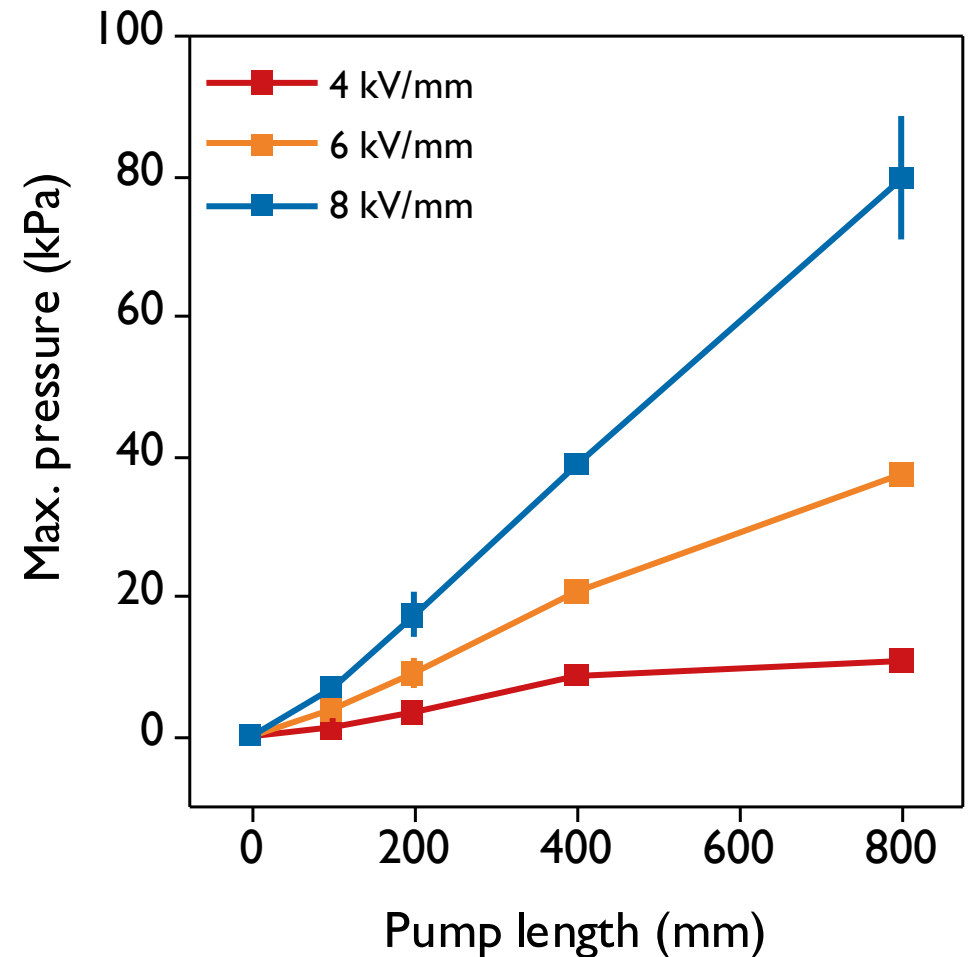
Charge injection electrohydrodynamics (EHD)

- Dielectric fluid becomes ionised at the negative electrode
 - Novec 7100 fluid
 - (or other insulating liquids)
- Ions are accelerated by electric field
- Asymmetrically spaced electrodes generate a net flow in chosen direction
- High voltage (kV)
- Low current (μA)
- Low power consumption (sub-W per meter)

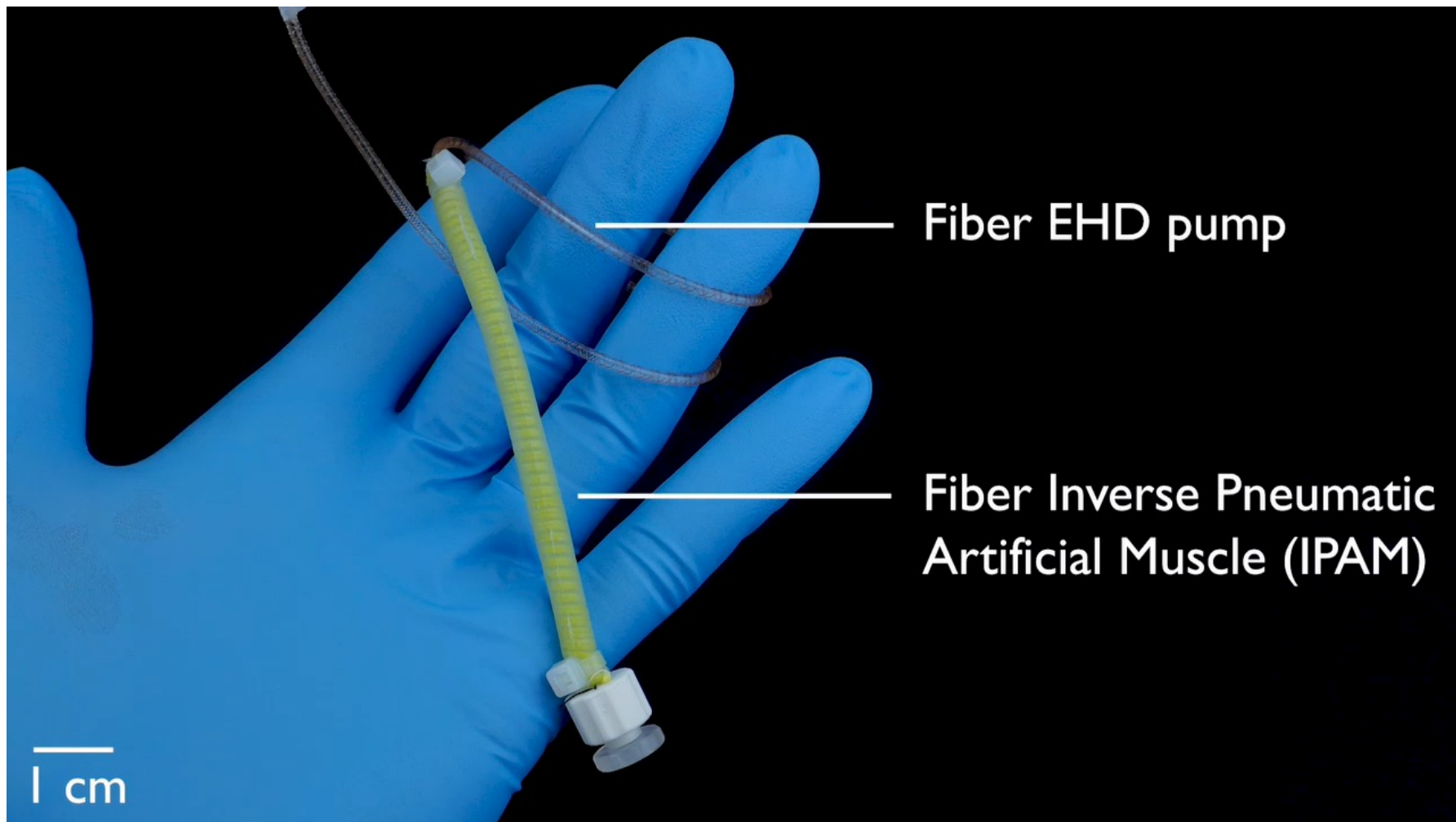


Pump performance scales linearly with pump length

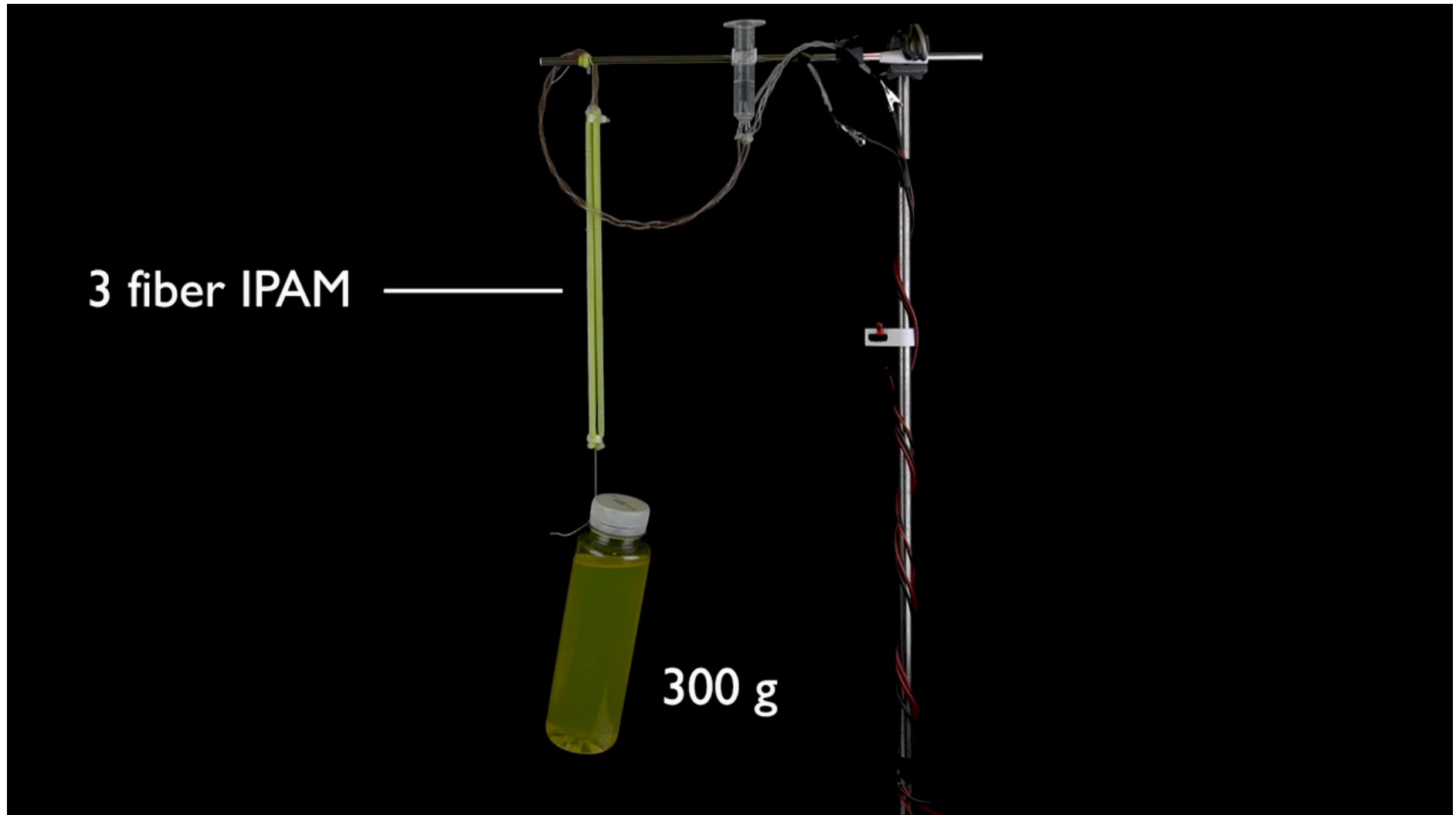
- Pressure per unit length of 100 kPa/m at 8 kV/mm (6.4 kV)
- Maximum flowrate is roughly constant for all pump lengths – around 55 ml/min
- Corresponds to a power density of:
 - 18 kW / m³
 - 27 W / kg
 - Equal to or greater than that of any other 'soft' pump
 - (But 10x lower than electrostatic zipping devices...)



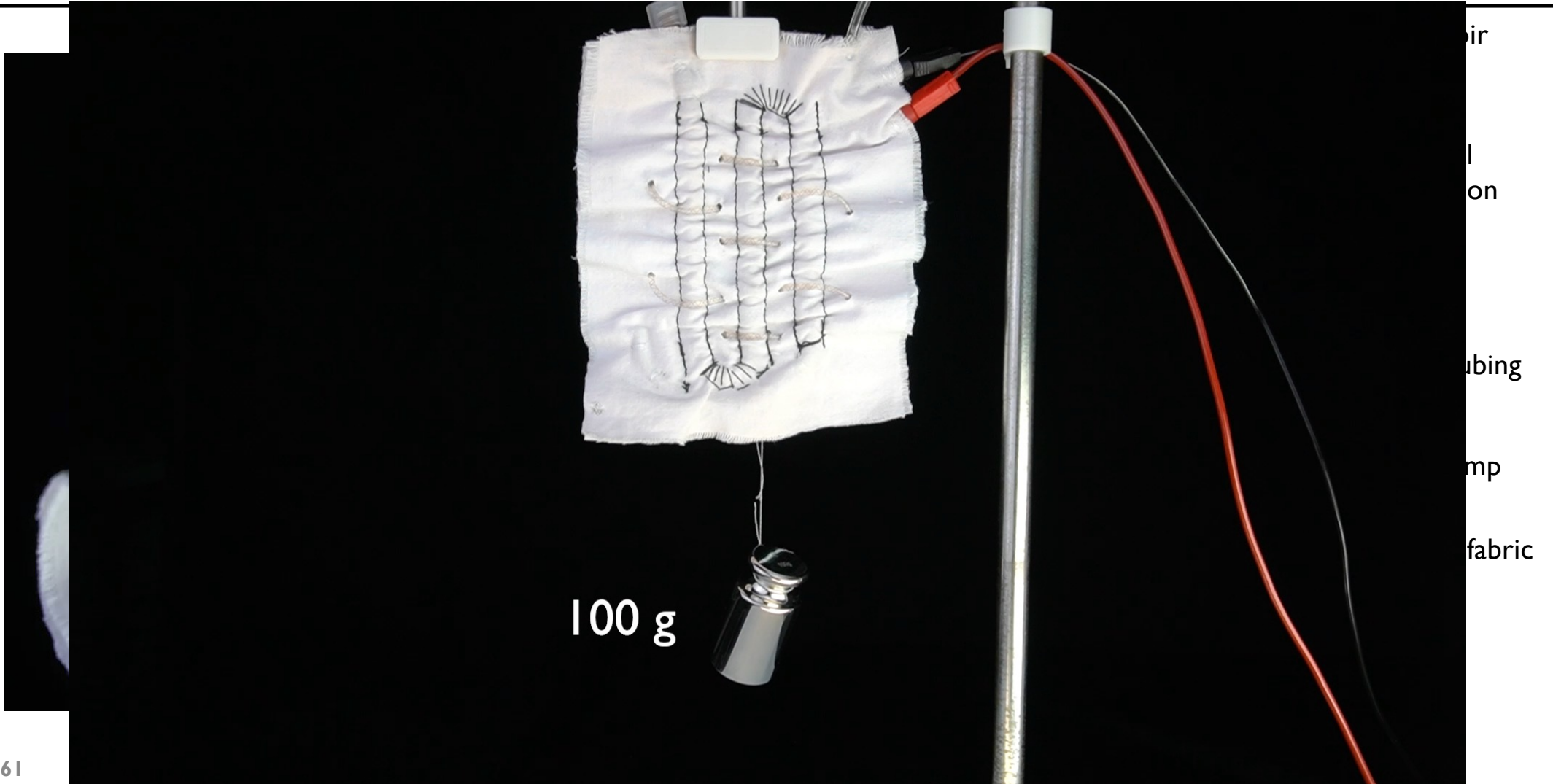
Fiber based actuators with integrated fiber pumps



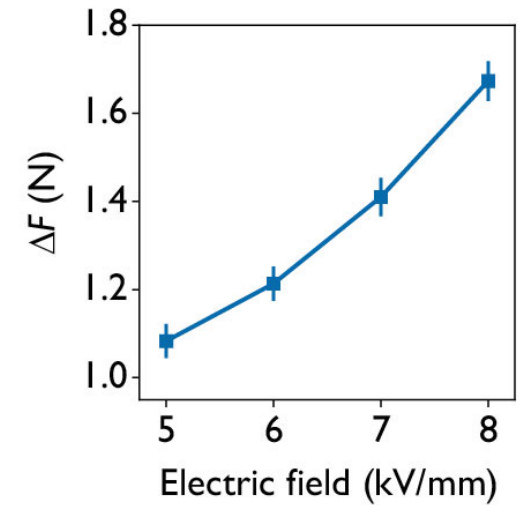
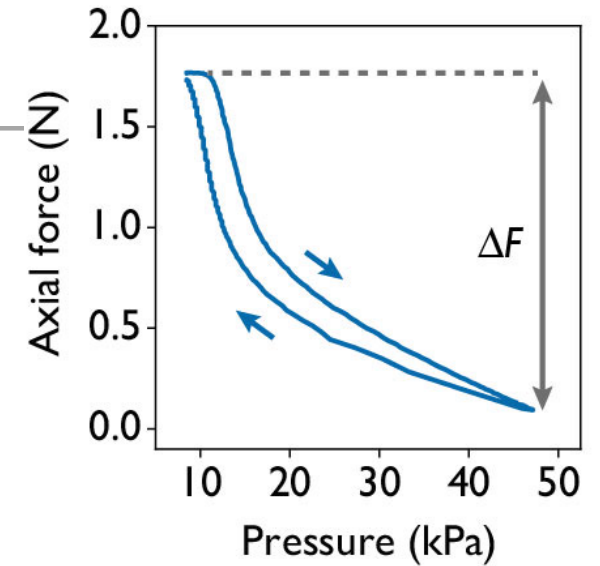
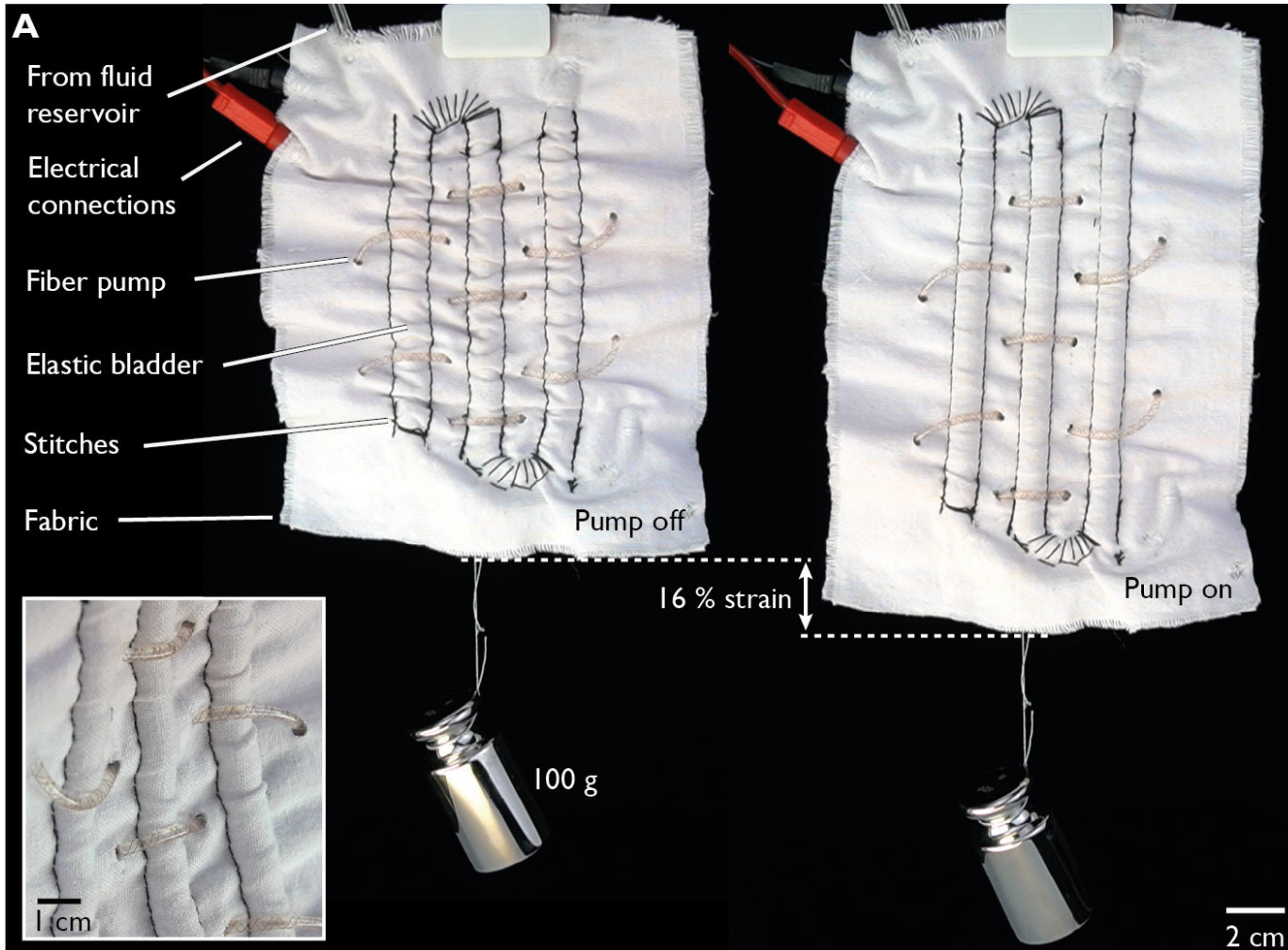
Fiber actuator response is fast, reliable and scalable



Fabric actuators operate on a similar principle to IPAM

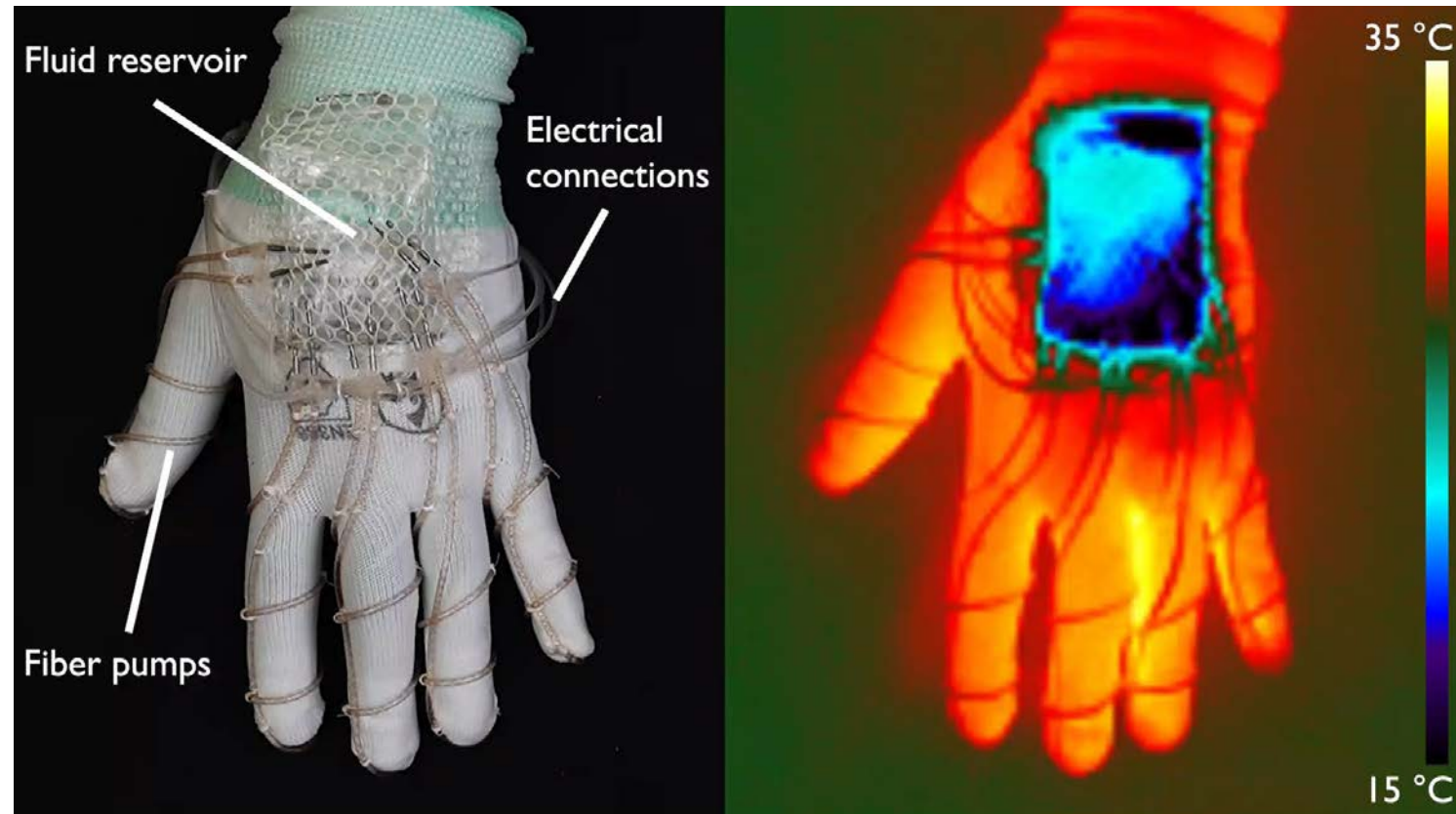


Fiber-pump in textile



Thermal haptic glove for immersive virtual reality

- Flexibility and stretchability of devices does not inhibit dexterity
- Distributed pumps allows each finger to be controlled independently
- Difficult to achieve using conventional pumps and equipment



Conclusions 1/2

- Many compelling use cases for haptics to
 - feel virtual worlds (training, surgery simulation, design, shopping, games), or
 - teleoperate (medical, industrial), or
 - add emotion to communication
- Haptic perception is highly subjective, individual, and changes over time
- Skin is mechanically complex. Skin surface is large
- By using haptic illusions and audio and video, we can reduce the requirements on actuators for highly immersive haptics
- Haptics can be added to many objects, or applied to the body

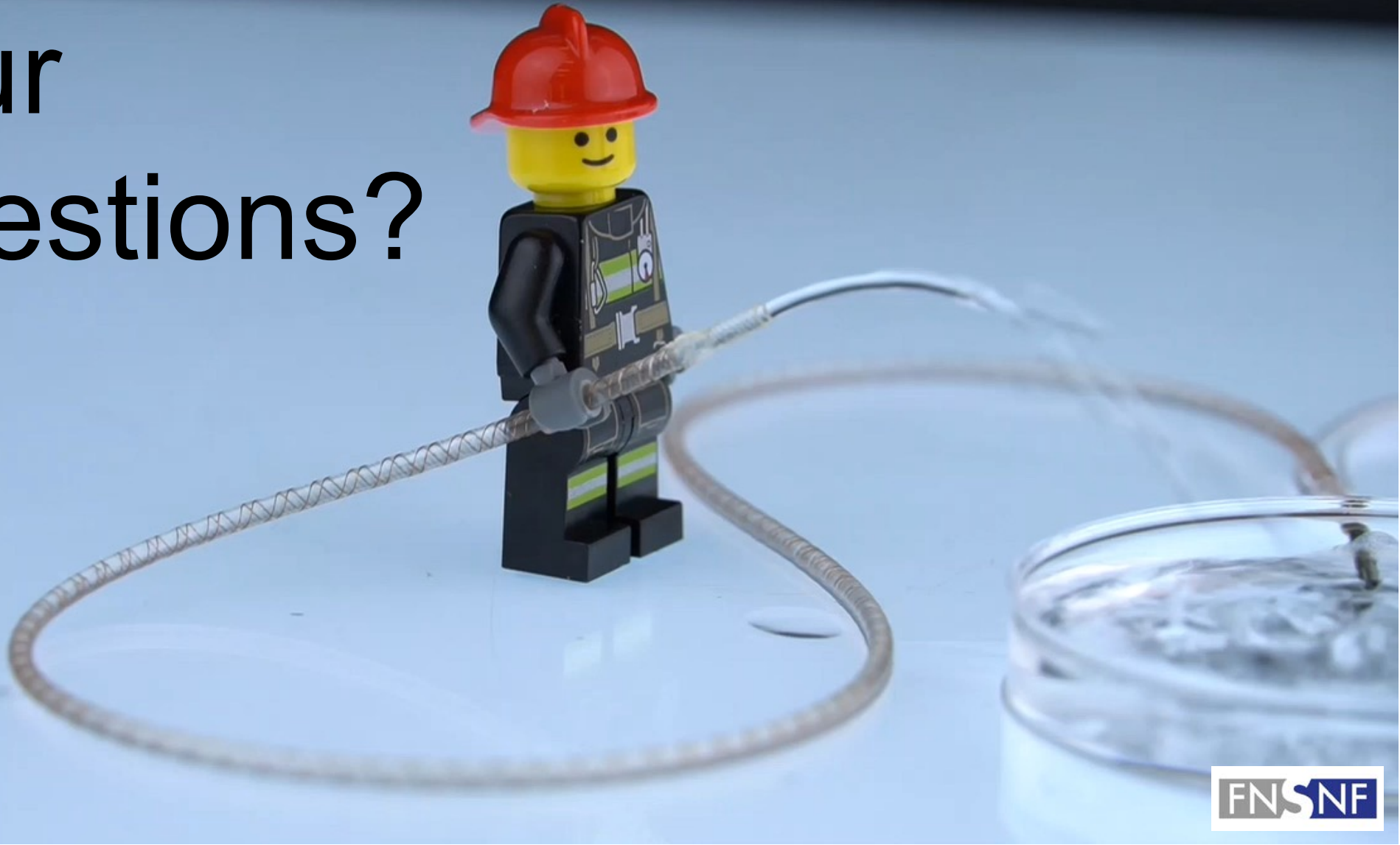


Conclusions / Outlook 2/2

- **Wearable** haptics challenges
 - Must be easy to put on and take off!
 - Should comfortably cover large parts of body, with hundreds of individual channels
 - Power, control and untethered operation
 - Need high force and high frequency from soft materials
 - Ultra-thin for on-skin mounting is intrinsically fragile
- Sensing ! Essential topic for closed loop operation
- Today, what works has either large external controllers (Haptx), or is mostly rigid. Hybrid?
- Social acceptance ? AR vs VR?



Your Questions?





Many thanks for your attention!

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