ENG-615: Topics in Autonomous Robotics

April 25 2023

Soft electrically-driven actuators for robotics and haptics

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EPFL-LMTS

Intro: actuators for soft robots

Electrostatic actuation

1. ES clutches
2. DEA
3. Zipping actuators
4. ElectroHydrDynamic (EHD) pumps

http://www.dailymail.co.uk/sciencetech/article-1032700/
Octopuses-given-Rubiks-Cubes-favourite-tentacle.html

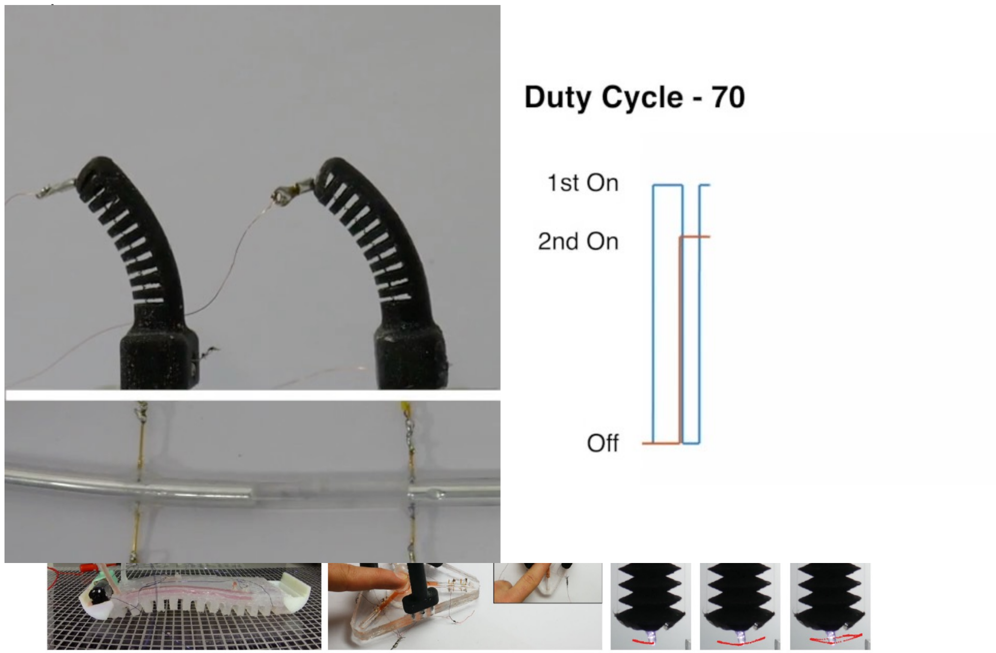
WHAT IS NEEDED TO MAKE A MACHINE SOFT, SMART, AND AUTONOMOUS?

EPFL

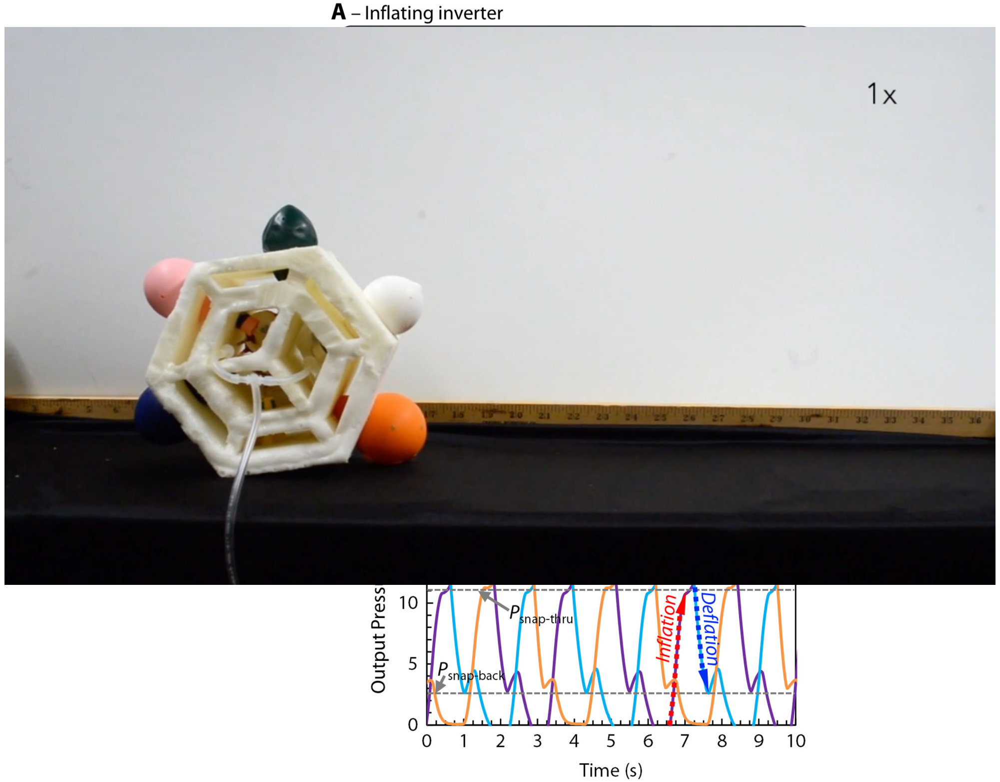
- Soft Distributed Sensors
- Soft Energy storage
- Soft Control & Computation
- Soft Actuators

Soft Computing

Include a nice Silicon CPU, or go all soft?

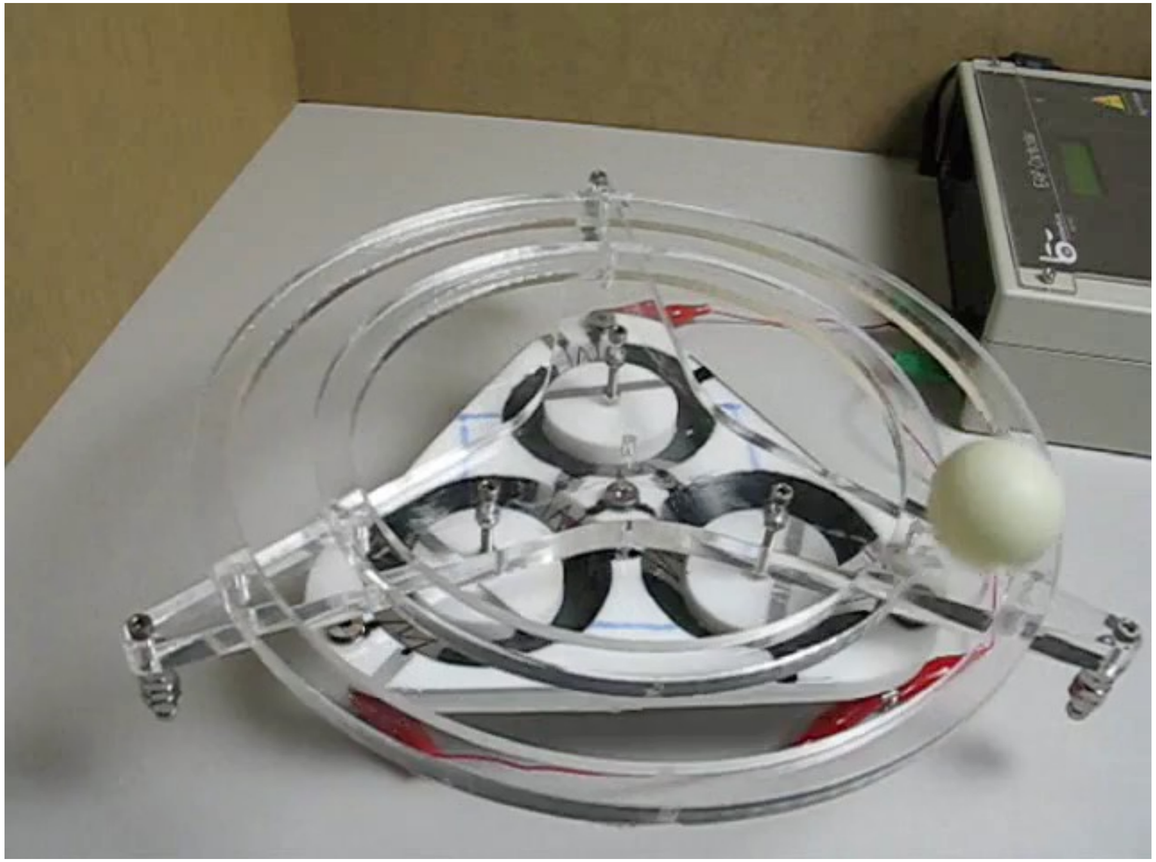


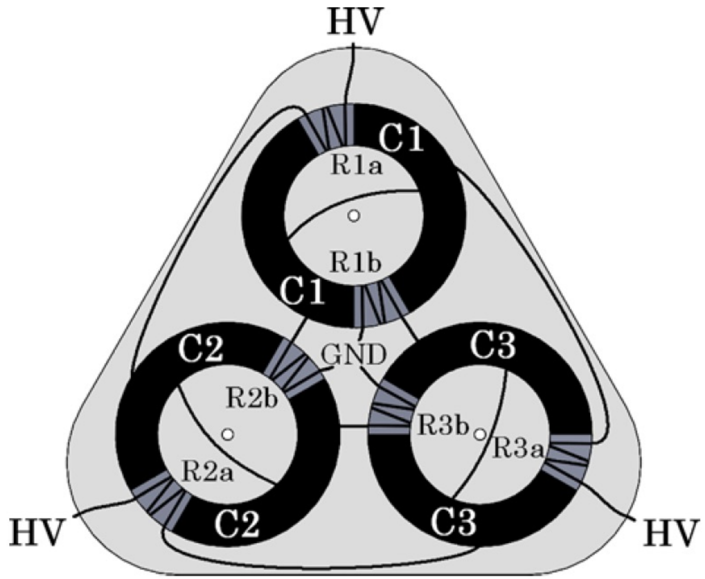
"Soft Matter Computer"
Garrad *et al*, Science Robotics 2019
Garrad et al, IEEE Robotics and Automation Letters 2021
https://doi.org/10.1109/LRA.2021.3068118



"A soft Ring Oscillator"
Preston et al. Sci. Robotics 2019

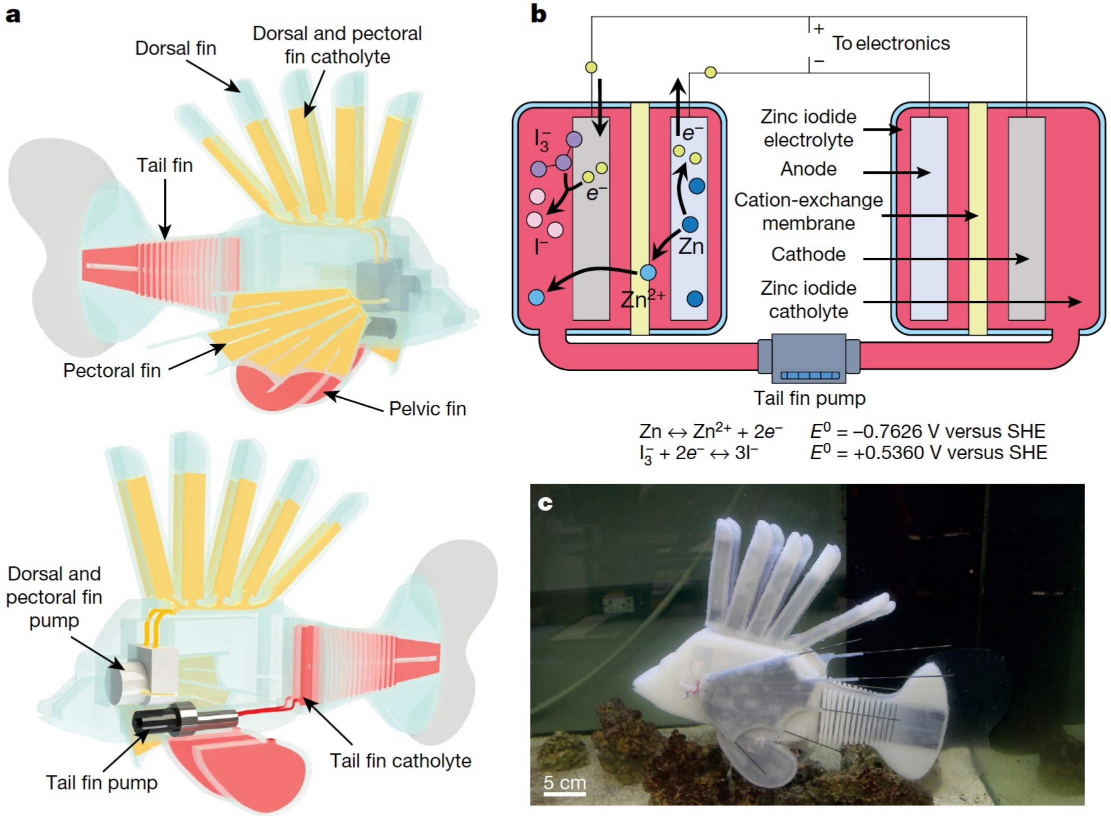
DEAs ring oscillator (self-sensing)





- O'Brien, B. M., Calius, E. P., Inamura, T., Xie, S. Q., & Anderson, I. A. (2010). Dielectric elastomer switches for smart artificial muscles. *Applied Physics A*, *100*(2), 385–389. http://doi.org/10.1007/s00339-010-5857-z

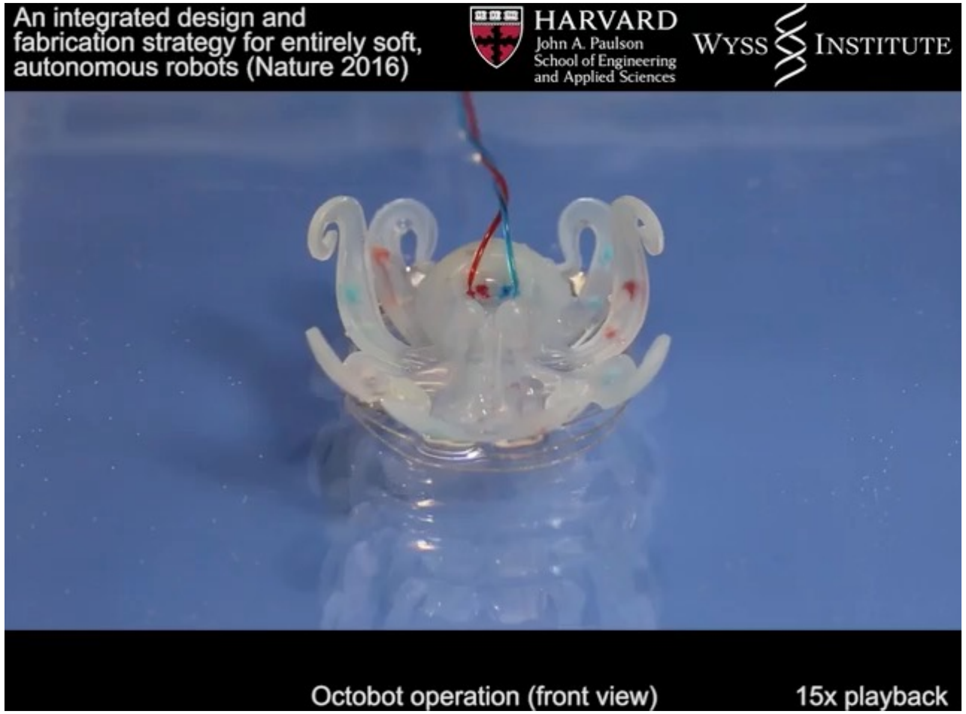
Soft & distributed Energy storage

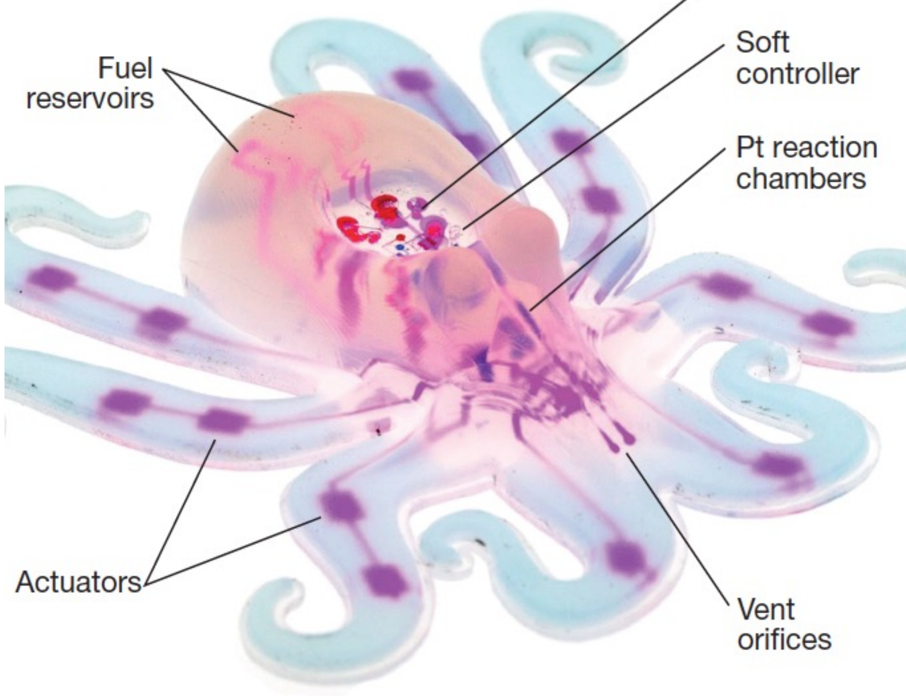


"Electrolytic vasculature"
Aubin *et al*, Nature 2019

"synthetic vascular system combines the functions of hydraulic force transmission, actuation and energy storage into a single integrated design that geometrically increases the energy density of the robot to enable operation for long durations"

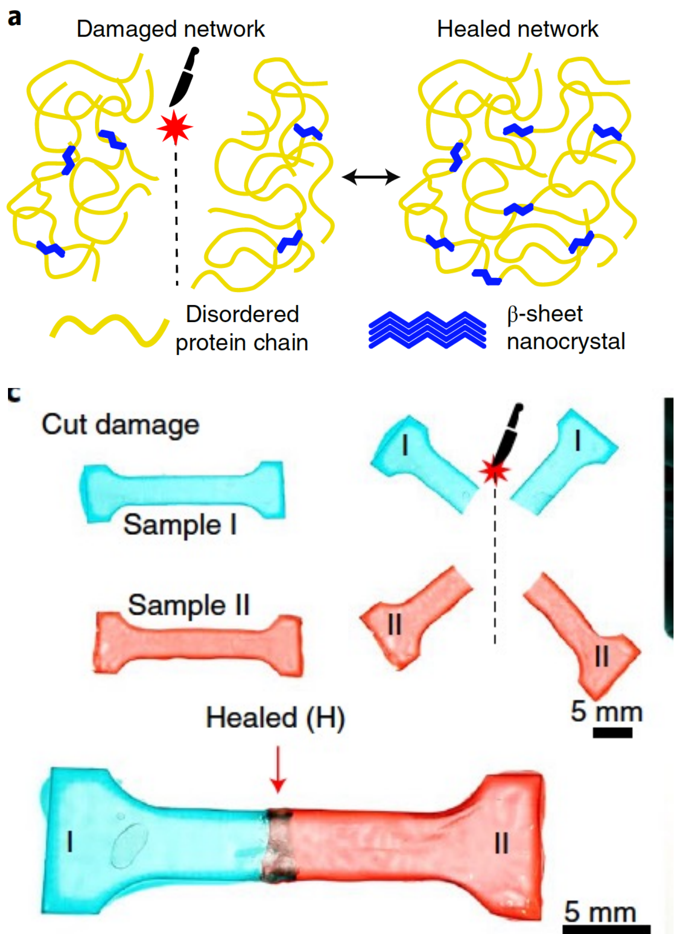
Fuel, control, actuators: all soft



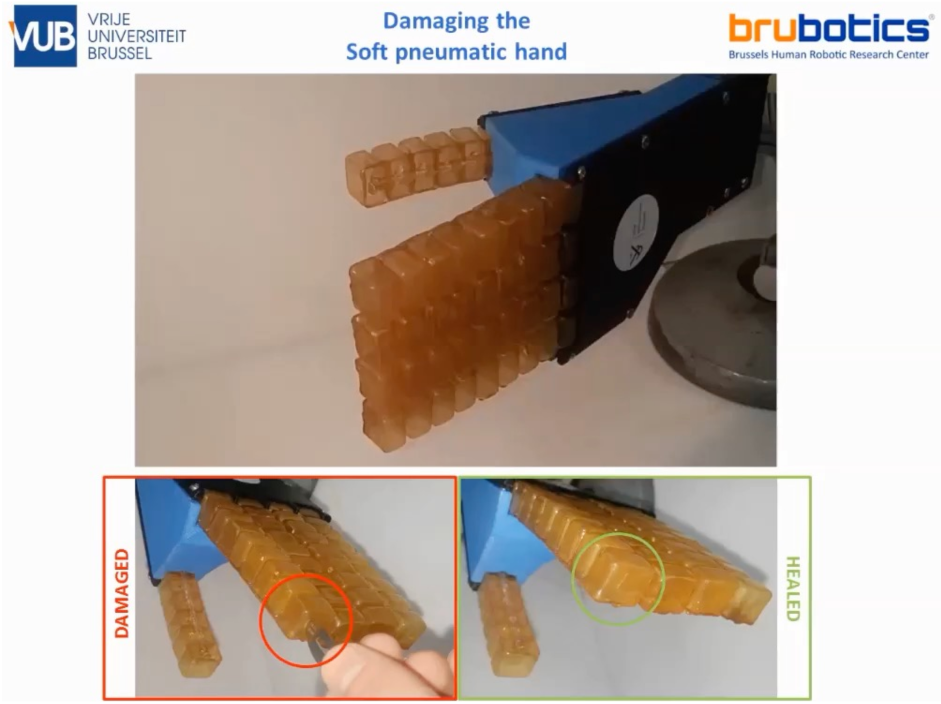


"Octobot" Wehner *et al*, Nature 2016

Self-healing soft materials



Pena-Francesch et al, Biosynthetic self-healing materials for soft machines. *Nat. Mater.* (2020), doi:10.1038/s41563-020-0736-2.



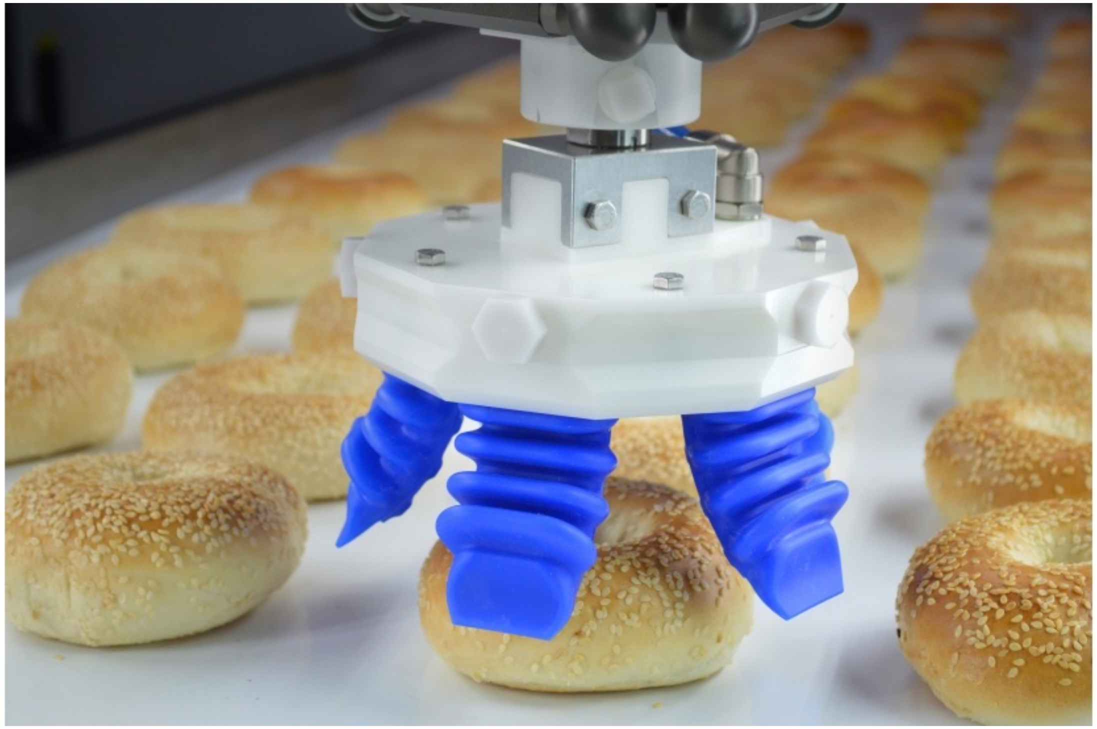
Diels-Alder polymers

S. Terryn et al, Self-healing soft pneumatic robots. *Sci. Robot* (2017).

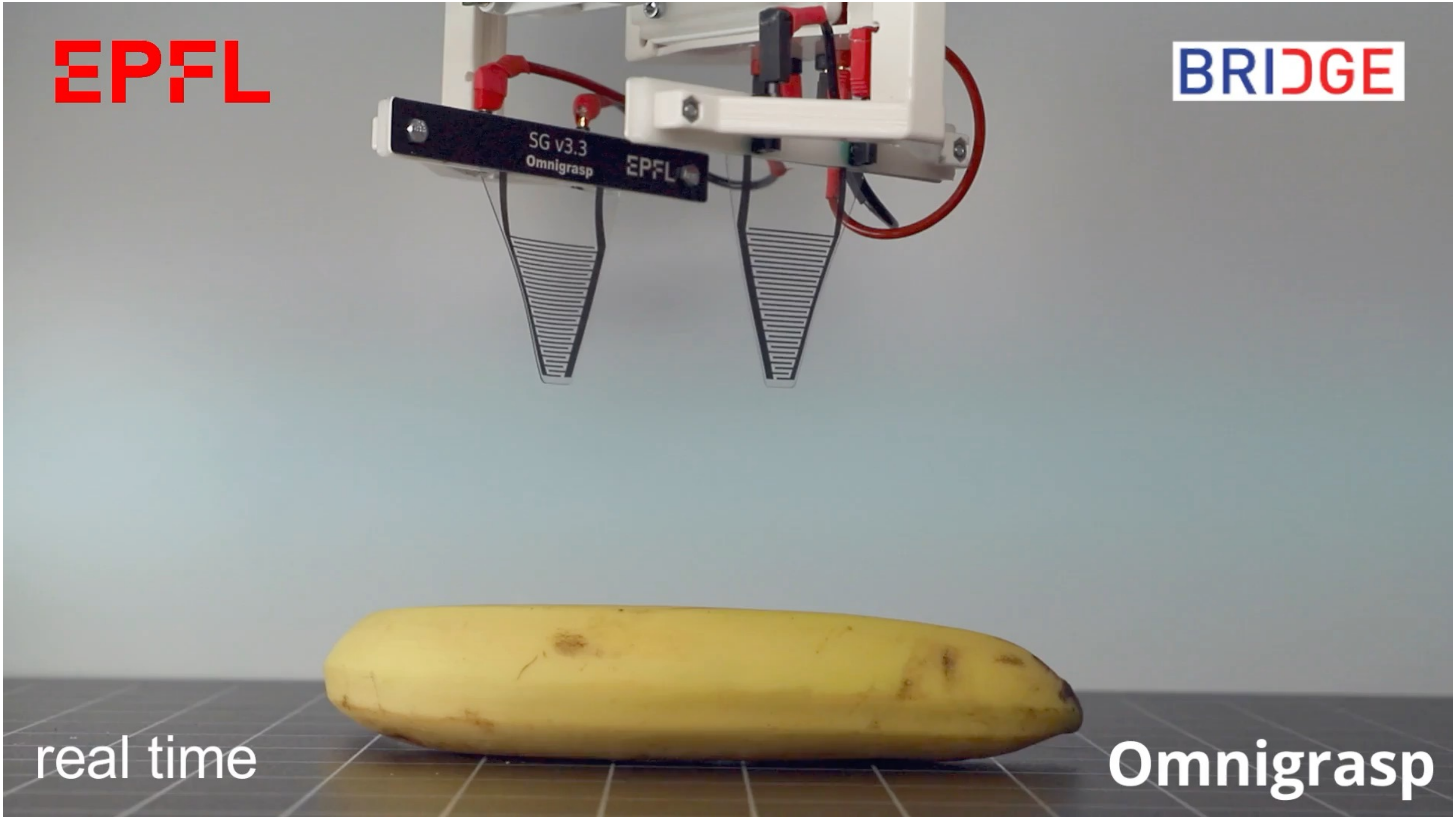
The key point of Soft machines is that they can change their shape

Ideally:

- Adapt their shape to match desired geometry
- Have sufficient mechanical stiffness to manipulate objects
- Hold their shape at zero power
- Are energy efficient
- Fast
- Simple to control



Soft Robotics Inc.


EPFL
BRIDGE
SG v3.3
Omnigrasp
EPFL
real time
Omnigrasp

WHAT IS NEEDED TO MAKE A MACHINE SOFT, SMART, AND AUTONOMOUS?

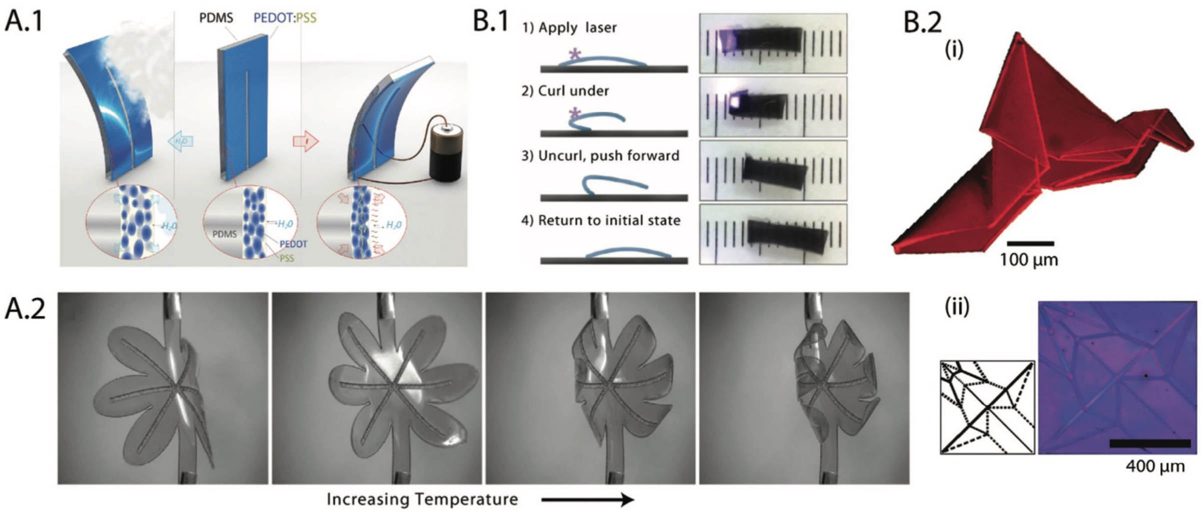
EPFL

- Soft Distributed Sensors
- Soft Energy storage
- Soft Control & Computation
- Soft Actuators

Soft Actuators: there is a very broad range of physical principles and materials

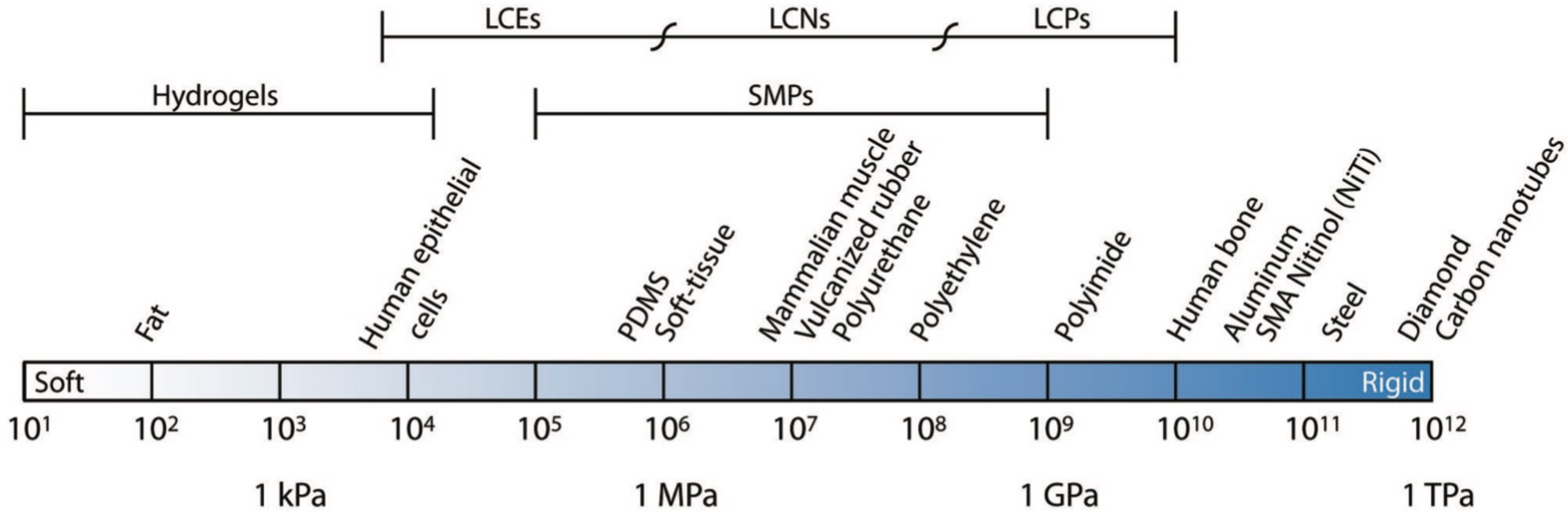
- Soft actuator
  - Electrically driven
    - DEA, zipping ES,
    - LCE
    - Ionogels
    - Ionic-polymer–metal composites (IPMCs)
    - Electrorheological fluid (ERFs)
    - Piezo
    - EHD- EWOD
  - Thermal phase change
    - Shape Memory Alloy (SMA),
    - Shape Memory Polymer (SMP)
    - Carbon nanotube (CNT) sheets, yarn
  - Pneumatic
  - Magnetic
  - Twisted yarns
  - Hygromorphic polymers
  - …..

- Materials
  - Often Elastomers
  - Liquid metals
  - So many options !



Good review on small scale soft actuators:
Hines et al, Adv. Mater. 2017, 29, 1603483

M. Zhu, S. Biswas, S. I. Dinulescu, N. Kastor, E. W. Hawkes, Y. Visell, "Soft, Wearable Robotics and Haptics: Technologies, Trends, and Emerging Applications". *Proceedings of the IEEE*, 1–27 (2022).



Hines et al, Adv. Mater. 2017, 29, 1603483, 2016

We want high:

- Strain & force

- force density
- power density
- energy density

- Speed

We also want high:

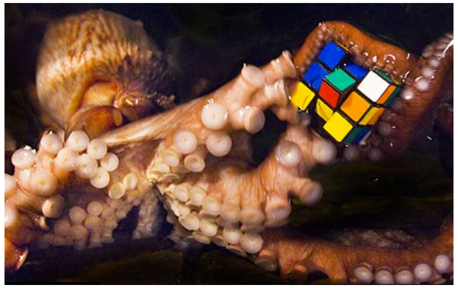
- Reliability
- Lifetime

- Energy efficiency

- Ease of integration
- Control: accuracy, simplicity

- Robust & reproducible manufacturing process

- Invisible power supply



SOFT ACTUATORS FOR SOFT MACHINES

EPFL

- Need (simultaneously!) high:
  - strain
  - force density
  - power density
  - energy density
  - speed
  - energy efficiency
  - reliability
  - easy integration
  - manufacturable

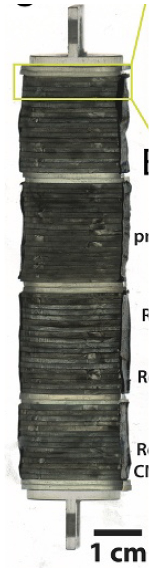
Table 1 | Comparison of soft actuation methods relevant to applications in untethered robots

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

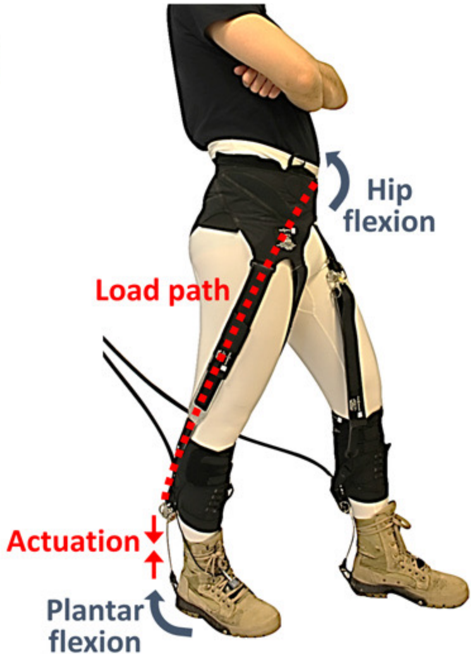
Rich, S. I., Wood, R. J. & Majidi, C. Untethered soft robotics. *Nature Electronics* **1**, 102–112 (2018).

Trade-offs …. Actuator choice depends on application

- Power consumption vs. work done
  - Eg, is a thermal actuator (eg SMA) a good solution to hold a fixed actuated position?
- Untethered (don't care about power supply) vs. wearable or untethered
  - Energy efficiency
  - Size of power supply
- Strain vs lifetime
  - Longer lifetime means lower force/strain
- Manufacturability

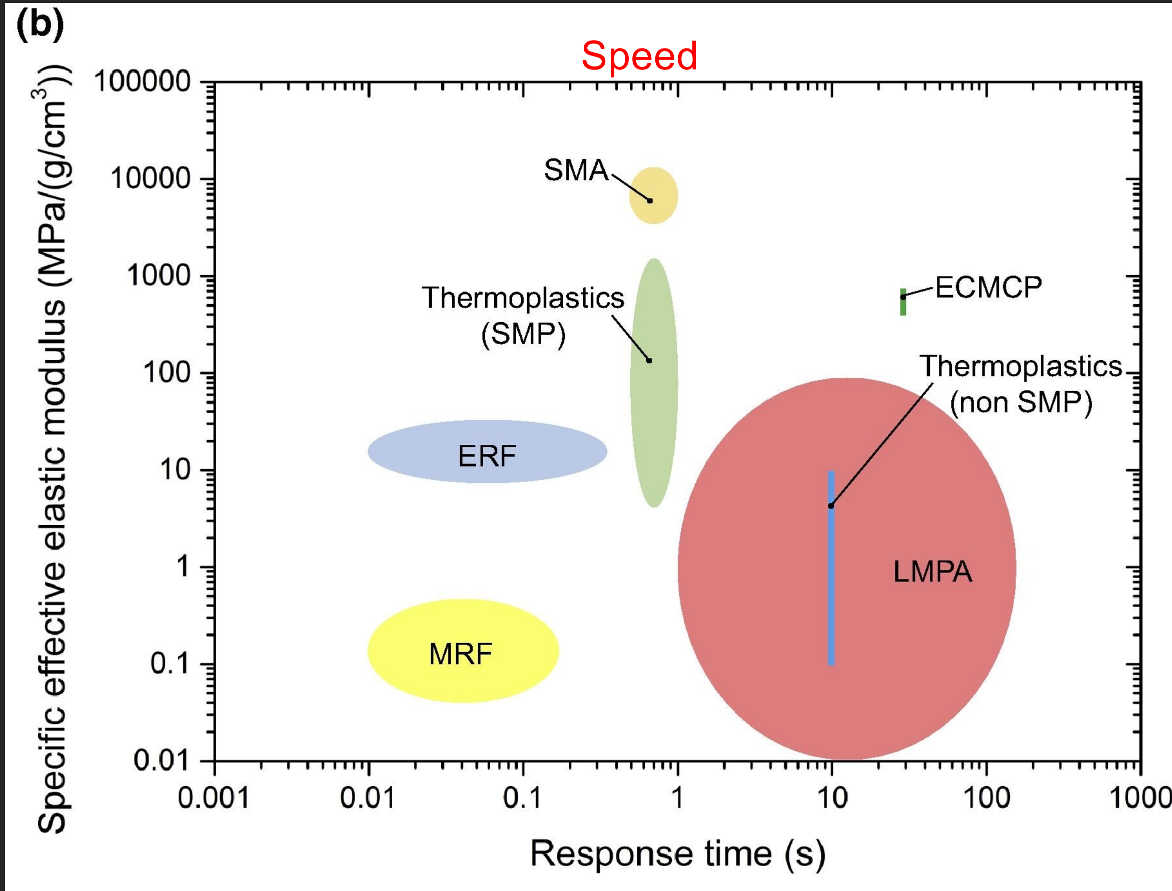


M. Duduta, Harvard



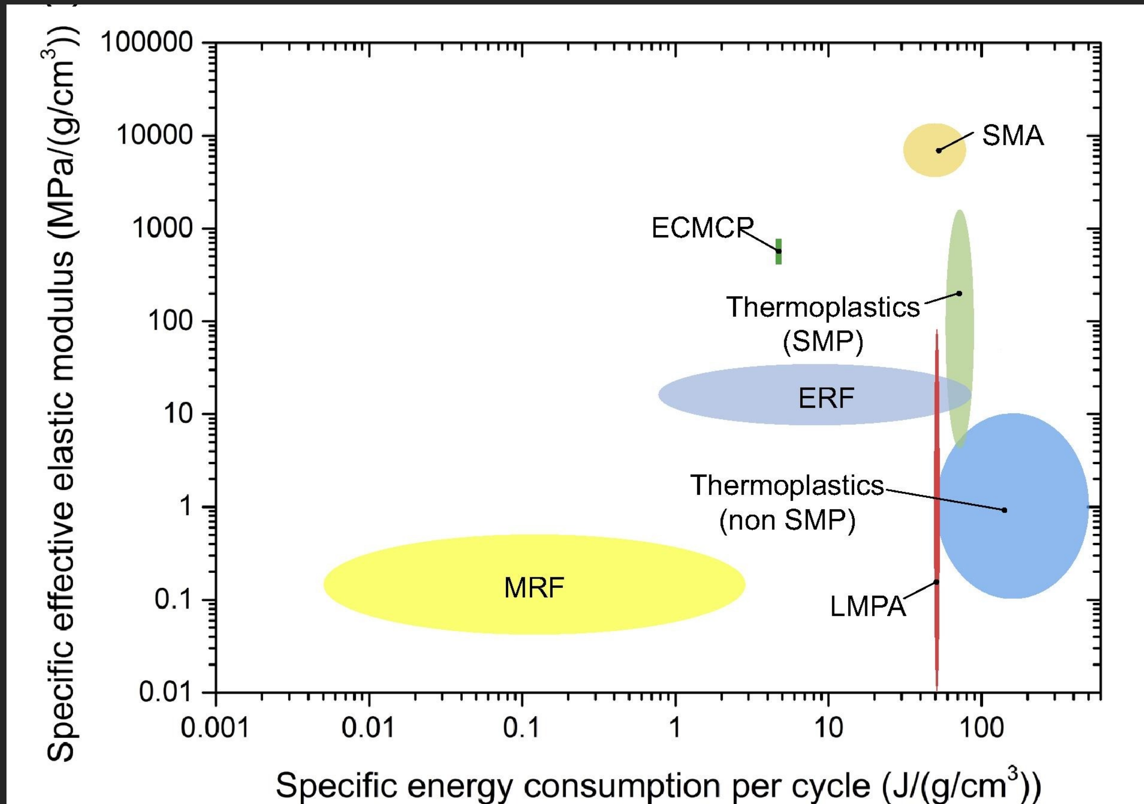
C. Walsh, Harvard

Materials that can dynamically vary stiffness



Wang, L. *et al.* Controllable and reversible tuning of material rigidity for robot applications. *Materials Today* **21**, 563–576 (2018).

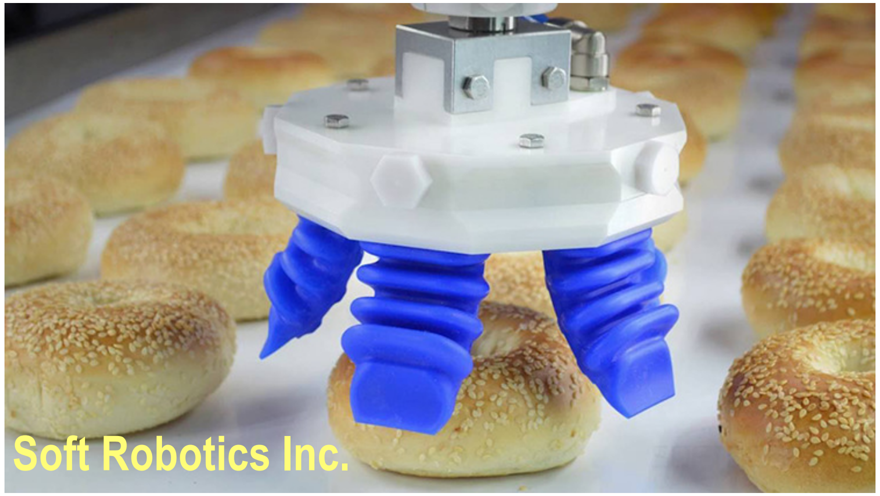
Energy considerations

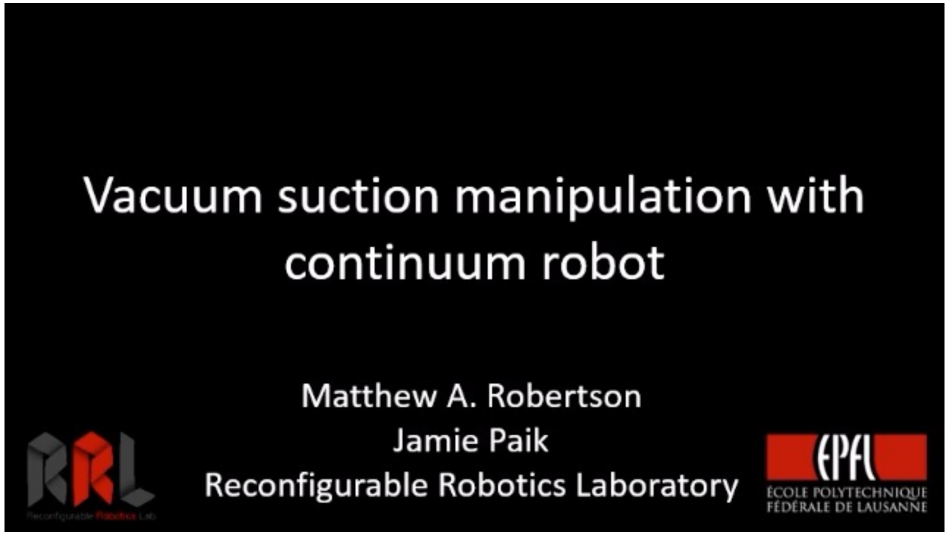


Wang, L. *et al.* Controllable and reversible tuning of material rigidity for robot applications. *Materials Today* **21**, 563–576 (2018).

How can we make effective artificial muscles?

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





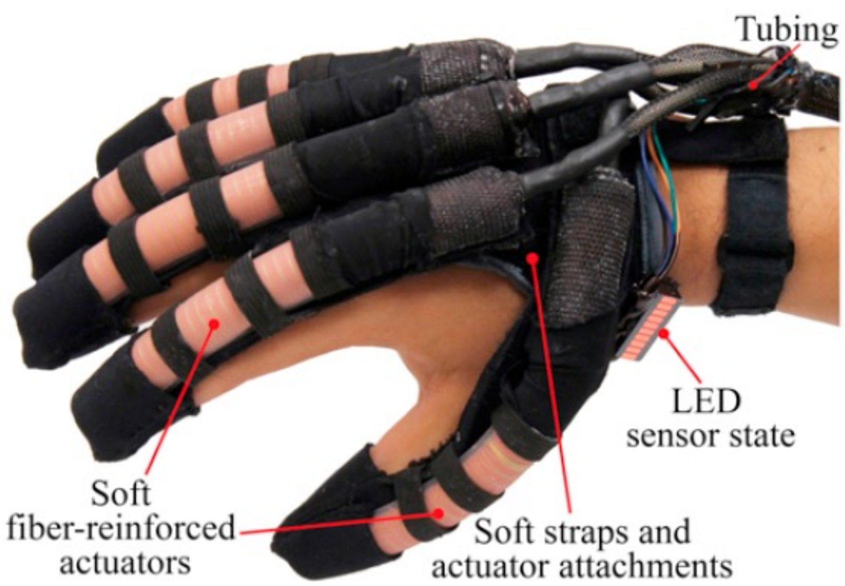
Robertson & Paik, Science Robotics (2017)

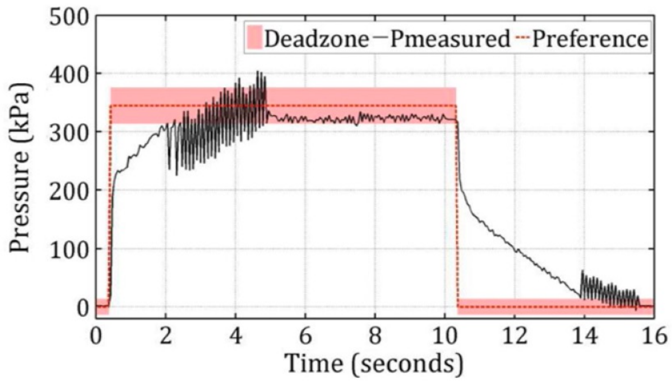
Pneumatic actuation can directly allow for high forces

Li et al, PNAS 1713450114 (2017)

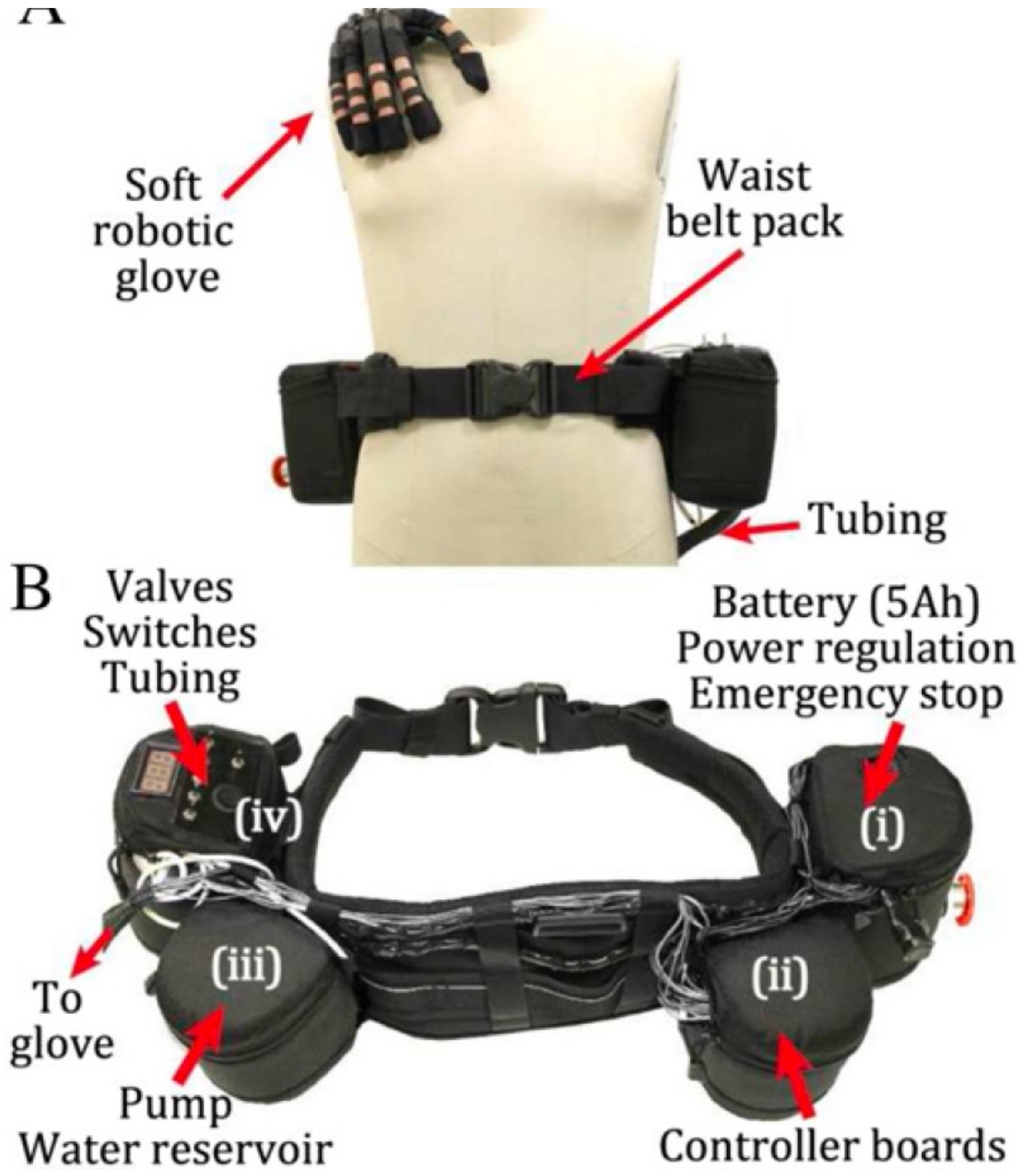
Suzumori lab, Tokyo Tech

But need to keep compressor running…



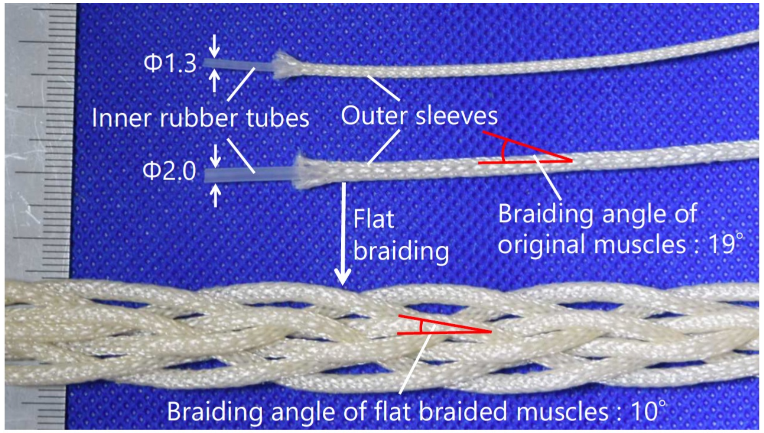


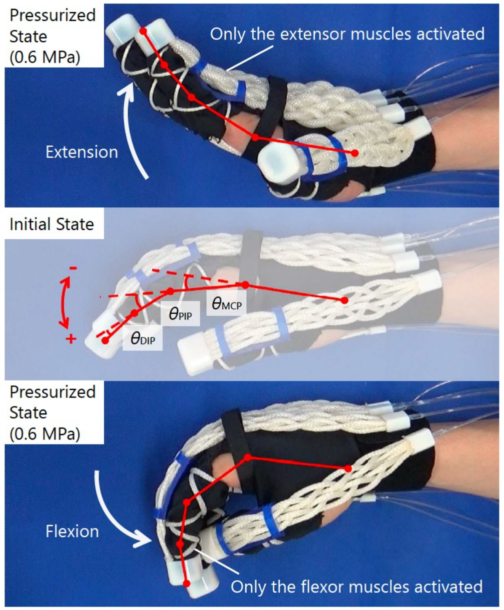
P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, “Soft robotic glove for combined assistance and at-home rehabilitation,” *Robotics and Autonomous Systems*, vol. 73, pp. 135–143, Nov. 2015



Beltpack: 3.3 kg

Thin McKibben actuators





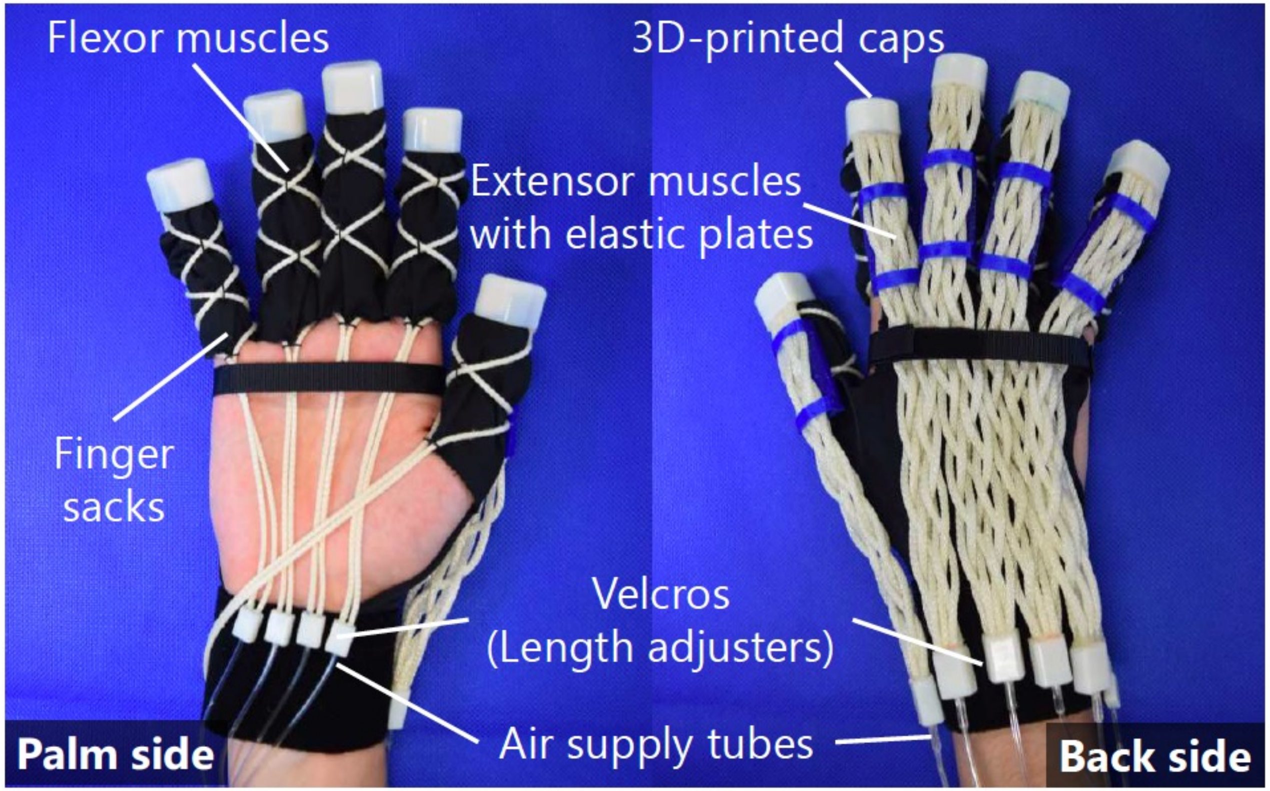


Fig. 2. Overview of soft robotic glove with thin McKibben muscles (64.7 g without air supply tubes, 10 DoF)

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.

Pneumatics are great, but they are tethered

Meta/ Facebook Reality Labs

Many good (soft?) actuation principles

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

Combining different operating principles can have major advantages

Some Criteria for choosing

- Scaling arguments
- Soft materials
- Energy + Power density
- Force density
- Power supply + Size of external controller

I will focus on soft actuators using **electrostatic** forces because

- Directly use electricity (no compressor)
- Fast
- High force + power density
- Energy efficient

- But requires high voltages and has materials challenges

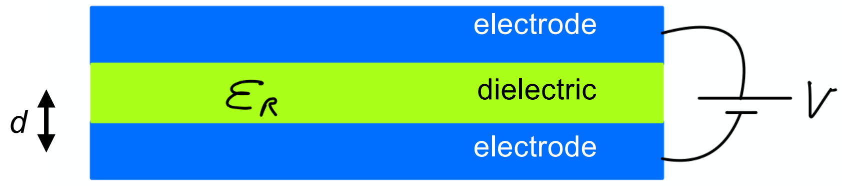
https://www.hildebrand-technology.com/en/know_how/electrostatic

ELECTROSATIC FORCES AND ACTUATORS

Parallel plate electrostatic actuator (generic)

- Normal electrostatic force for an applied voltage V:

$$F_{ES} = \frac{1}{2}\varepsilon_0\varepsilon_r A E^2$$



- **Maximum energy density and force are given by breakdown field E_{BD} and permittivity ε_r**

$$w_{ES} = \frac{1}{2}\varepsilon_0\varepsilon_r E^2$$

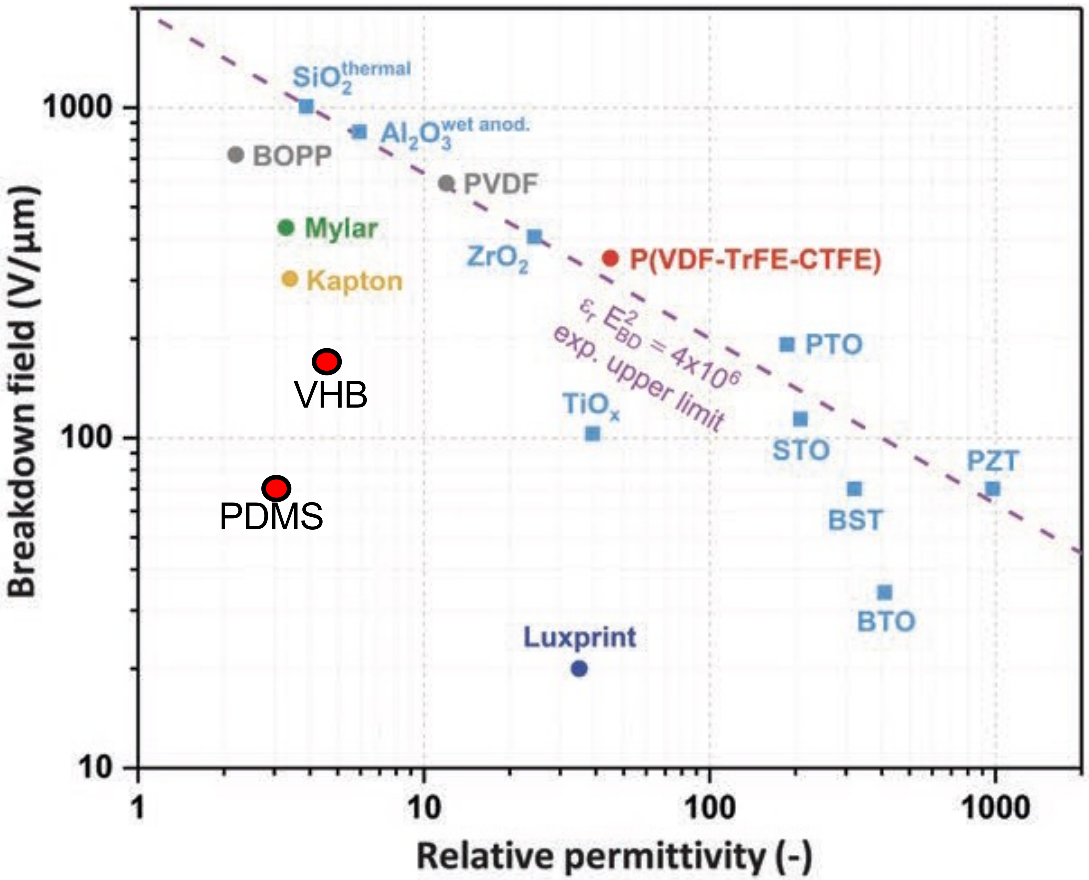
E=electric field, *V*=voltage,
d=insulator thickness, *A*= electrode area
ε_0 = permittivity of free space
ε_r = relative permittivity

What soft materials to choose?
- Good electrical performance

and

- Good mechanical performance (eg **soft** and robust)

There is an empirical upper limit to $\varepsilon_r . E_{BD}^2$ product

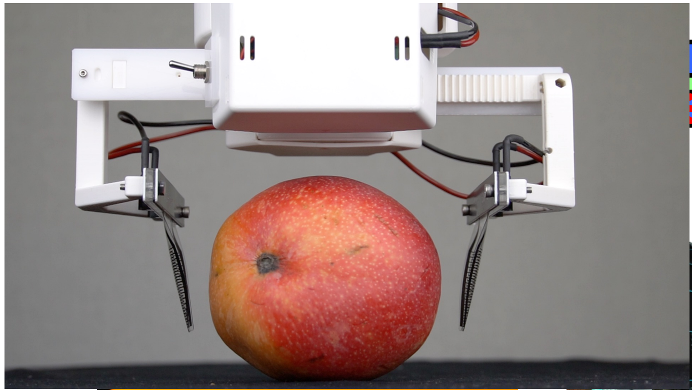


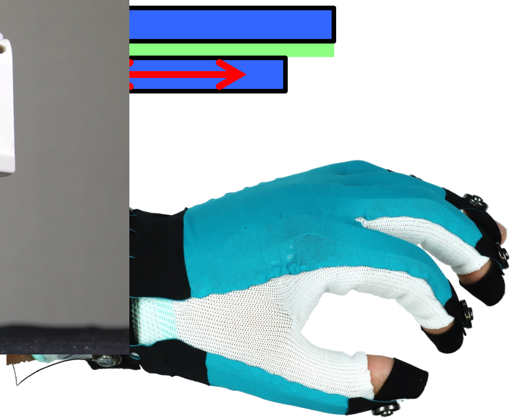
- Want materials with high ε_r and high $E_{breakdown}$
- But softer materials have lower breakdown field…
  - Elastomers typically have E_{DB} 100 V/µm,
  - SiO_2 has E_{DB} 1 kV/µm

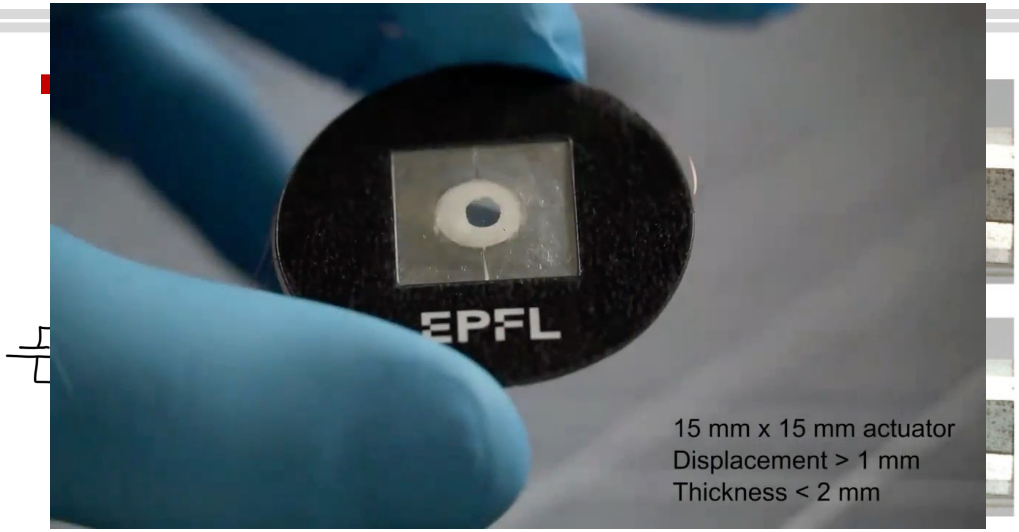
$$w_{ES} = \frac{1}{2}\varepsilon_0 \varepsilon_r E^2$$

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

Four ways we use electrostatic forces in flexible systems







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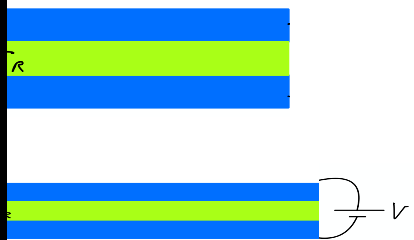
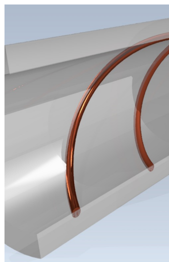
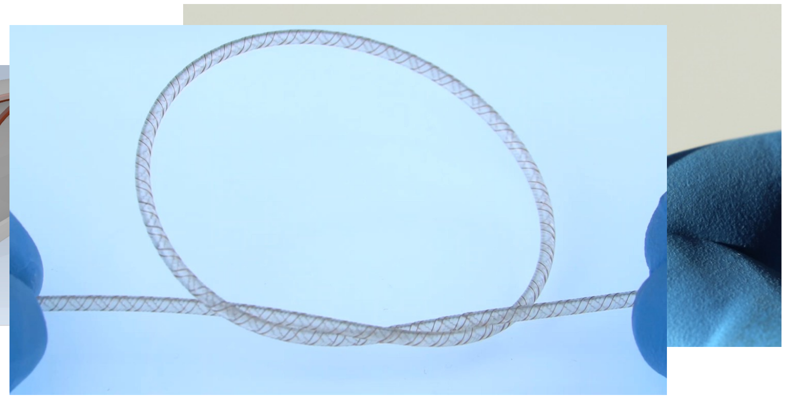


- **Pumping (EHD)**





HAPTICS

Very short intro

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)

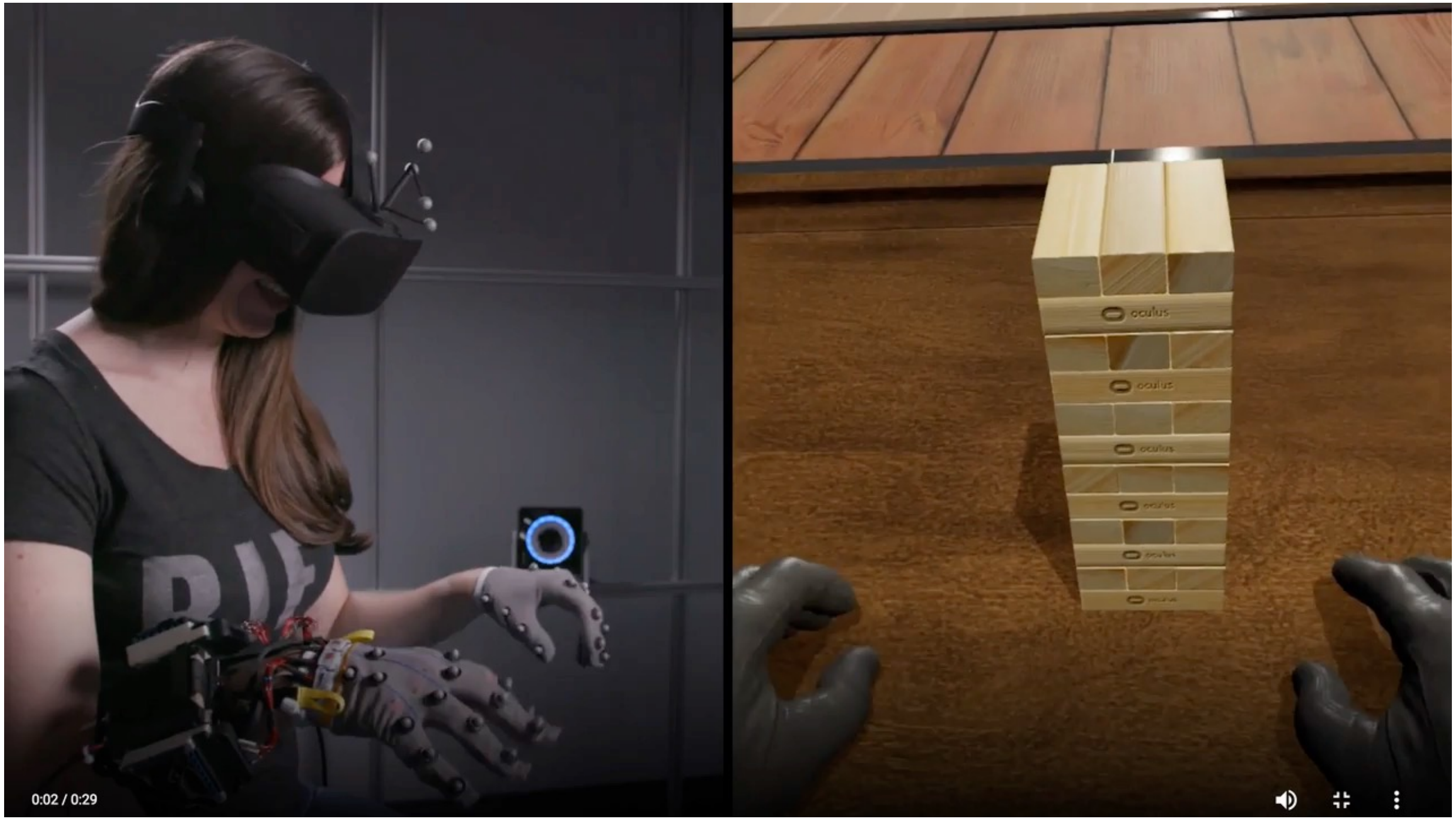
Ankit, T. Y. K. Ho, A. Nirmal, M. R. Kulkarni, D. Accoto, N. Mathews, Soft Actuator Materials for Electrically Driven Haptic Interfaces.
Advanced Intelligent Systems, 2100061 (2021).

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*



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

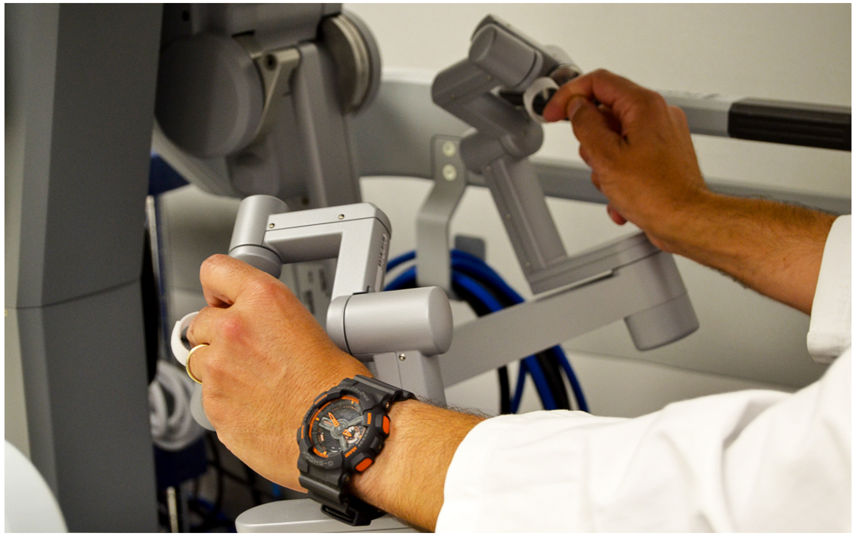
Facebook Reality Labs

Missing:

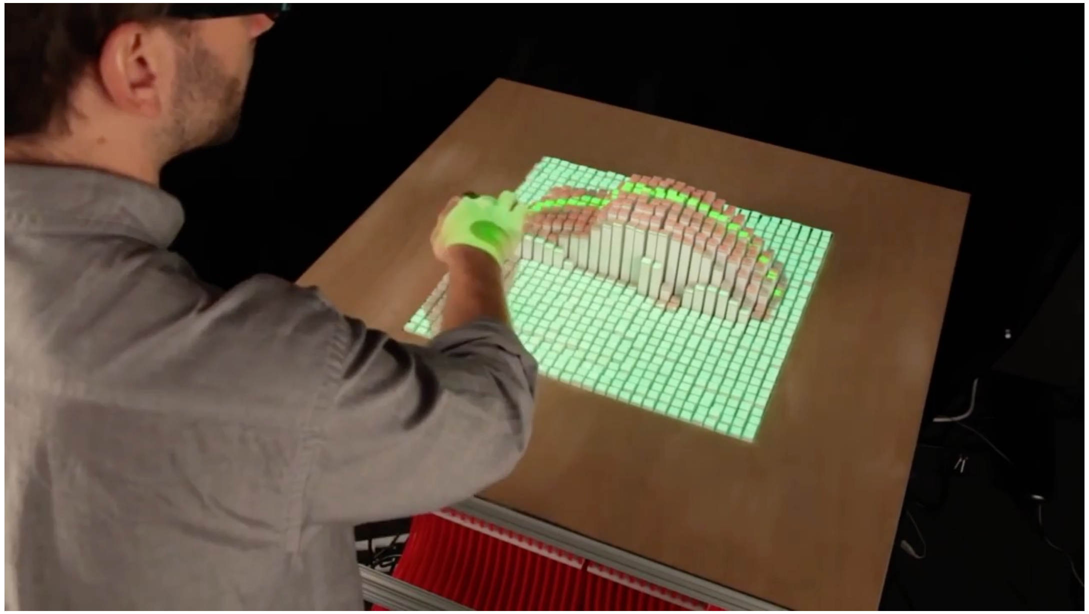
- blocking fingers to make objects feel solid,
- sense of touch beyond buzzers

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

Wearable actuators are even more challenging to develop!



[Da Vinci,
by Intuitive Surgical]



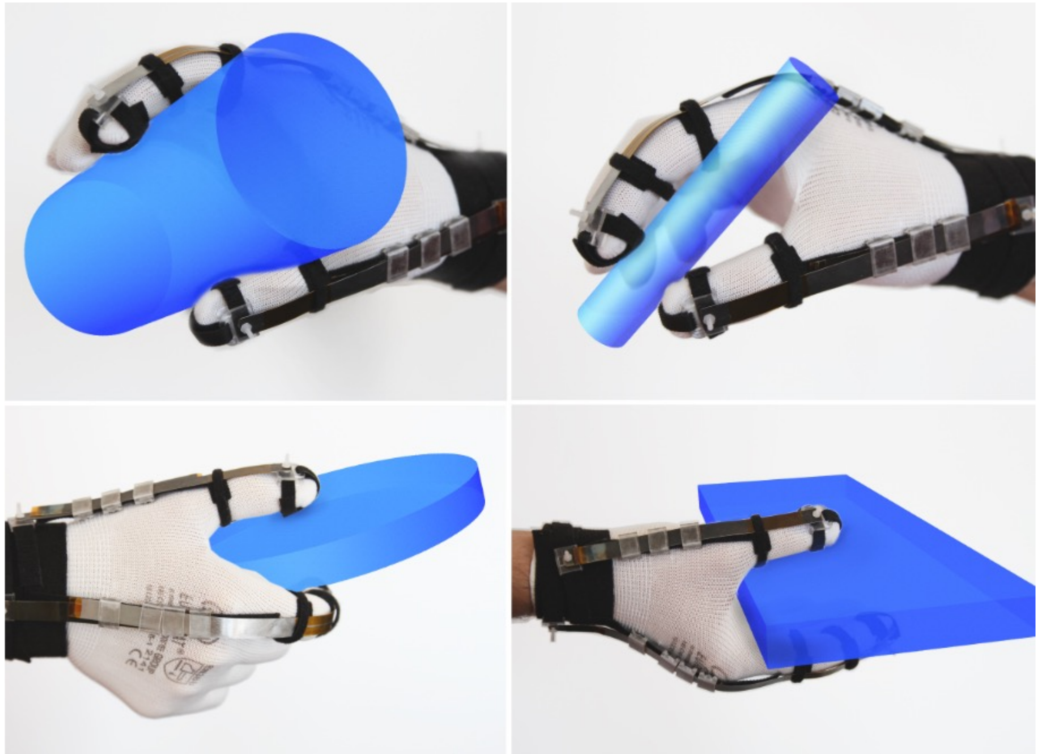
[MIT Media Lab:
Tangible - InForm]

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

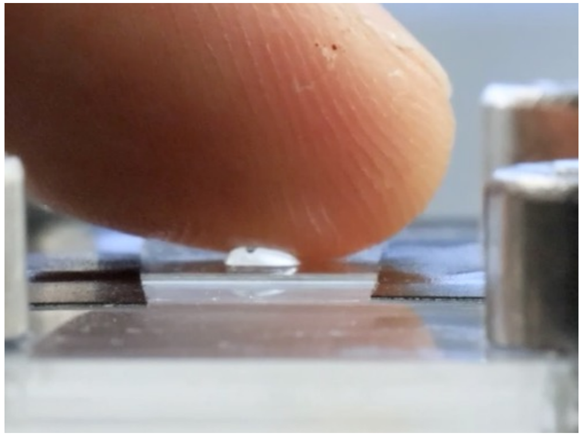
1. <u>Kinesthetic</u> : control joint motion
Feel hardness of a virtual object: block finger from penetrating

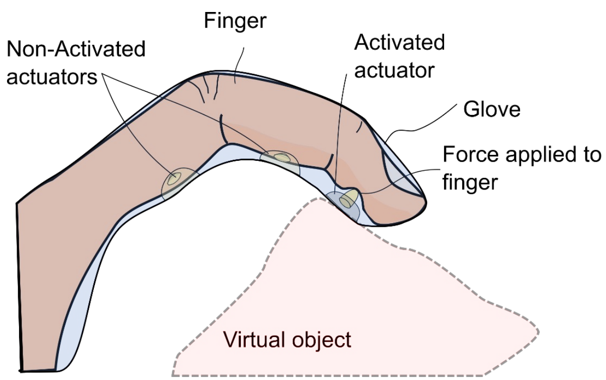
AND

2. <u>Cutaneous</u>:
Feel surface of a virtual object



DextrES: doi:10.1145/3242587.3242657





Real versus Virtual

Kinesthetic feedback to avoid interpenetration

EPFL

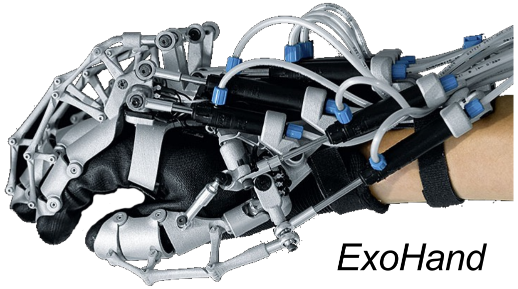
2007: Cables

Electric **motor** & tendons

Electric **motor** + tendons

Pneumatic exoskeleton

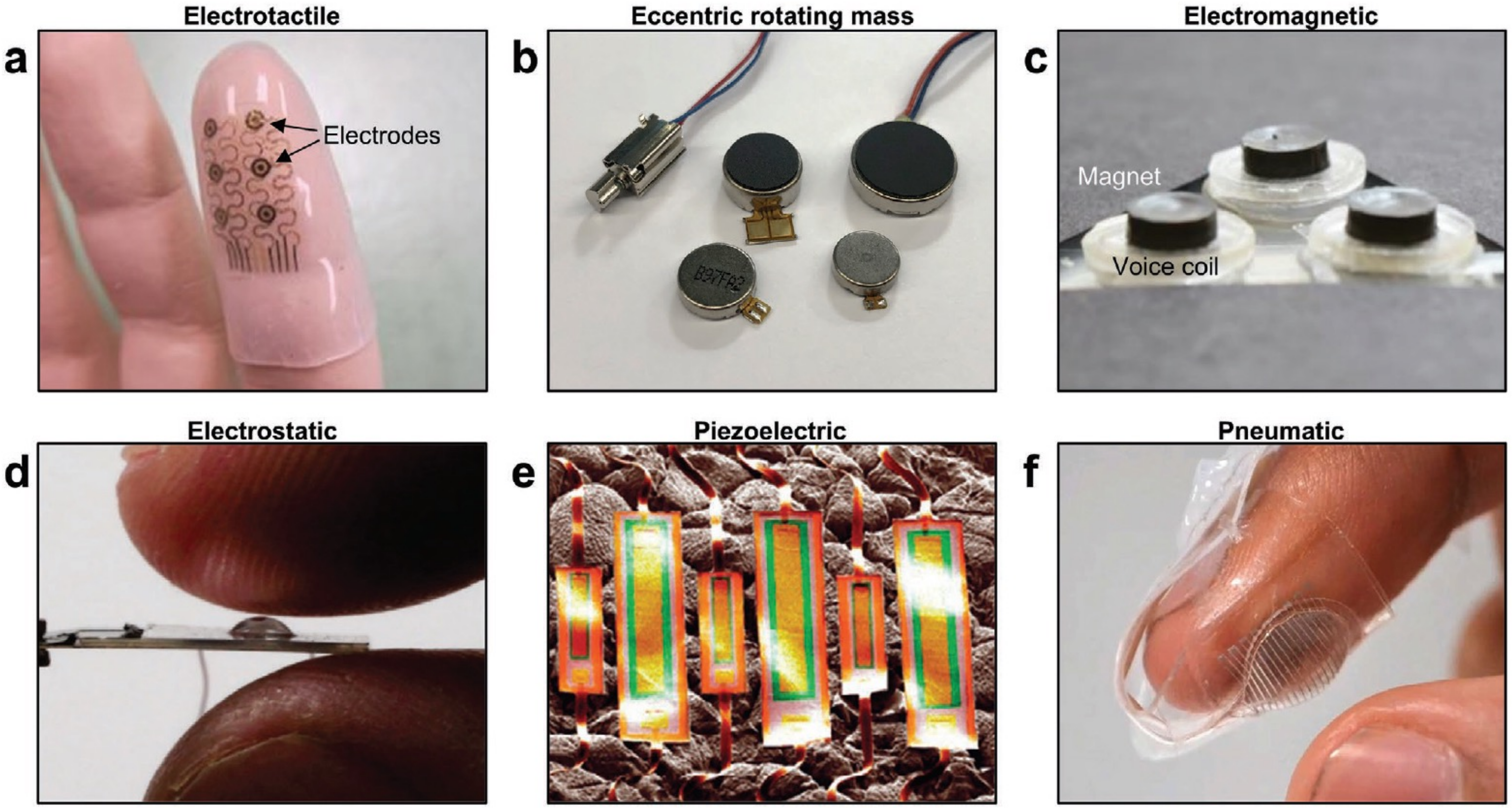
Hydraulic exoskeleton



Electric **motor** exoskeleton

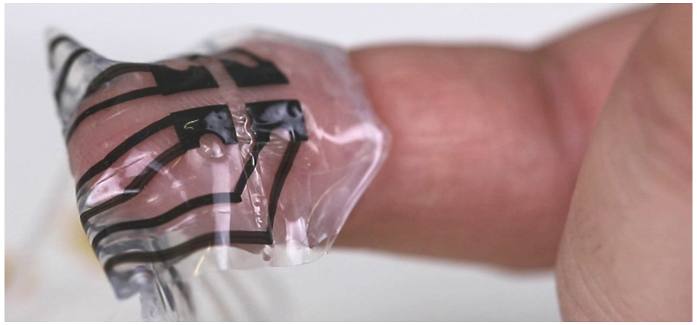
Want a slim form-factor, dense, fast, easy to don/doff, no large controller

Many ways to make wearable cutaneous haptics



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

Wearable Cutaneous haptics conforming to the skin



Tactile perception on fingertip:

- Threshold for *static:* 100 µm and 10 mN
- Threshold for vibration at 200-300 Hz: 0.1 µm
- 3 mm two-point threshold

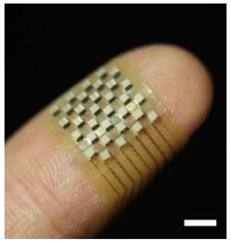
From the literature:

Pneumatics

(H. Sonar, Adv. Intel. Sys, 2021)

slow

Piezoelectric



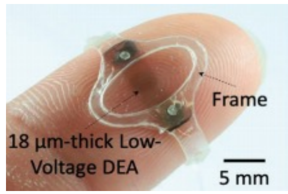
(Jin et al., npj Flex. Electron., 2022)

Electro-tactile

(Withana et al., ACM User Interface, 2018)

Only vibration (> 100 Hz)

DEAs



(Ji et al., Adv. Funct. Mater., 2021)

Low lifetime

Zipping Actuators

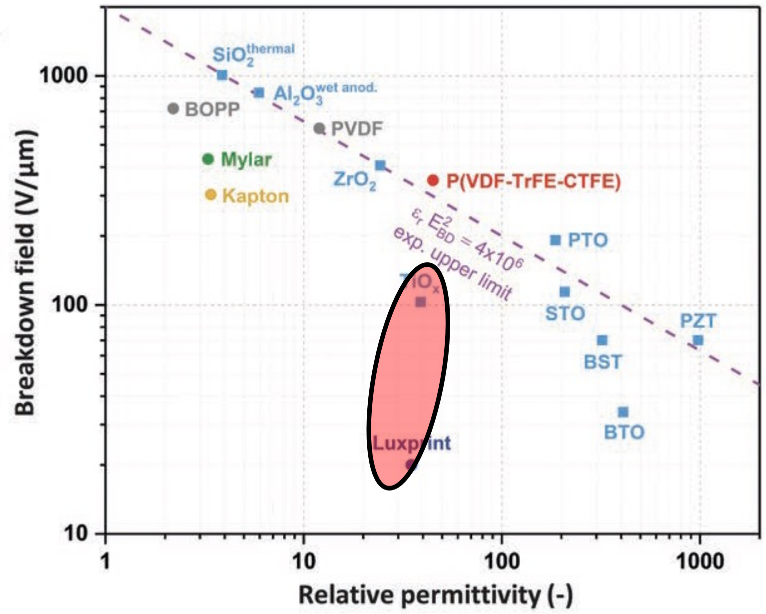
(Leroy, Adv. Mater., 2020)

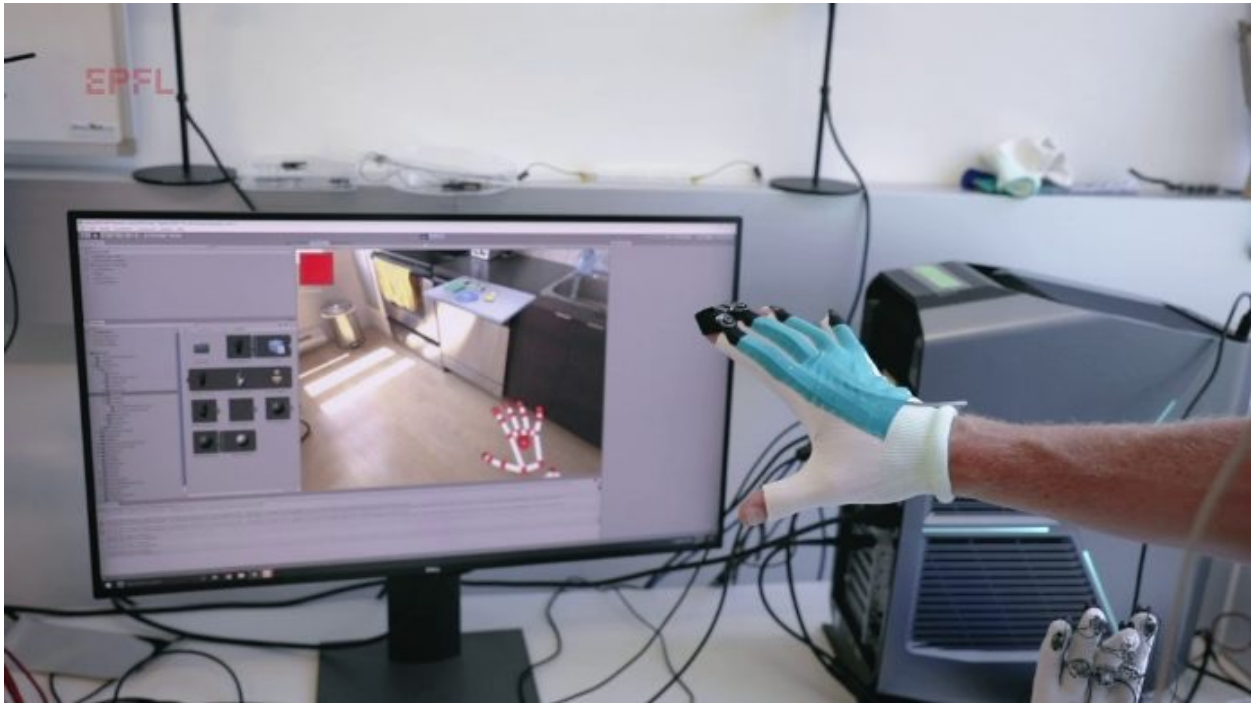
Too stiff

1. SLIDING ELECTROSTATICS

- Flexible but not stretchable dielectrics

- Flexible but not stretchable electrodes



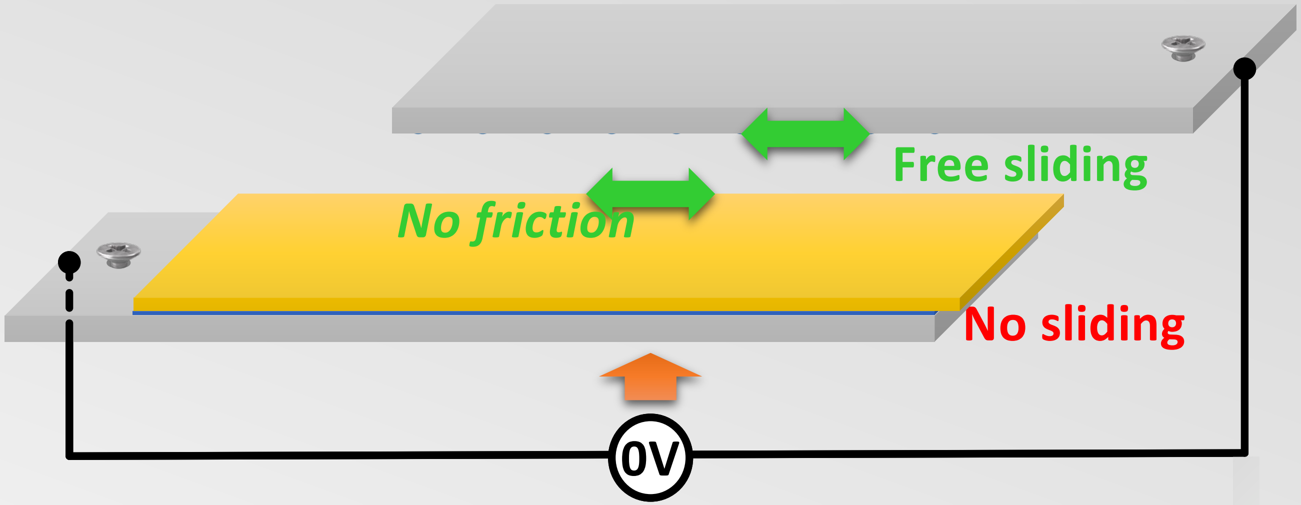


Haptic glove for VR + AR

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

Hinchet and Shea, Adv. Mat. Tech. 2019

How does the ES clutch block motion?



No voltage

➢ Finger is free

Voltage on

➢ Finger is blocked

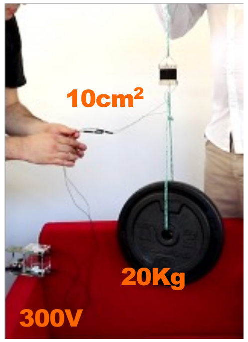
$$F_{ES} = \frac{1}{2}\varepsilon_0 \varepsilon_r A E^2$$

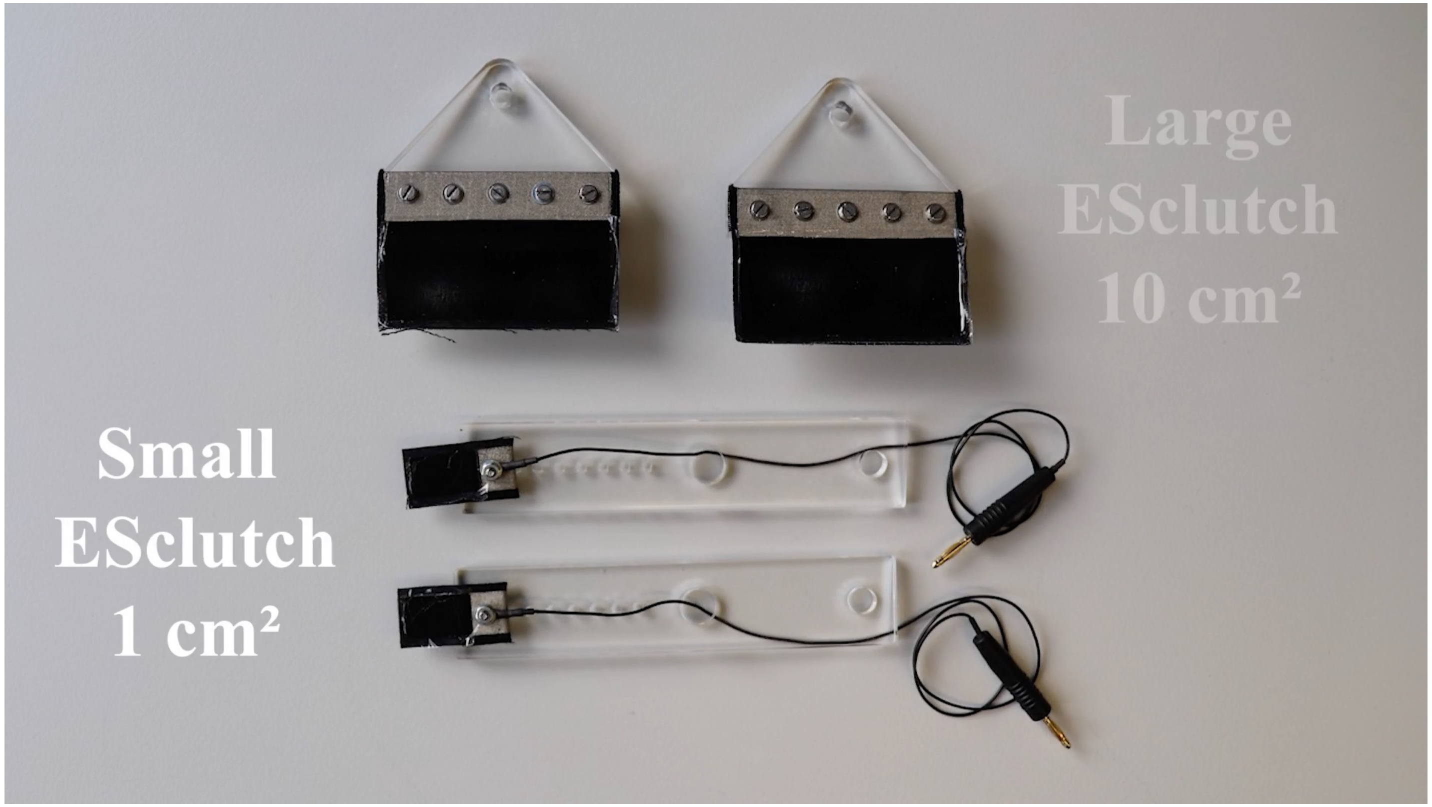
$$F_{fric} = \mu \frac{1}{2}\varepsilon_0 \varepsilon_r A E^2$$

EPFL Textile ESclutch can block 2 kg/cm^2 at 300 V

Small ESclutch

Large ESclutch

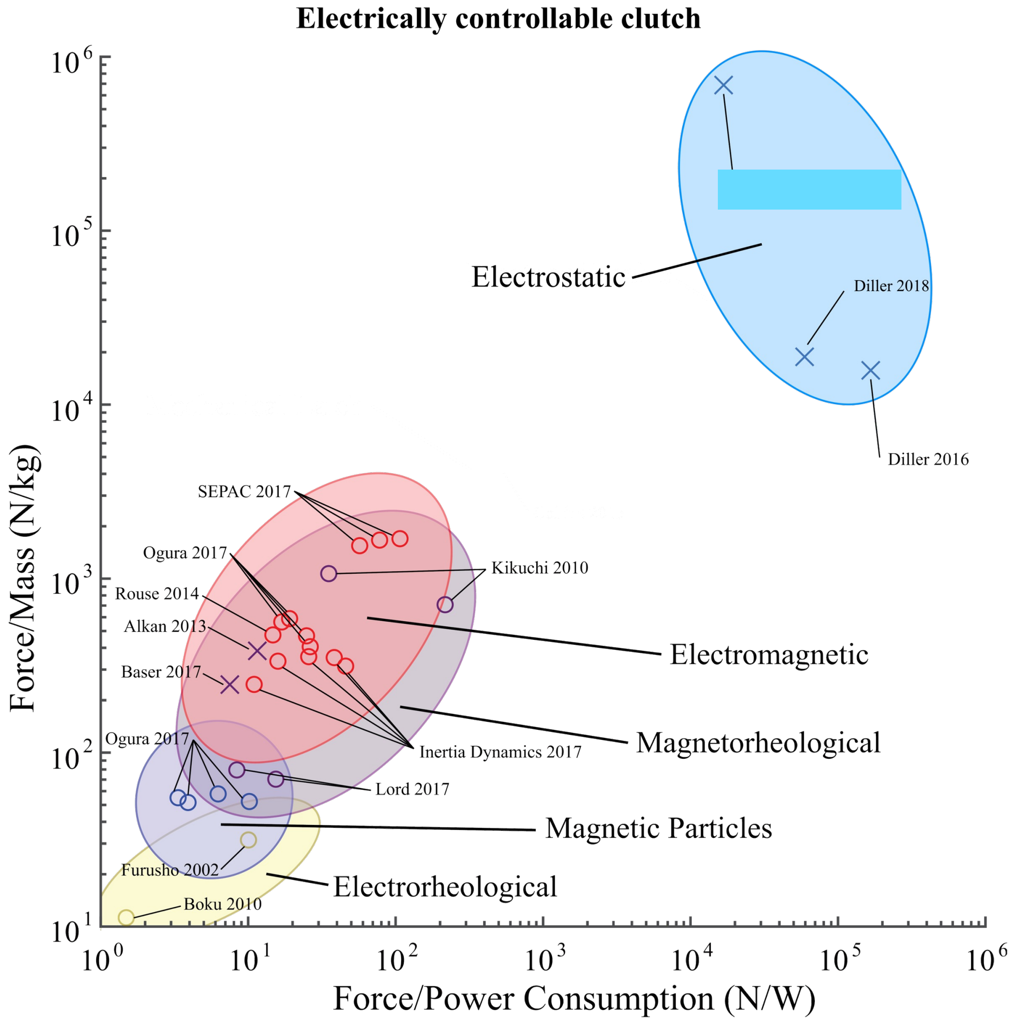




- High holding force :
  20 N/cm^2 at 300 V
- low power ***1.2 mW/cm^2***
- Flexible, Lightweight ***30 mg/cm^2***
- Fast ***< 15 ms***
- Tuneable Stiffness

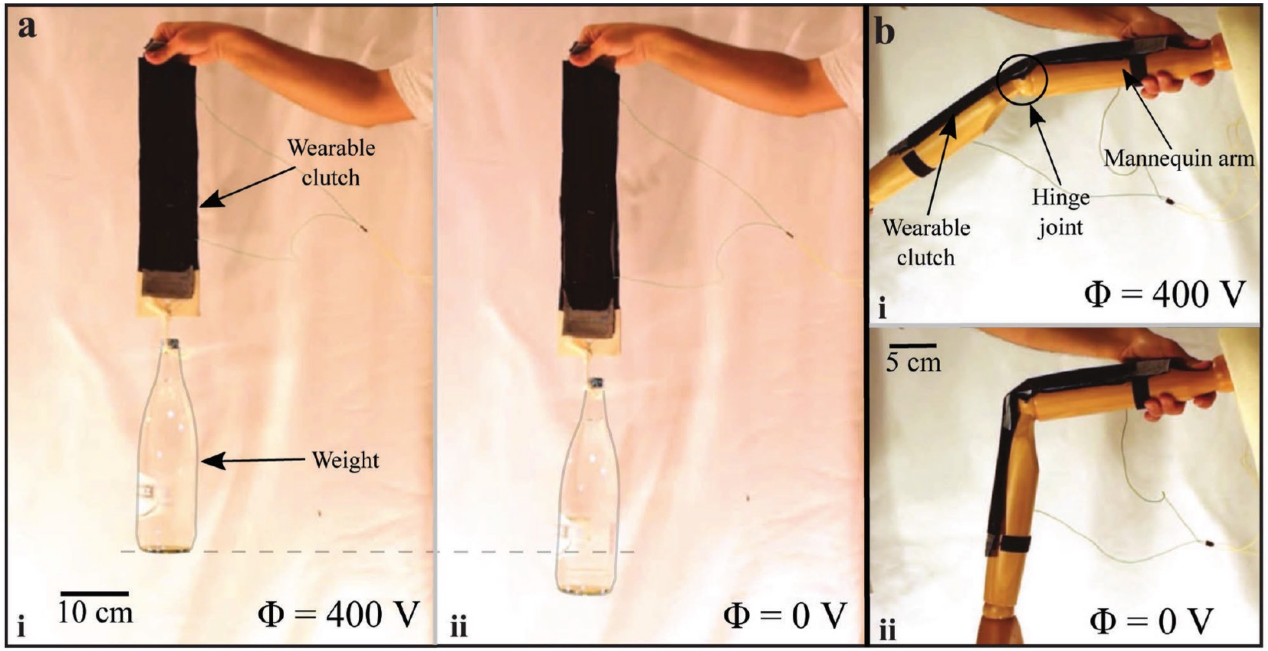
- Performance comes from use of ε_r=40 material, with E_{BD} >100 V/µm and from fabrication method.
- mW power enables use in in exoskeletons and full-body haptics
- Textile format

Hinchet and Shea, Adv. Mat. Tech. 2019



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

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



B. Exoskeleton

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**

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

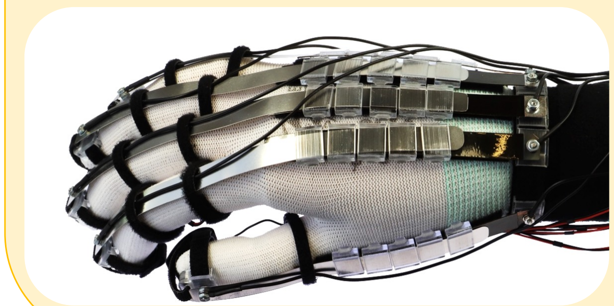
Hinchet and Shea, Adv. Intel. Sys., 2022

Evolution of our ES clutch glove

DextrES v1

Proof of concept

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



DextrES v2

Improvement of actuators

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

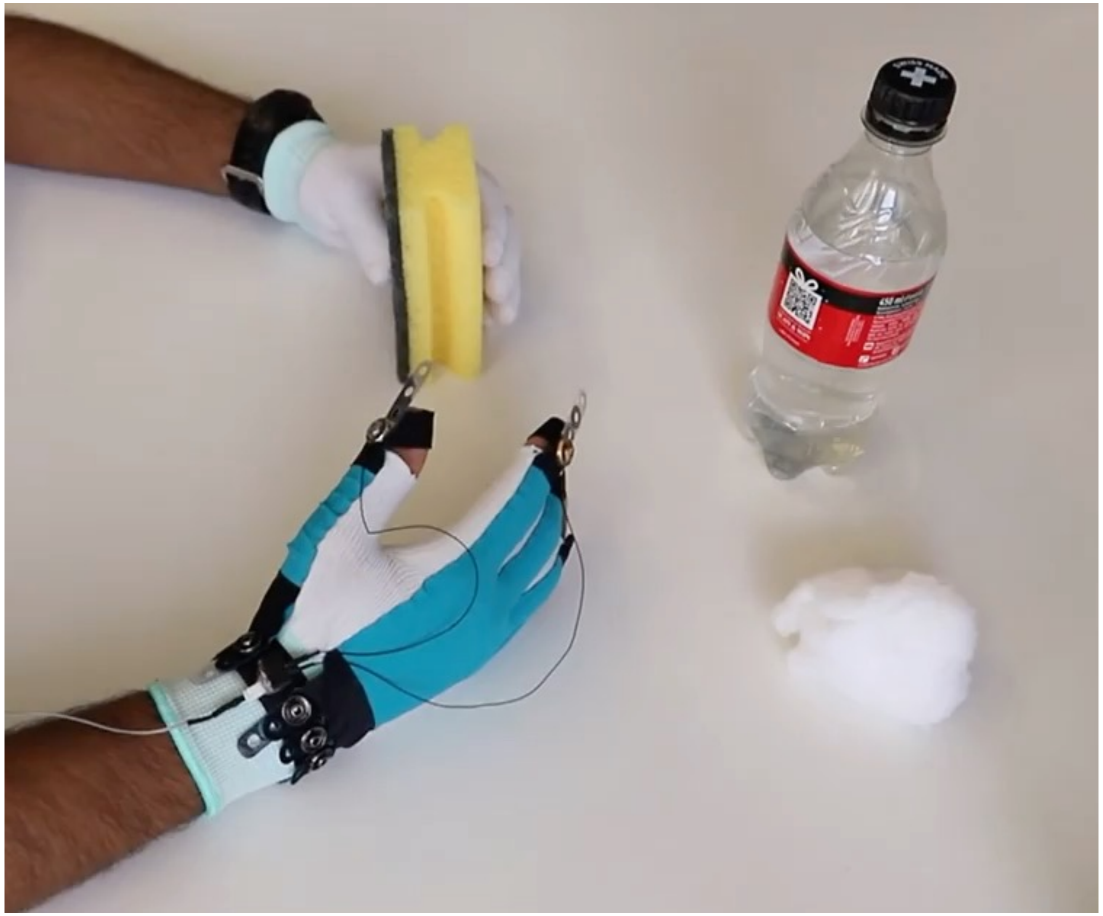
DextrES v3

Better actuators & integration

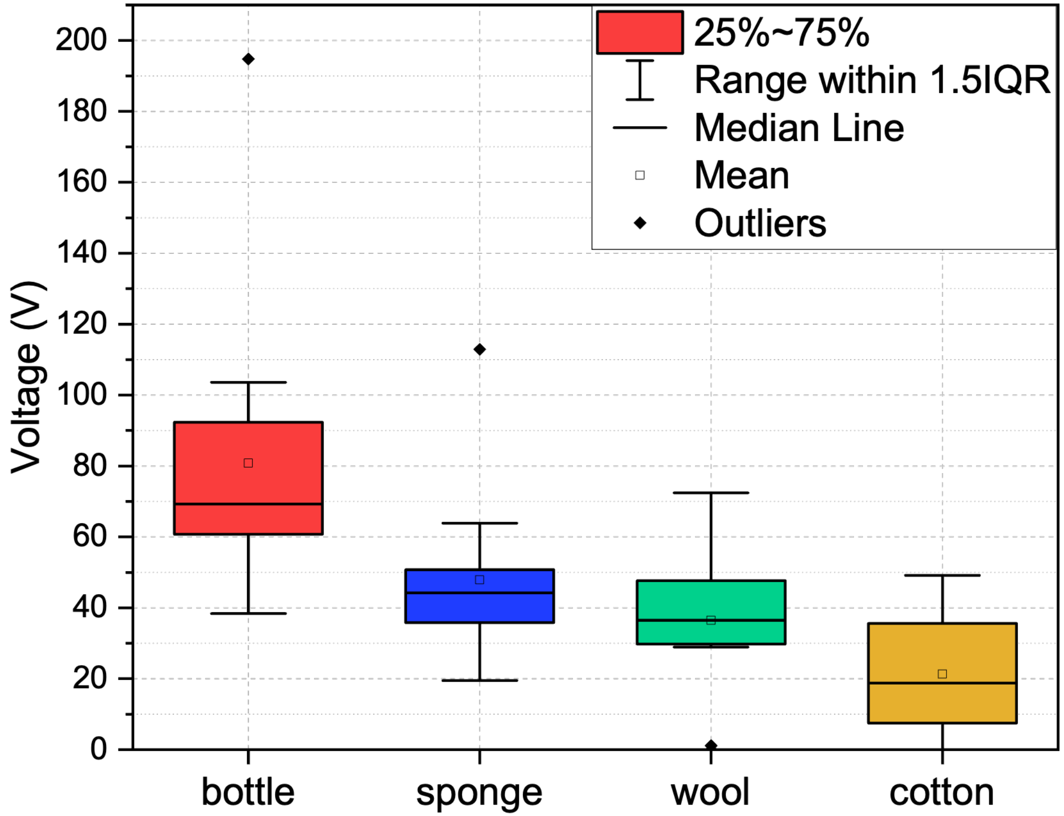
- PET film ESclutch
- High force low voltage
- Variable stiffness
- Soft textile integration
- Quick and easy to fit
- Very comfortable

EPFL

Can allow controlled sliding



Average for 13 people



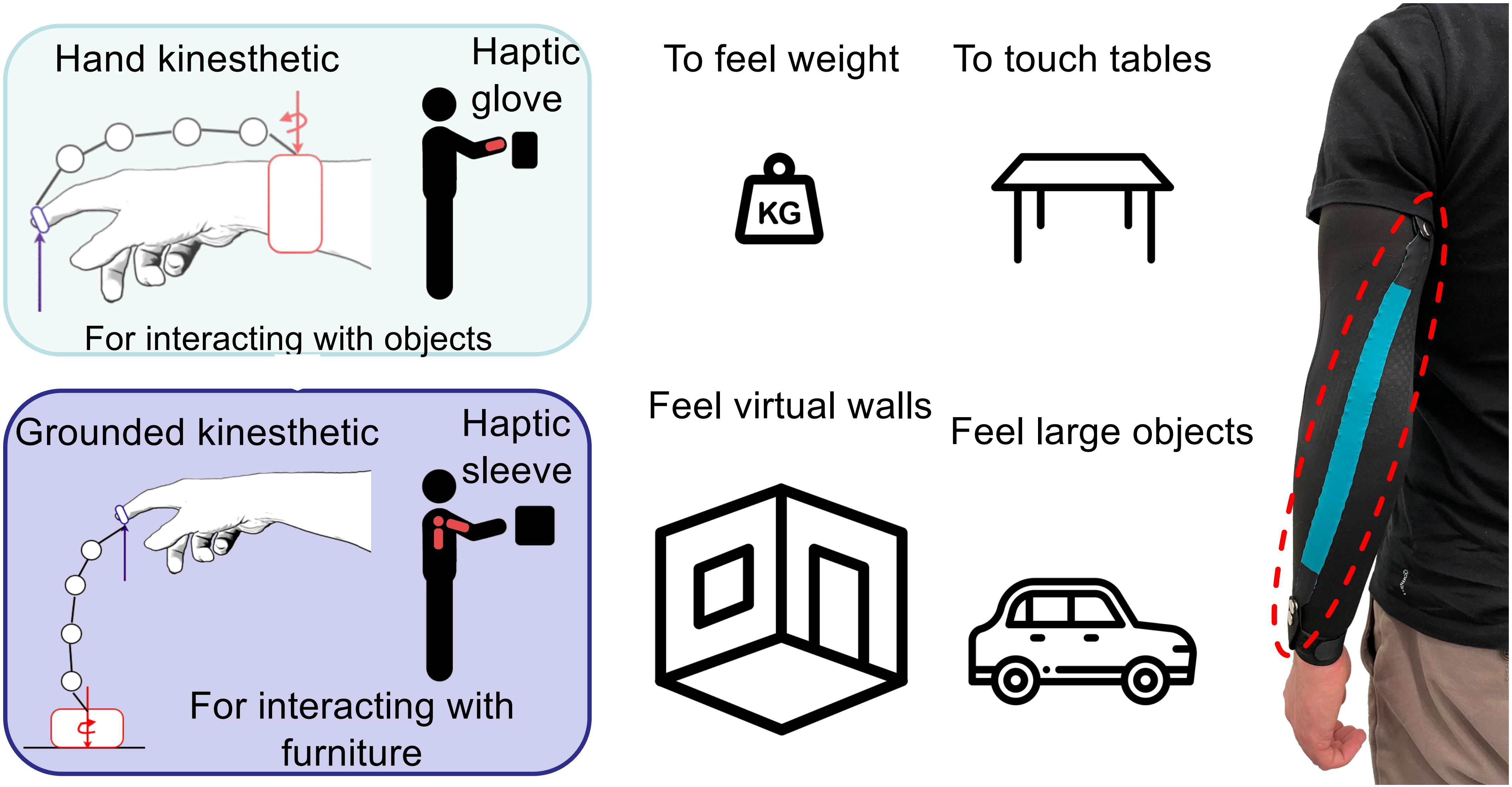
VR tests: sort cubes of different stiffnesses

<u>VR scenario</u>
- 5 VR cubes of different stiffness

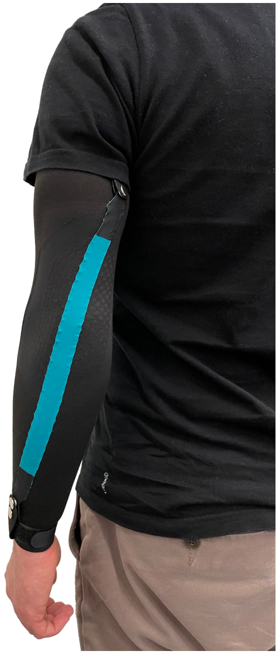
VR cube stiffnesses \ Stiffness user identification	1	2	3	4	5
5	0%	0%	0%	2,2%	97,8%
4	0%	0%	0%	97,8%	2,2%
3	0%	0%	100%	0%	0%
2	6,7%	93,3%	0%	0%	0%
1	93,3%	6,7%	0%	0%	0%


Dock VR View
Full Screen

Extend concept to elbow and shoulder for grounded kinesthetic feedback



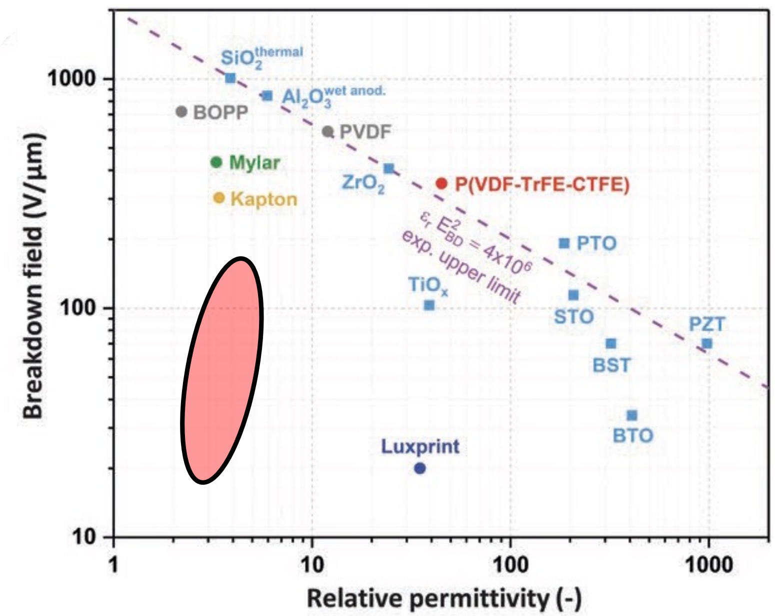
Feeling inertia in body-grounded haptics



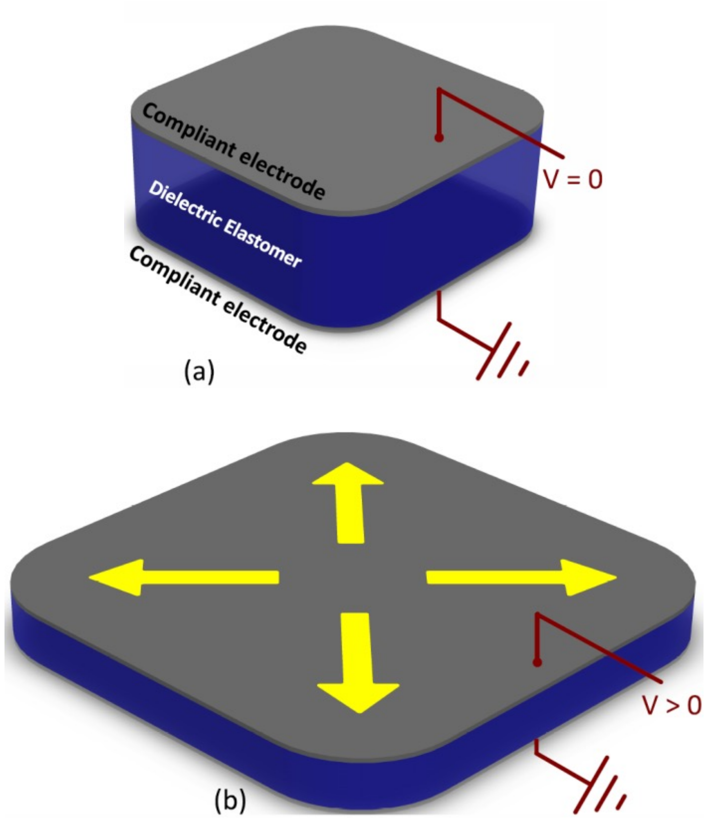
Hinchet and Shea, Adv. Intell Sys, 2022

2. DEA

Dielectric Elastomer Actuators (DEAs)



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



$$p_{\mathrm{el}} = \epsilon_0 \epsilon_r \left(\frac{V}{t} \right)^2$$

Pelrine, *Science* 2000

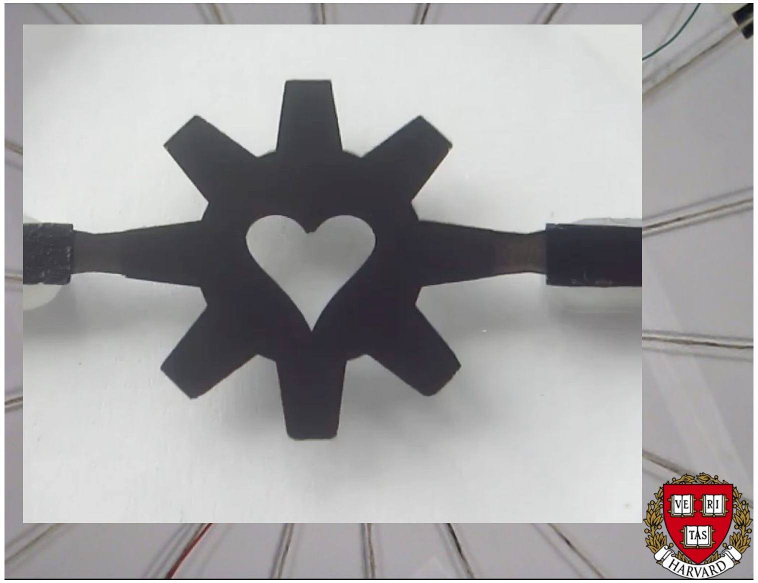
Simple structure

Compliant materials
(~1 MPa)

Large strain
(> 100%)

Fast actuation
(>kHz)

Self-Sensing



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

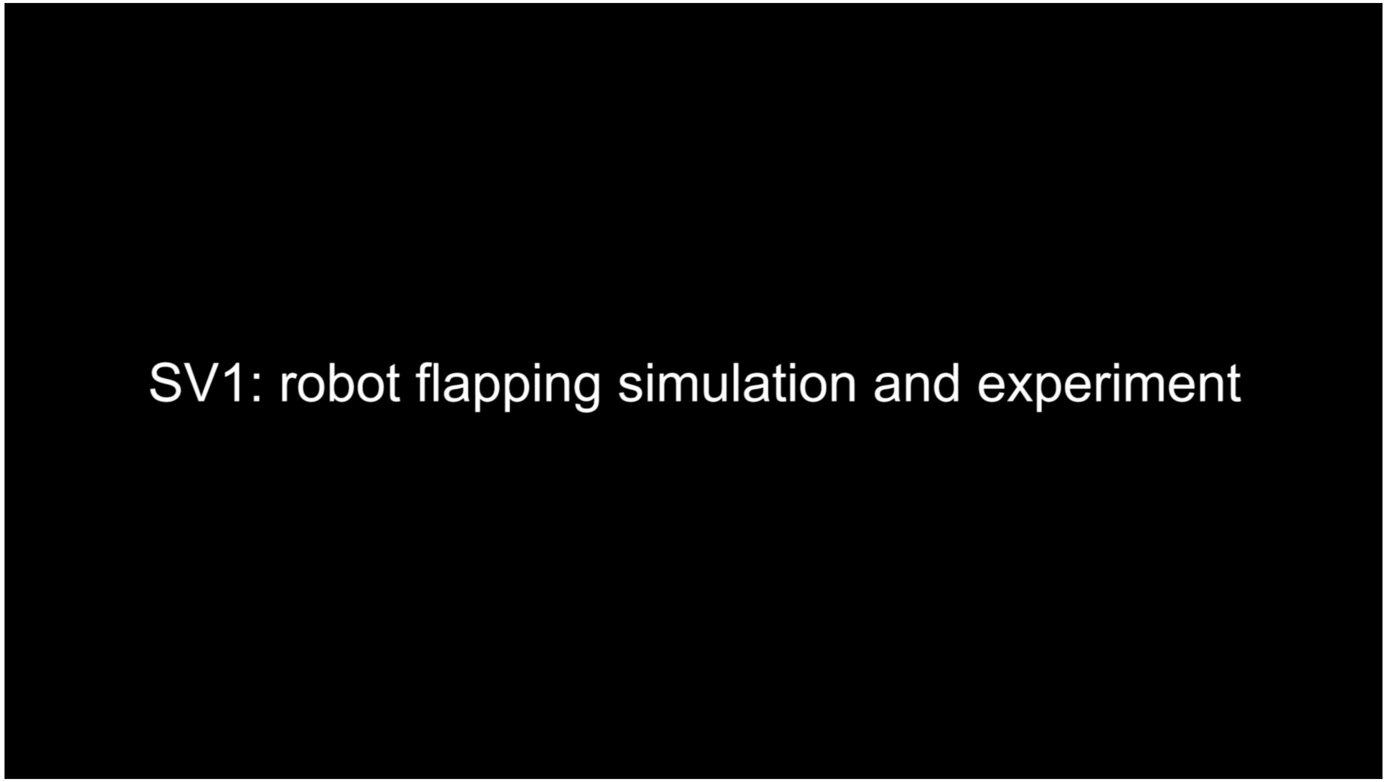
Typical elastomer thickness 20 to 50 µm
Typical voltages 1 – 5 kV

(nice) Features of Dielectric Elastomer Actuators (DEAs)

- **Large strain**:
  - over 1400% area strain demonstrated,
  - But only 15% to 40% strain for long-term operation today
- Lightweight: Energy density 3 MPa/m^3
- Soft: Young's modulus ≈ 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

When operated at 400 Hz, this 140 mg DEA generates forces of 0.36 N and displacements of 1.15 mm



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.

Y. Chen, S. Xu, Z. Ren, and P. Chirarattananon, “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.

Y. Chen *et al.*, “Controlled flight of a microrobot powered by soft artificial muscles,” *Nature*, Nov. 2019, doi: 10.1038/s41586-019-1737-7.

DEA as actuators

Advantages

- No vibration
- No noise
- Inherent self-sensing
- Lightweight
- High strain
- Soft
- Very little heat
- Nearly zero power consumption to hold position

Disadvantages

- HV power supply (kV)
- Low Maturity
- Manufacturability/cost
- Force
- Position accuracy
- Lifetime

Applications in the lab

- Tunable optics
- Compliant grippers
- Pumps
- Soft robotics
- Loudspeakers
- Haptic devices
- Valves
- Etc.

Commercial applications

Real commercial devices (*canceled*)

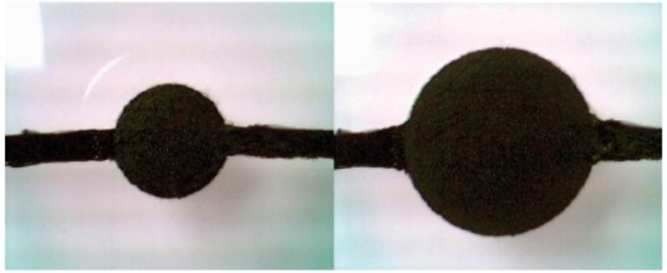
- Haptic devices for ipod touch
- Headphone shaker
- Laser speckle reducer

Nearly on market

- Multi-layer stacks for haptics?

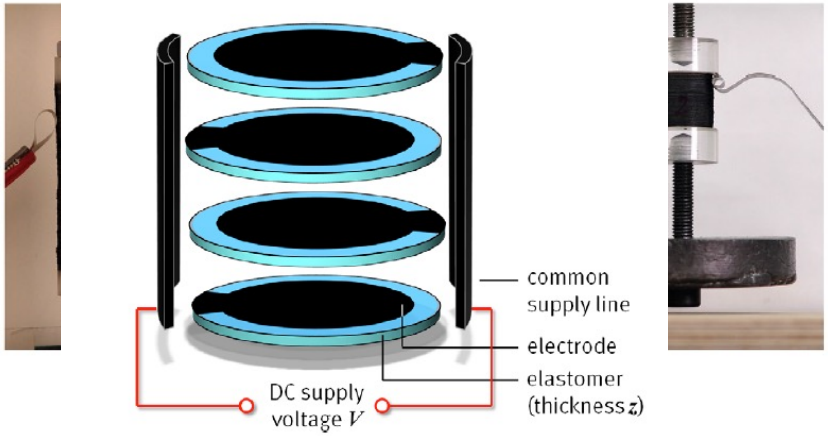
Two Main actuation modes of Dielectric Elastomer Actuators (same physics)

- **In-plane expansion** of a single layer
  - Easier fabrication
  - Usually on a frame, prestretched
  - Limited force but large strain



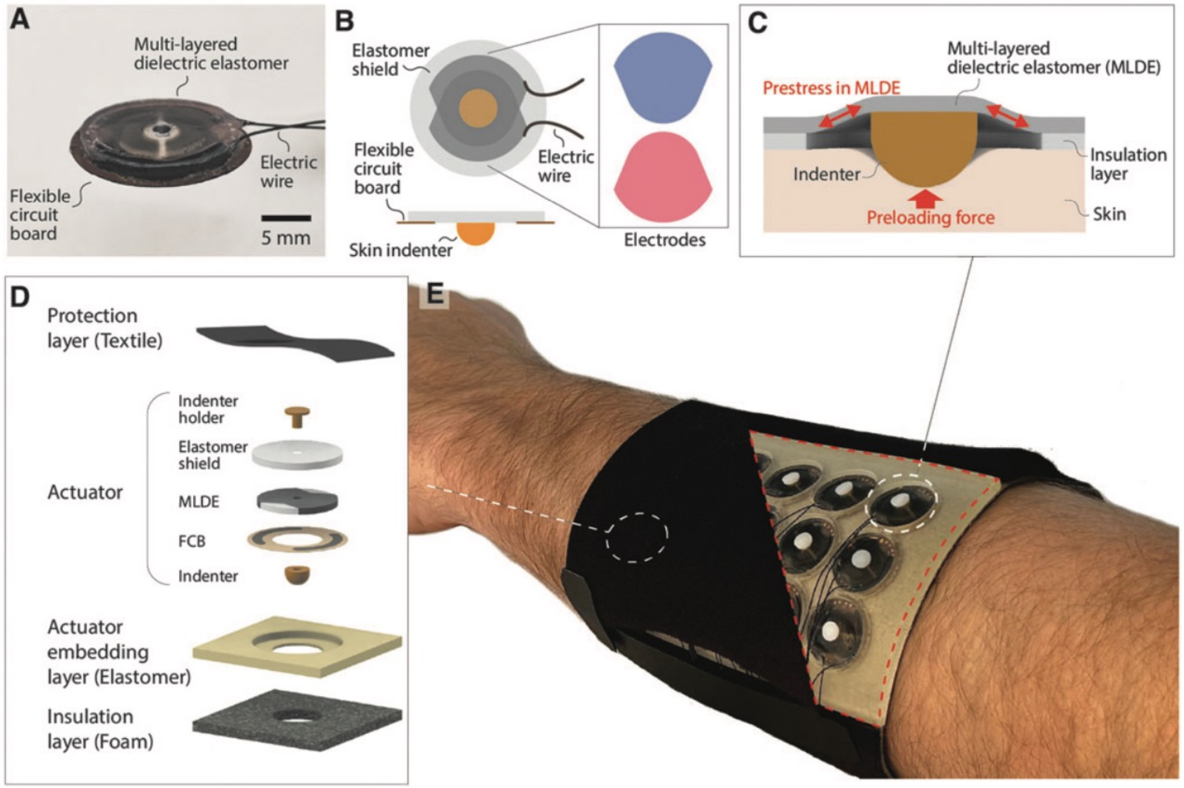
T. A. Gisby, et al, Proc. SPIE 7287, 728707 (2009).

- **Out-of-plane contraction** using multi-layers
  - Force scales with # of layers (can achieve several Newtons)
  - More involved fabrication for up to 1000 layers (100 is typical)
  - Often Self-standing (no frame)



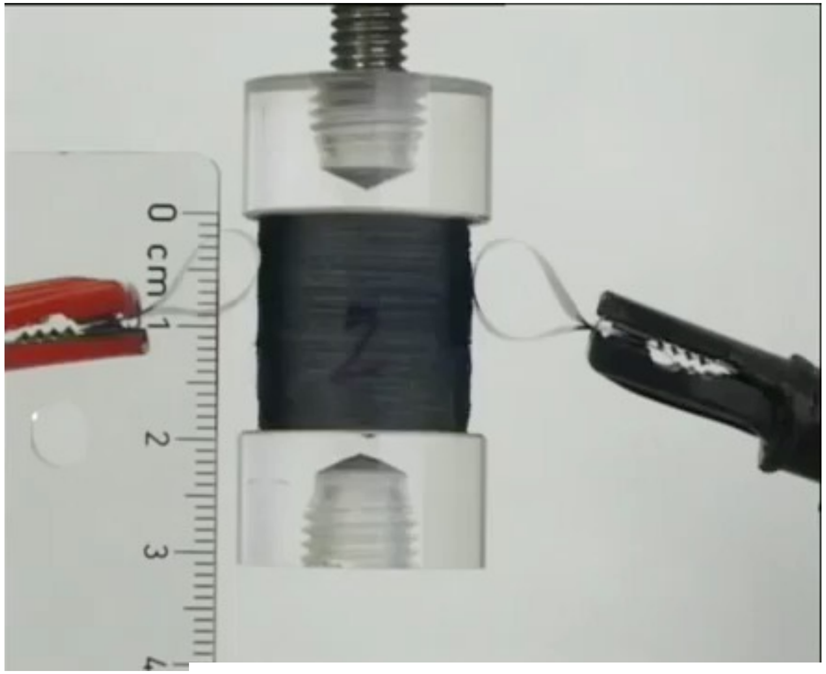
G. Kovacs et al, Sens. Actuators, 155A(2), 299 (2009).

One example of wearable DEAs for haptics



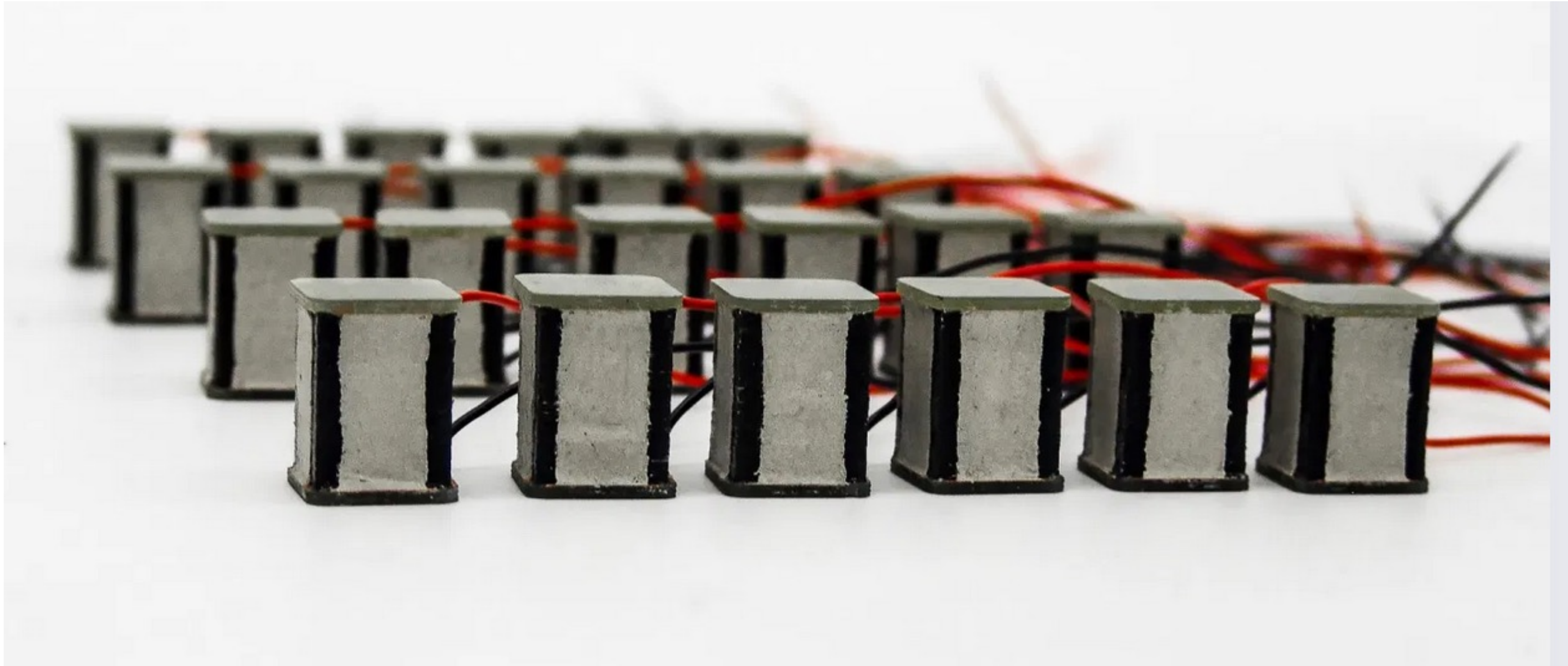
D.-Y. Lee *et al.*, "A Wearable Textile-Embedded Dielectric Elastomer Actuator Haptic Display," *Soft Robotics*, Jul. 2022, doi: 10.1089/soro.2021.0098.

Examples of multi-layer DEA applications



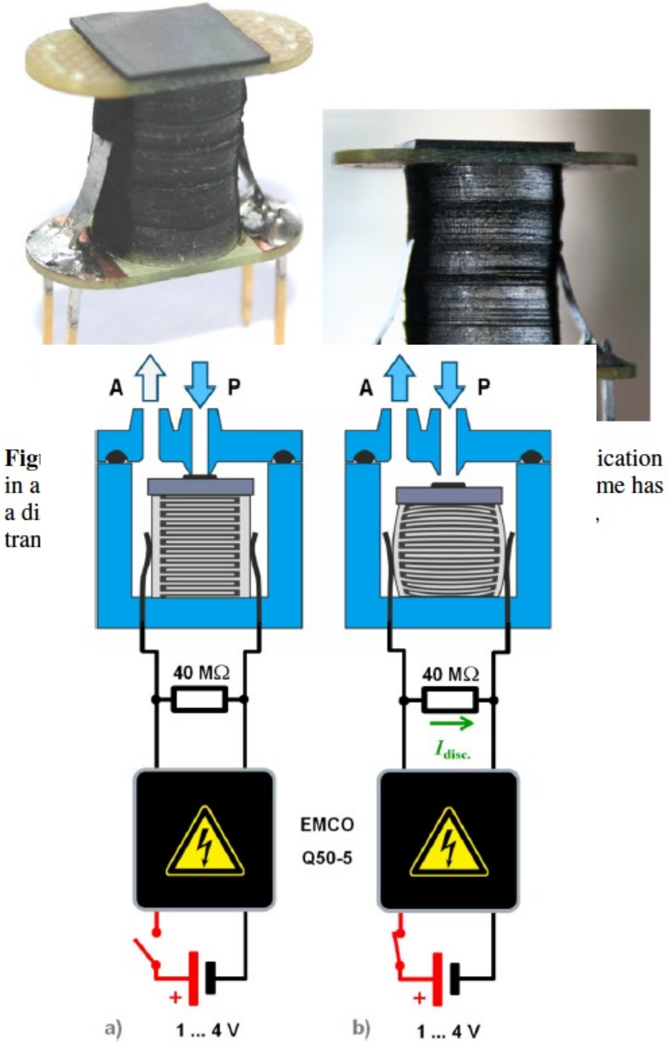
[164] F. Carpi, C. Salaris and D. D. Rossi, "Folded dielectric elastomer actuators," *Smart Materials and Structures*, vol. 16, no. 2, pp. S300–S305, 2007.

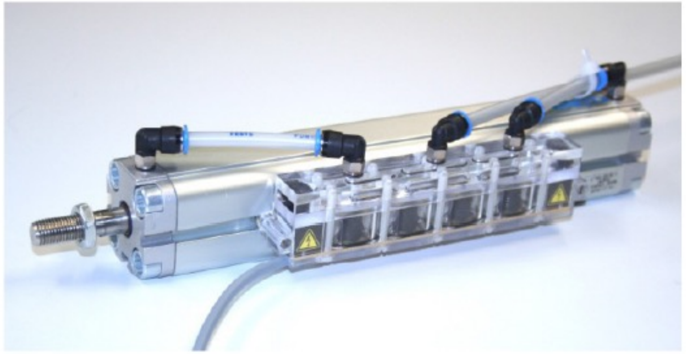
[165] G. Kovacs, L. Düring, S. Michel and G. Terrasi, "Stacked dielectric elastomer actuator for tensile force transmission," *Sensors and Actuators A: Physical*, vol. 155, no. 2, pp. 299–307, 2009.



https://ct-systems.ch/technology/ctstack-the-transducer-technology/

Stacked DEA actuator used as proportional valve





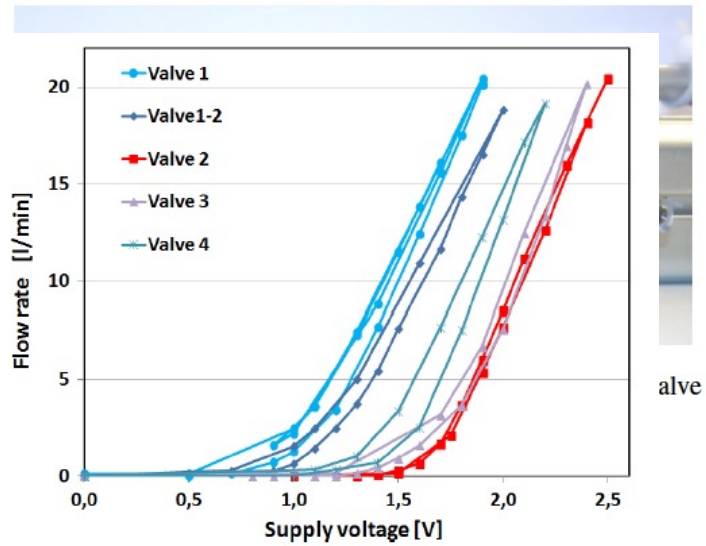
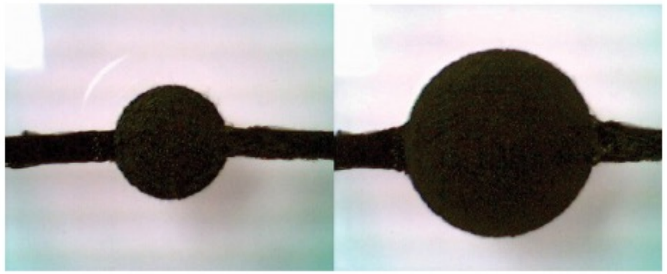


Figure 10. Flow rate of five valve demonstrators tested with an absolute air pressure of 3 bar.

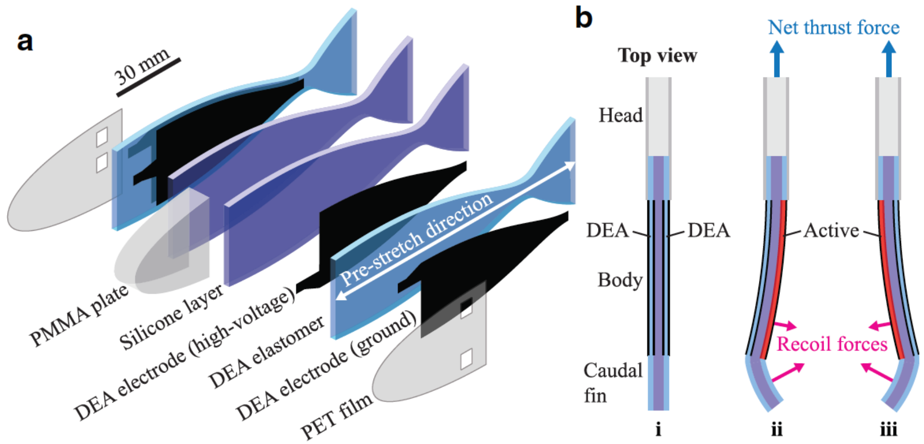
Advantage = Low power consumption

M. Giousouf, G. Kovacs; 2013 Smart Mater. Struct. 22 104010

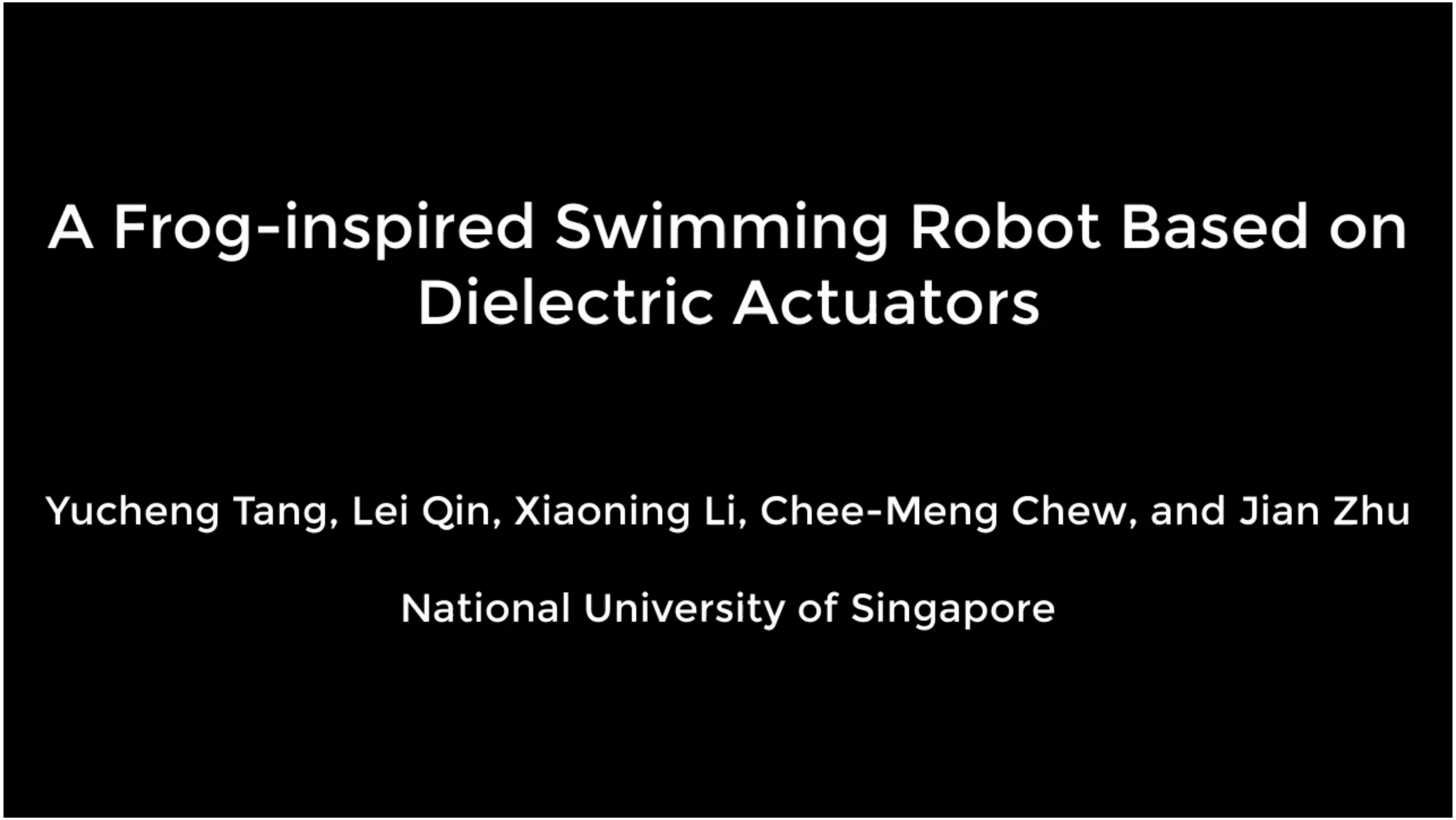
Examples of single layer DEA applications



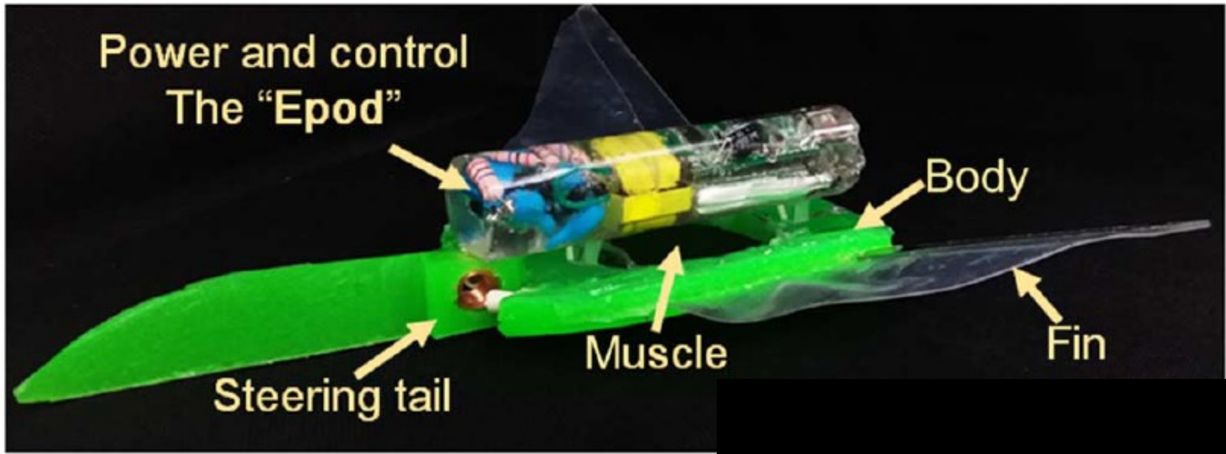
Swimming is easier than walking, especially when one has to carry a heavy power supply…



J. Shintake, V. Cacucciolo, H. Shea, D. Floreano,
Soft Biomimetic Fish Robot Made of Dielectric Elastomer Actuators.
Soft Robotics. **5**, 466–474 (2018).



Y. Tang, L. Qin, X. Li, C.-M. Chew, J. Zhu, in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (2017), pp. 2403–2408.



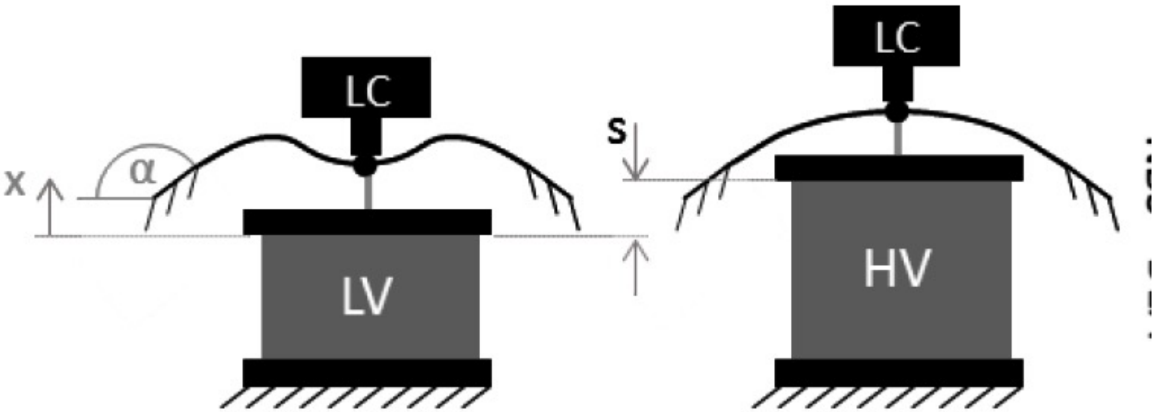
(then shown at 10 km depth)

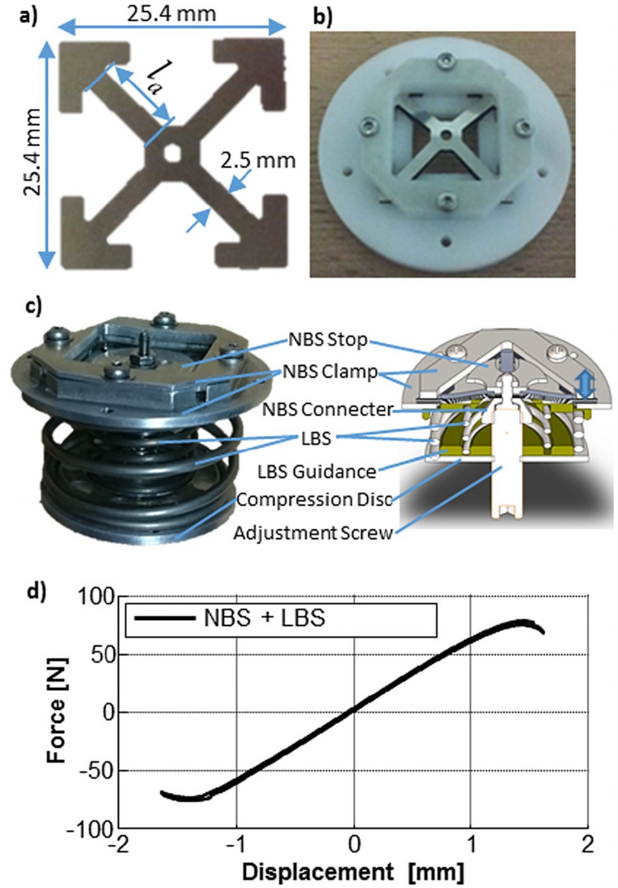
The untethered robot with on-board power source, swims and turns.

T. Li, et al, Fast-moving soft electronic fish. *Science Advances*. **3**, e1602045 (2017).

G. Li et al. *Nature*. **591**, 66–71 (2021).

Adding a non-linear (buckling) spring can greatly improve DEA performance



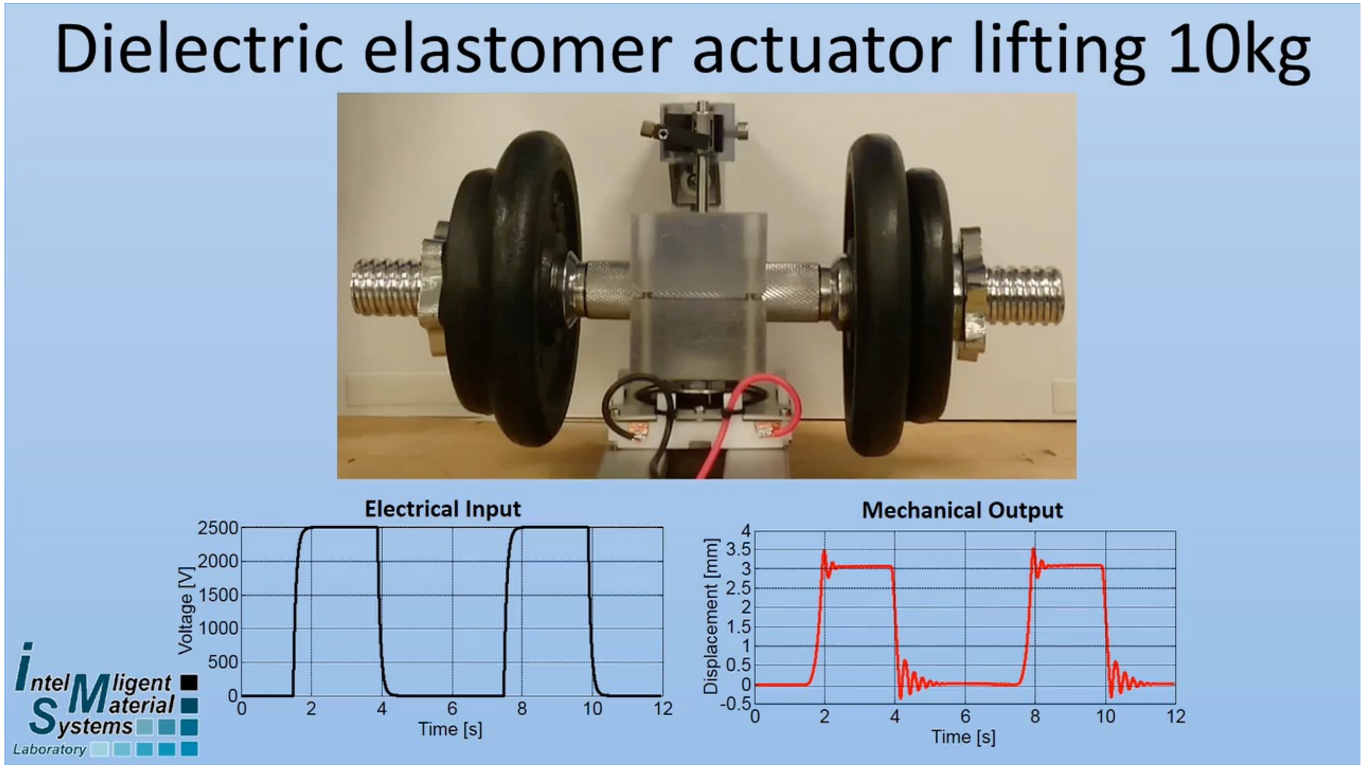


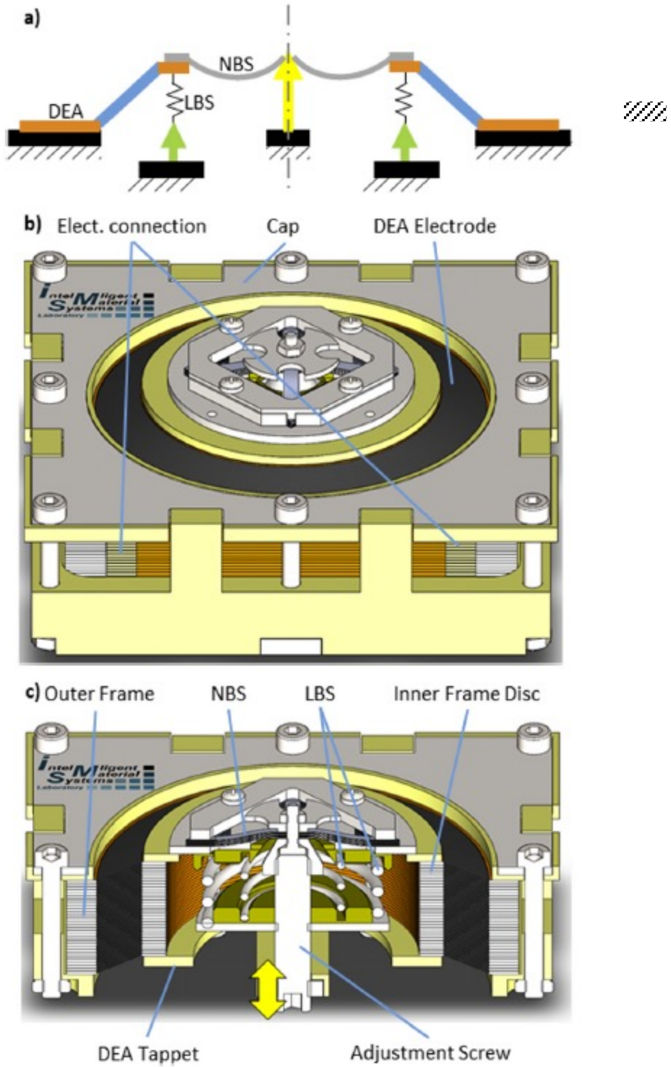
S. Hau, P. Linnebach, G. Rizzello, S. Seelecke, in *Electroactive Polymer Actuators and Devices (EAPAD) XXI* (International Society for Optics and Photonics, 2019 vol. 10966, p. 109660N.

S. Hau et al, Extreme Mechanics Letters 23 (2018)

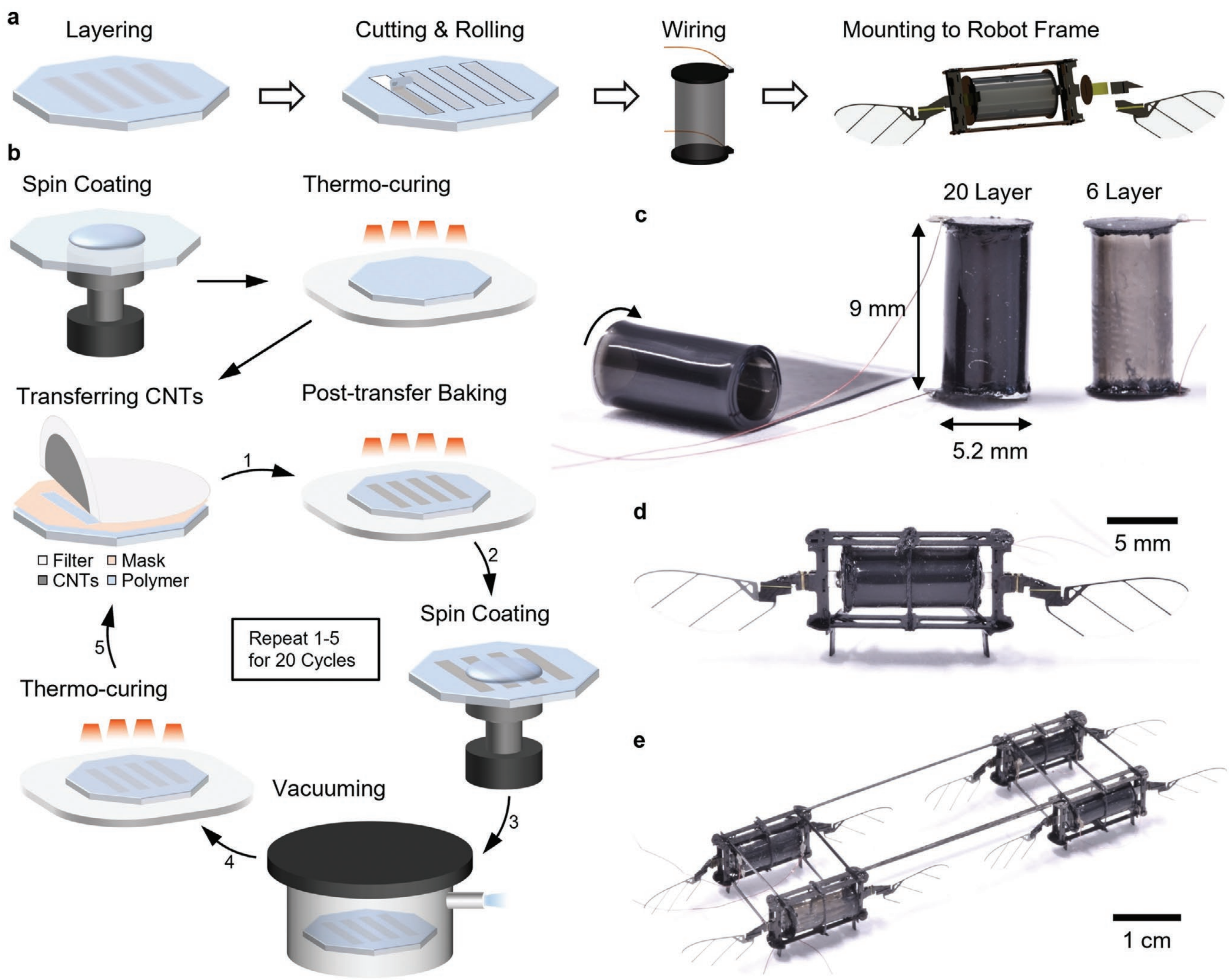
High-force DEA with spring bias, but not stretchable…

Stacked single layers and buckled spring



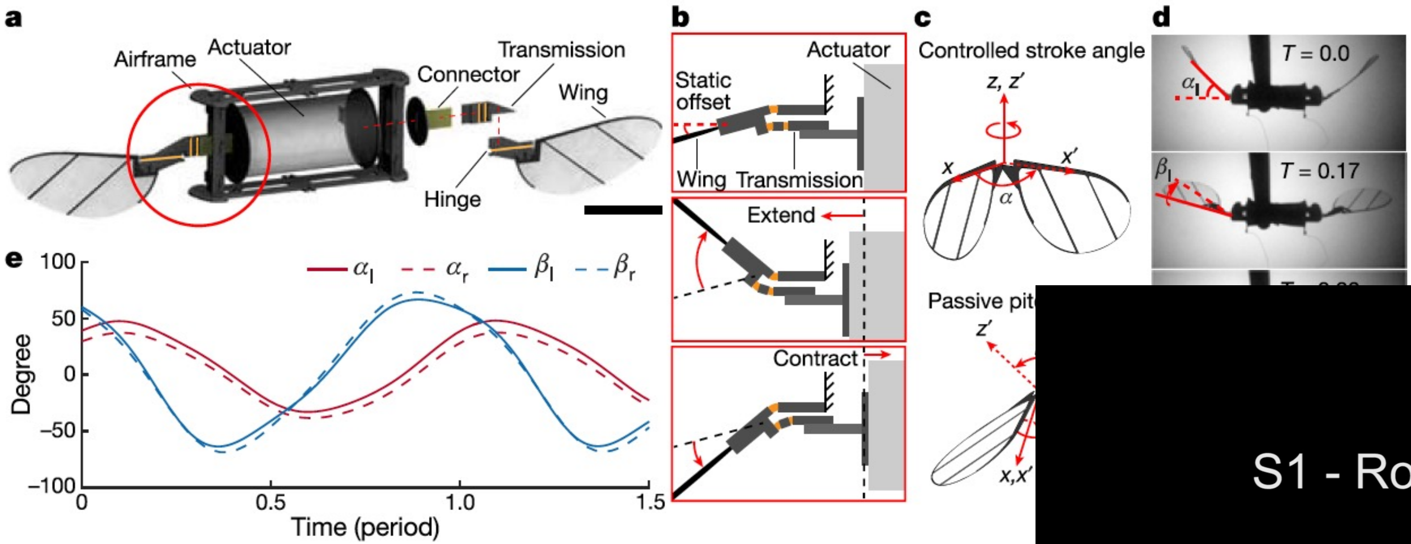


Hau, S., G. Rizzello, and S. Seelecke. "A Novel Dielectric Elastomer Membrane Actuator Concept for High-Force Applications." *Extreme Mechanics Letters* 23 (September 1, 2018): 24–28. https://doi.org/10.1016/j.eml.2018.07.002.



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.

Flying is hardest: need very high energy density and effectvce flapping motion.



- multi-layered rolled DEA
- 100 milligrams each
- resonance frequency of 500 Hz
- power density of 600 watts per kilogram.

Y. Chen, H. Zhao, J. Mao, P. Chirarattananon, E. F. Helbling, N. P. Hyun, D. R. Clarke, R. J. Wood, Controlled flight of a microrobot powered by soft artificial muscles. *Nature* (2019), doi:10.1038/s41586-019-1737-7.

Much improved control of flying DEA insects – very robust thanks to DEA compliance

SV3: robot hovering demonstration

SV6: robot somersault demonstration

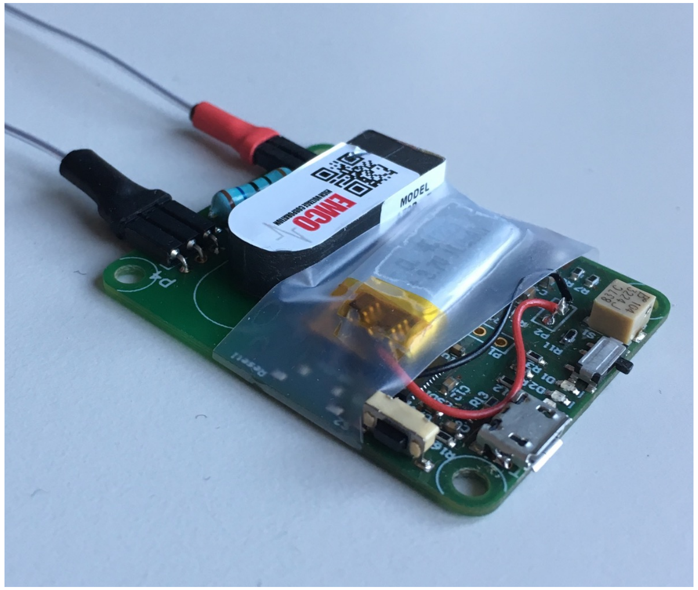
665 mg aerial robot that is powered DEA achieves high power density (1.2 kW/kg) and high transduction efficiency (37%).

Careful choice of Silicone (low visco-elasticity)

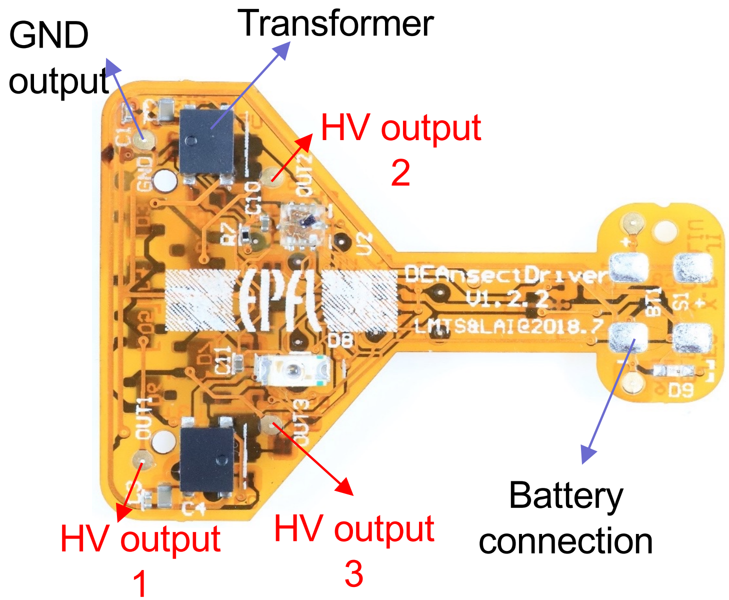
Y. Chen, S. Xu, Z. Ren, P. Chirarattananon,
Collision Resilient Insect-Scale Soft-Actuated Aerial Robots With High Agility.
IEEE Transactions on Robotics, 1–13 (2021).

If reduce voltage to below 500V, can use very compact electronics

…and thus a path to intelligent machine with complex control



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

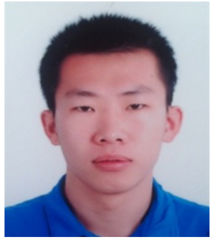


Miniature 2 channel 500 V 1 kHz power supply:
0.35 g

An obvious path to lower voltages: use thinner dielectric layers in the DEA

Sounds easy… but with very thin DEAs:

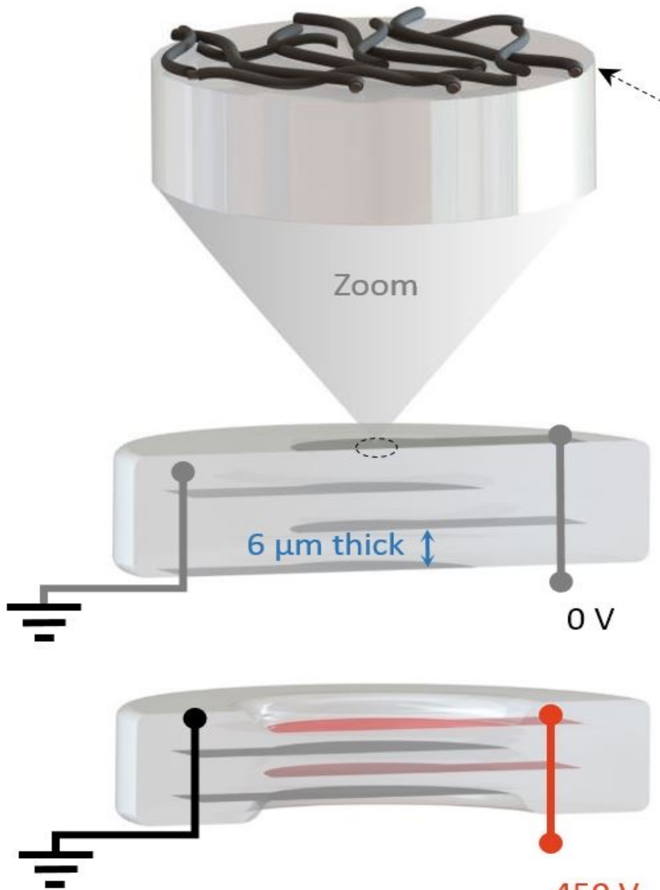
- Need to stack DEAs to get enough strain
- need extremely soft and thin electrodes!
  - RC time constant must be high
  - But tricky if electrodes nm thick…



Xiaobin Ji

Low-voltage stacked DEAs using Langmuir-Blodgett assembled CNT monolayer electrodes

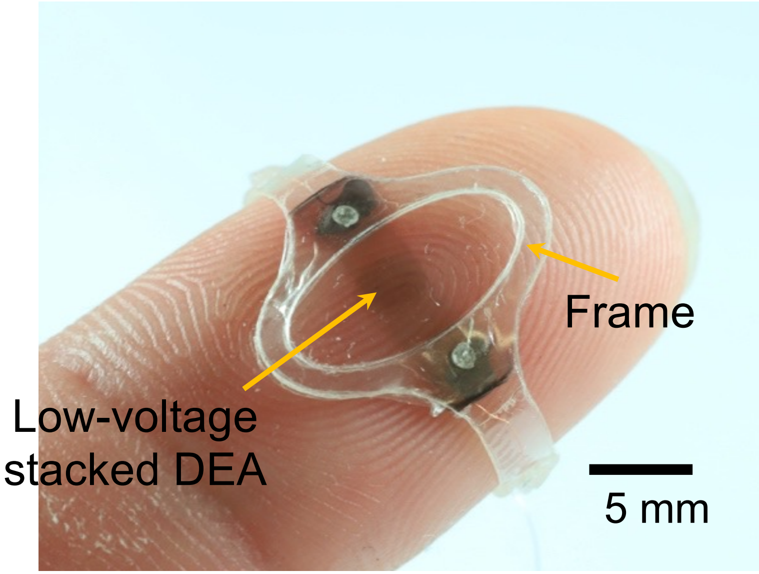
Full DEA strain at 450V, up to 500 Hz



Collaboration with Université de Cergy Pontoise - LPPI

X. Ji et al, Science Robotics 2019

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

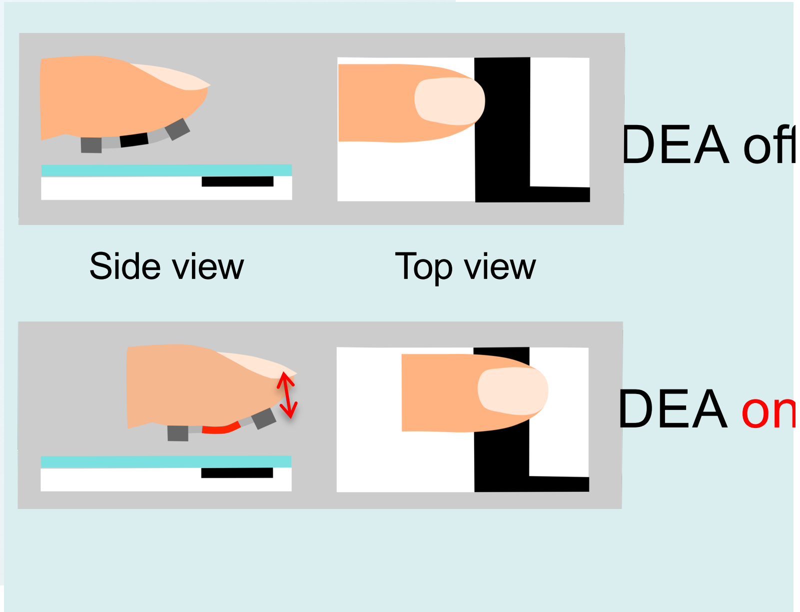


Key features:

- “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

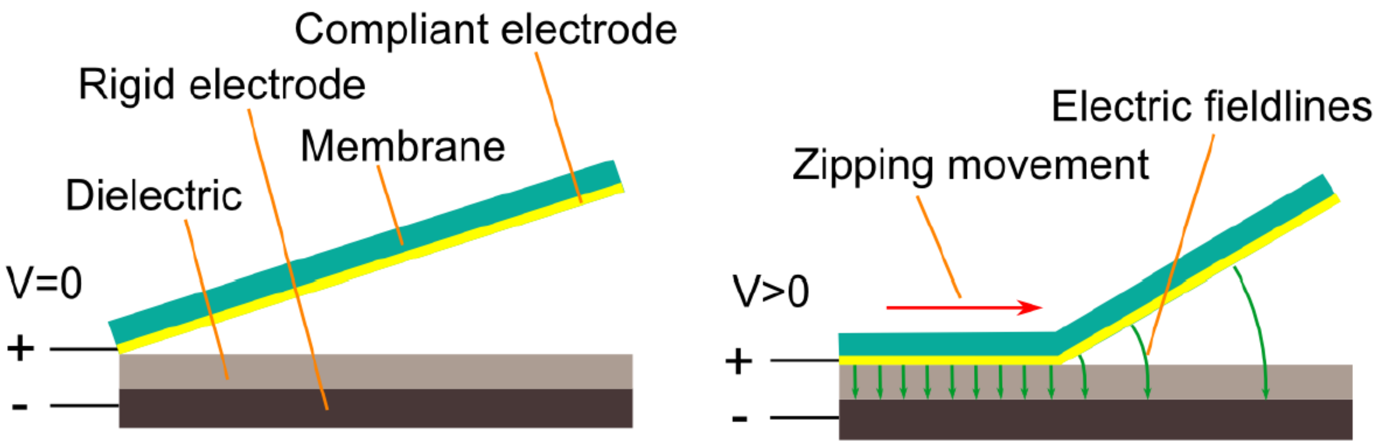
Control: with ”low-V” electronics: can have some processing power

Electronics made by EPFL-LAI



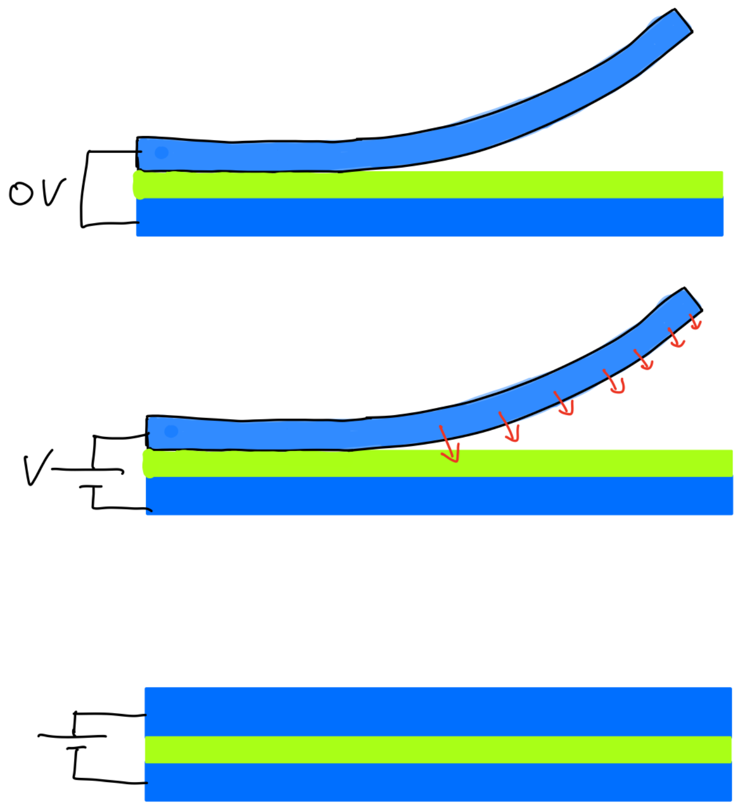
Use a finger to "see" letters!

3. ZIPPING ELECTROSTATICS



Zipping 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



Zipping is an “old” concept, used in MEMS since the 90s

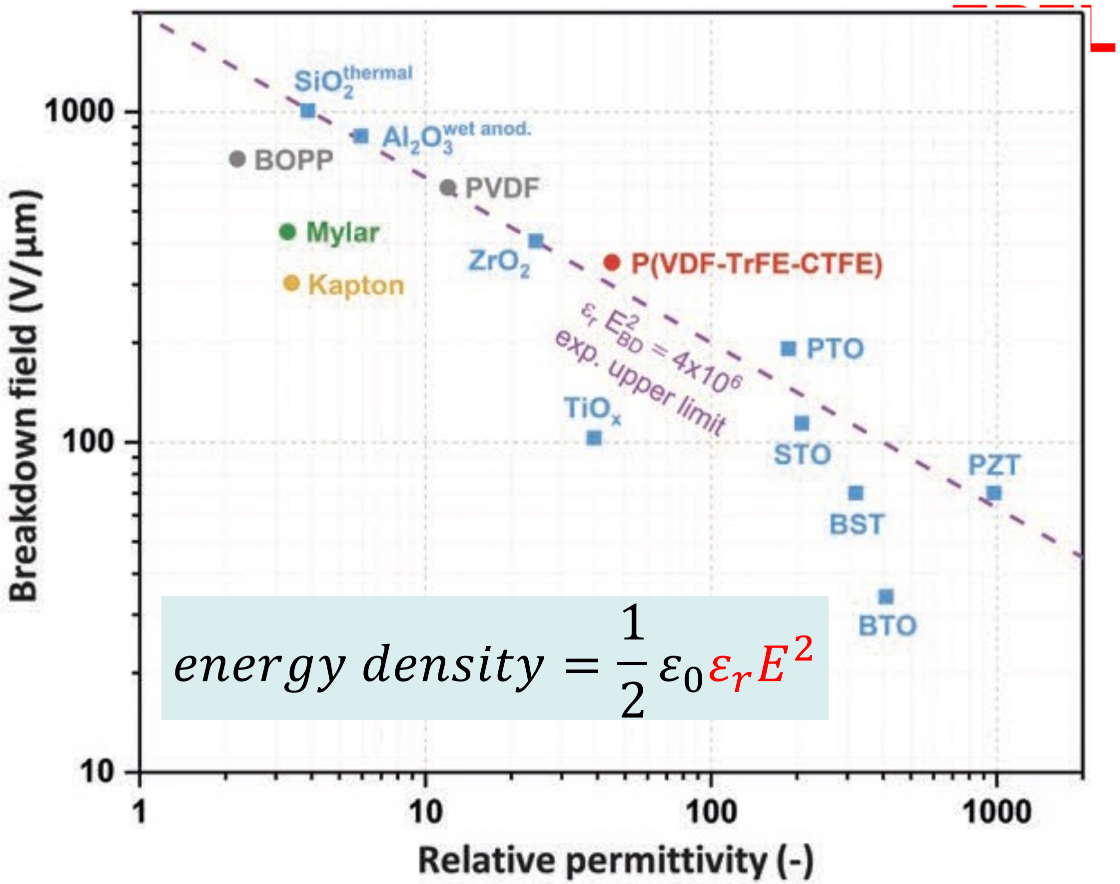
Electrostatic Zipping

Benefits:

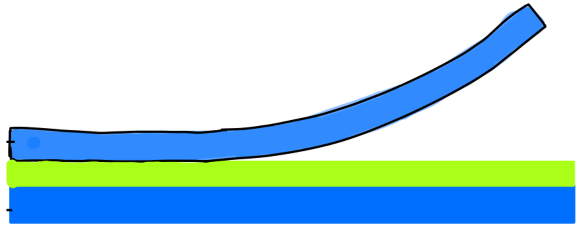
- High energy density from electrostatics (100x DEA)
- Thin
- Flexible

Drawbacks:

- High voltages (several kV, though only mW power)
- Limited pressure generated
- Not as robust as pneunet



$$energy\ density = \frac{1}{2}\varepsilon_0 \varepsilon_r E^2$$

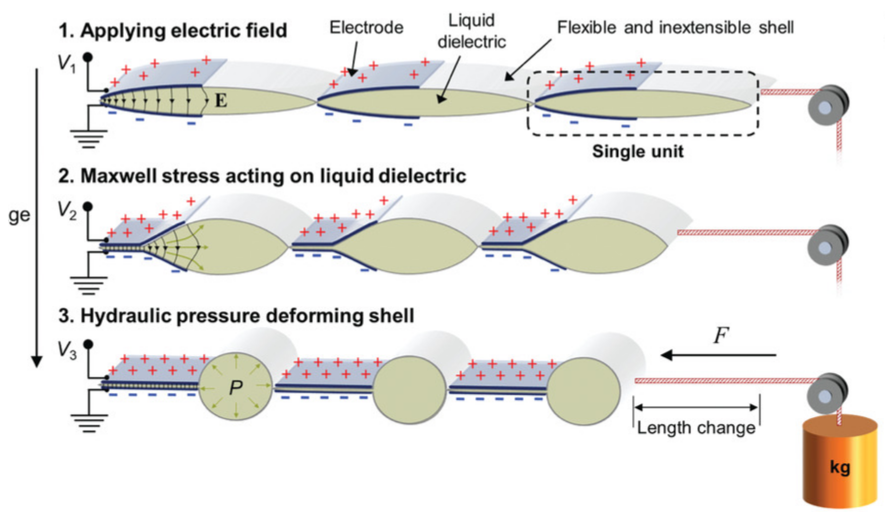


Zipping electrostatic actuators

Very active research area!

- **Peano Hasel (Keplinger group) are the best known example**

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



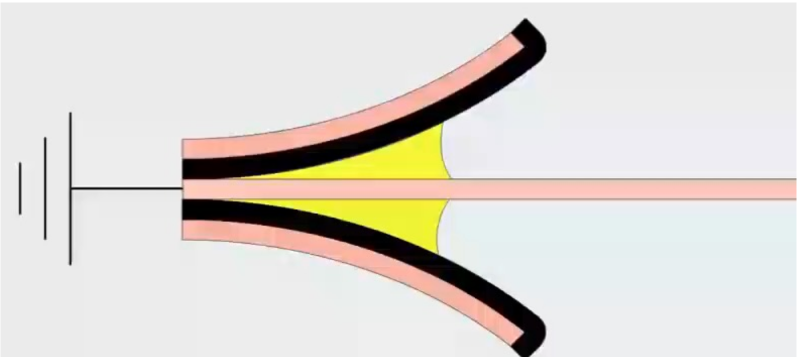
Rothermund … Keplinger, Adv. Mat 2020

- Can be accurately modeled
- But does not use higher permittivity insulator

Zipping electrostatic actuators

Very active research area! for instance

- **Electro-ribbon actuators (Rossiter group), Bristol**



Liquid-amplified zipping actuators for micro-air vehicles, T. Helps, Sci. Rob. 2022.

Electro-ribbon actuators and electro-origami robots

Majid Taghavi, Tim Helps, Jonathan Rossiter

Movie S2 | Isotonic and isometric actuation of a standard electro-ribbon actuator.

(**A**), A standard electro-ribbon actuator lifts a 20 g mass 51.75 mm. Applied voltage is 8 kV. Contraction is 99.31 %.

(**B**), Isometric testing of a standard electro-ribbon actuator. Applied voltage is a step input, starting at 1 kV and increasing by 1 kV every five seconds to a maximum voltage of 6 kV. The actuator extension is held constant at 24 mm.

University of BRISTOL

Bristol Robotics Laboratory

Taghavi … Rossiter, Science Robotics 2018

Electro-pneumatic Pumps for Soft Robotics

Richard Suphapol Diteesawat, Tim Helps, Majid Taghavi, Jonathan Rossiter

Movie S1: Actuation of a pneumatic artificial muscle by an Electro-pneumatic Pump.

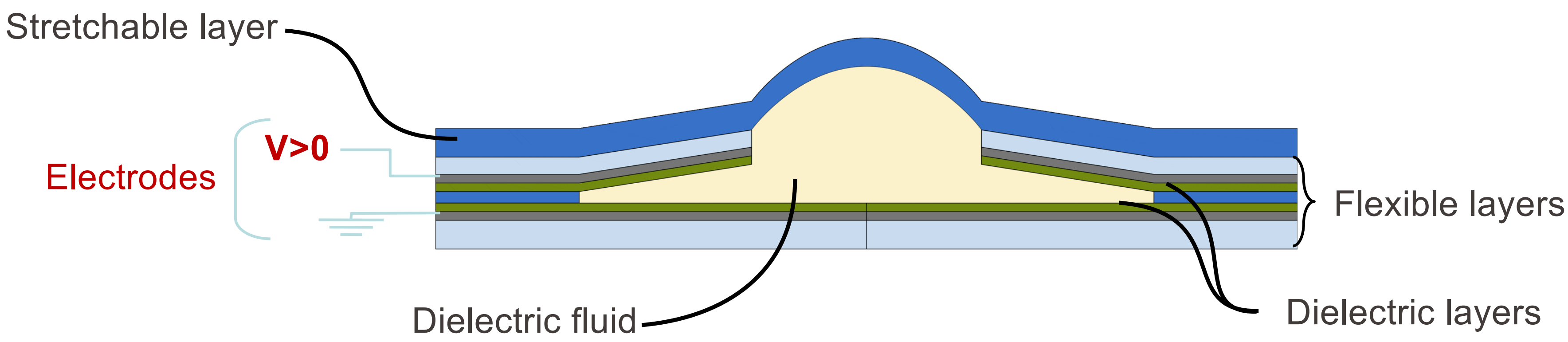
An Electro-pneumatic Pump (EPP) was actuated to inflate a Bubble Artificial Muscle (BAM), showing (**A**) contraction of the BAM, and (**B**) progressive zipping of the EPP at 8 kV.

University of BRISTOL

Bristol Robotics Laboratory

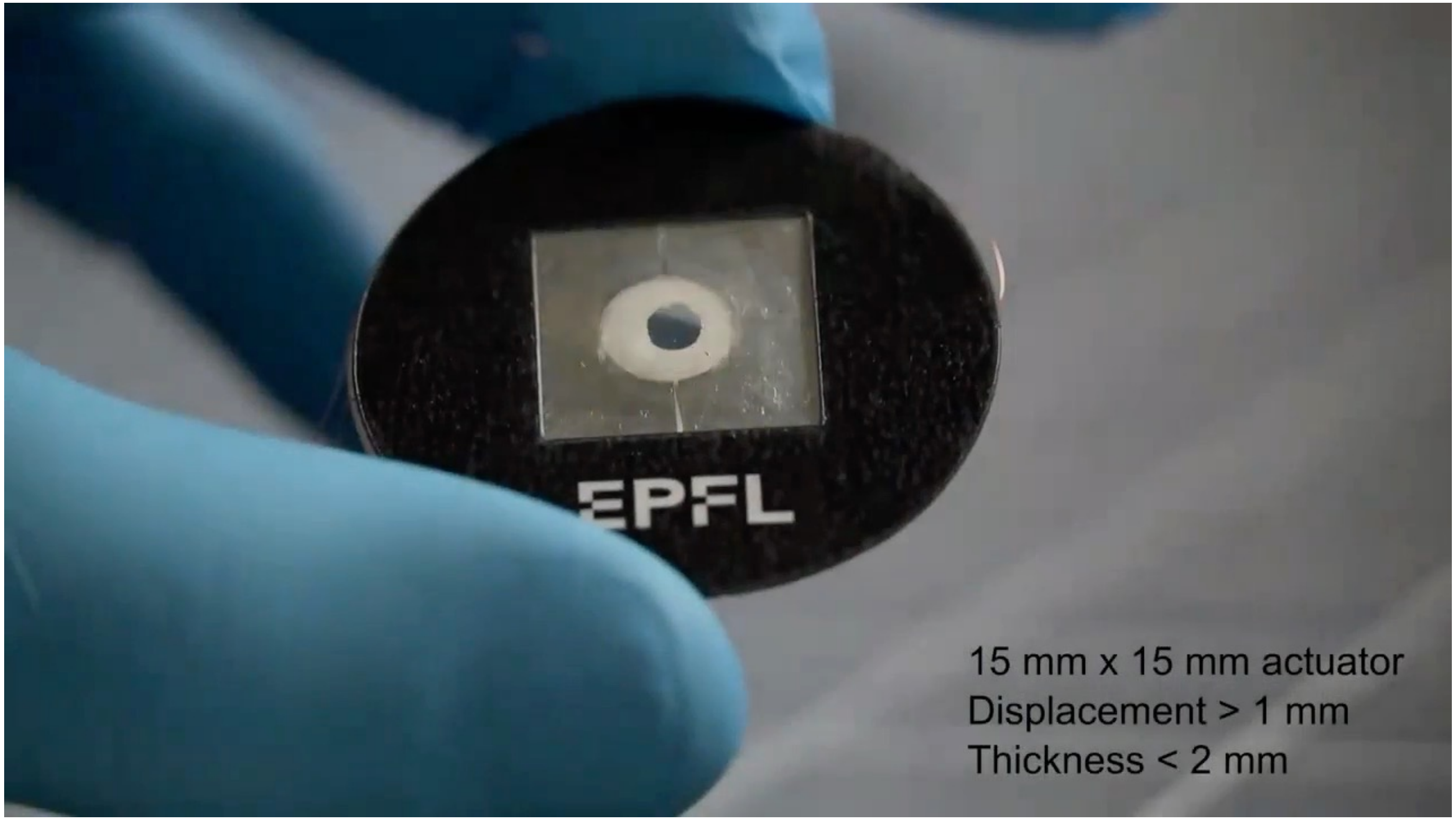
R. S. Diteesawat, et al, Electro-pneumatic pumps for soft robotics. *Science Robotics*. **6** (2021), doi:10.1126/scirobotics.abc3721.

HAXELs:
Hydraulically Amplified electrostatic taXELs



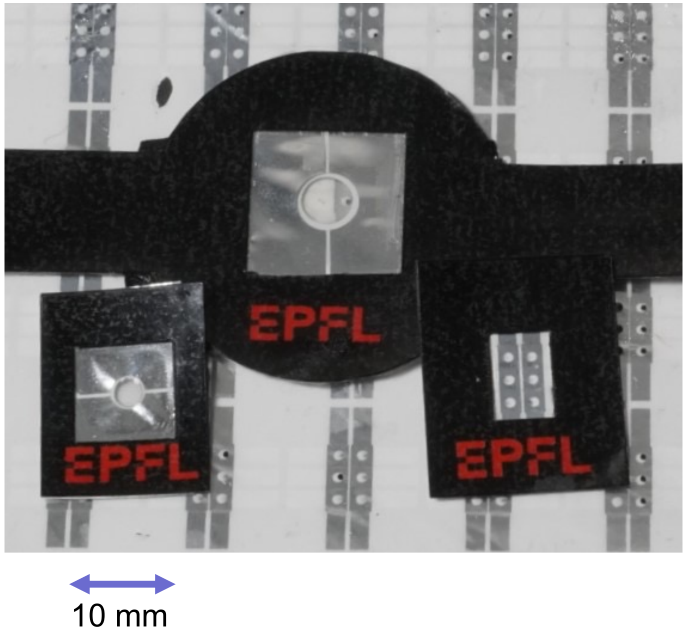
- Built-in hydraulic amplification
- central stretchable silicone region:
  - allows for higher strain
  - Good mechanical impedance match to the skin
- high-ε (ε_r=40) dielectric

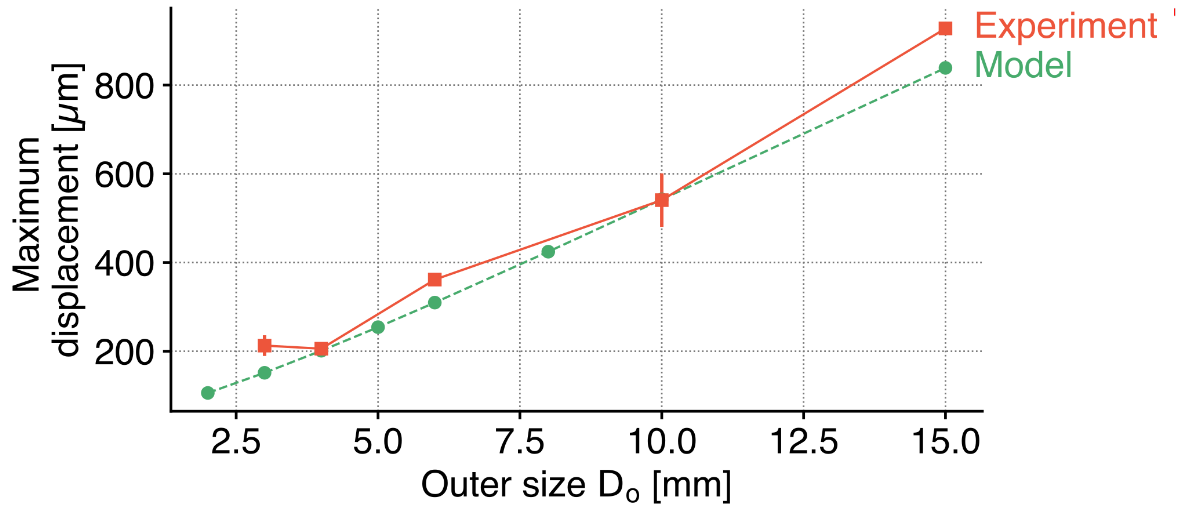
E. Leroy, R. Hinchet, H. Shea,
Multimode Hydraulically Amplified Electrostatic Actuators for Wearable Haptics.
Advanced Materials. **32**, 2002564 (2020).

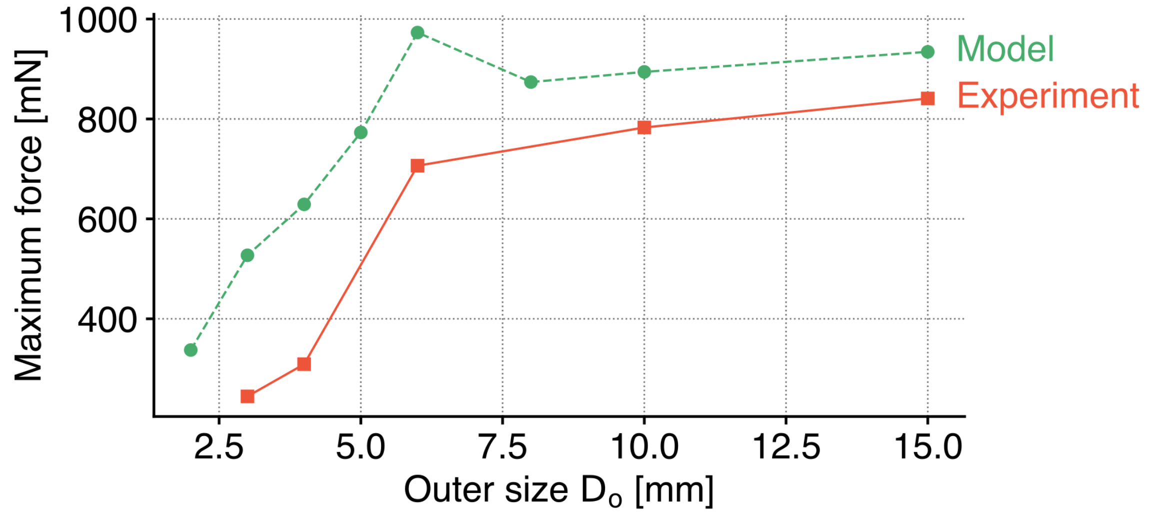


By separating electrostatic actuation from region of motion, can use higher energy density materials to displace the coupling, and soft materials for large deformations

HAXELs scale from 2 mm to 20 mm

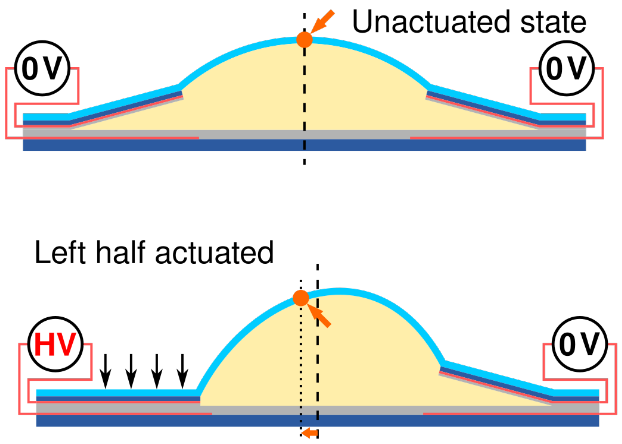


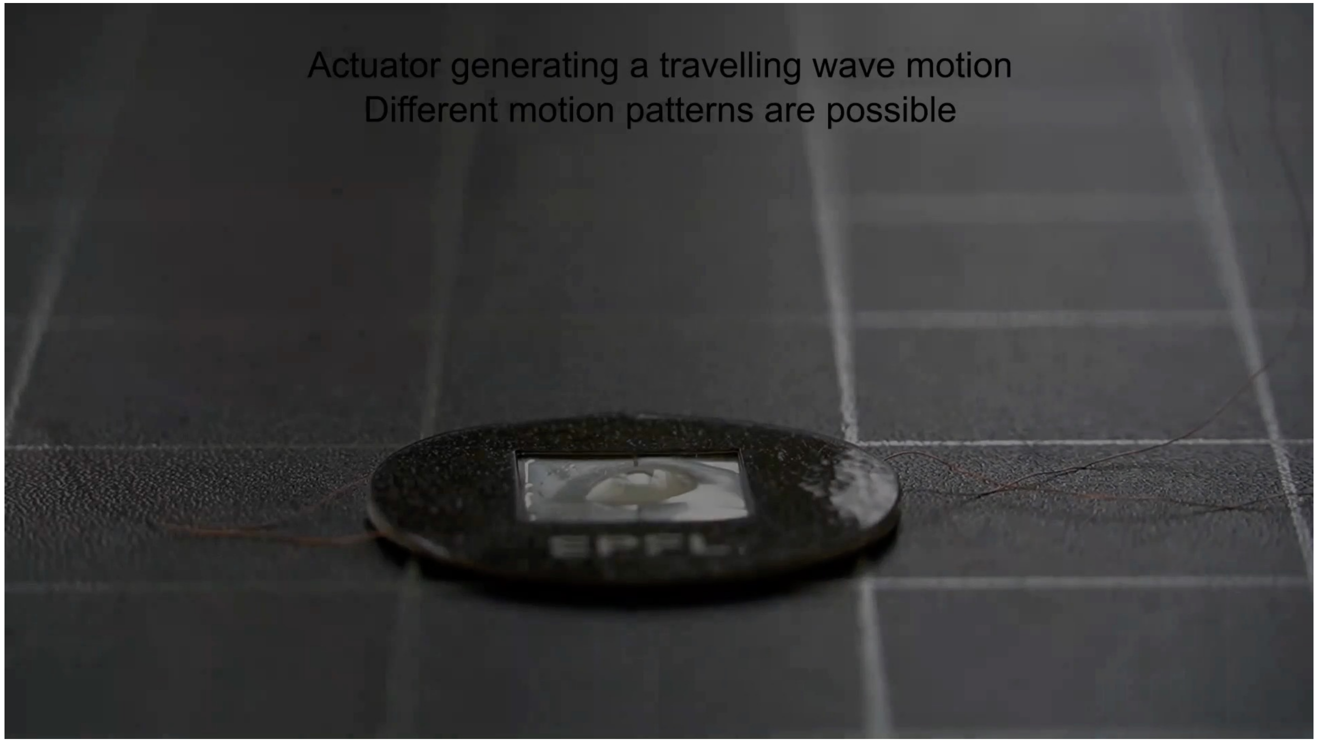




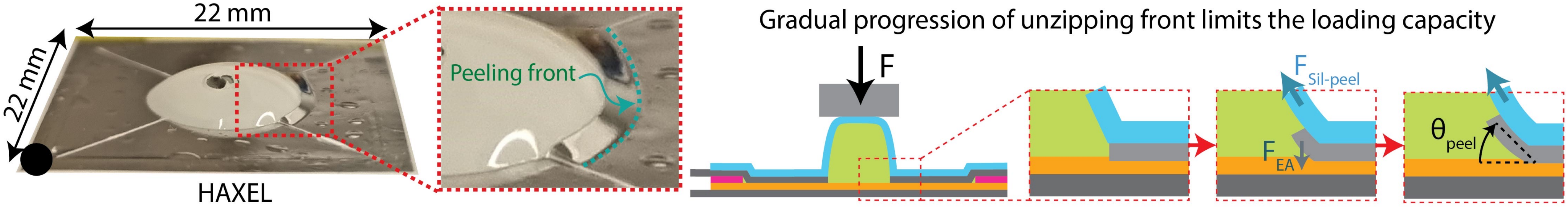
E. Leroy *et al*, Adv. Mat. Tech., revision, 2023

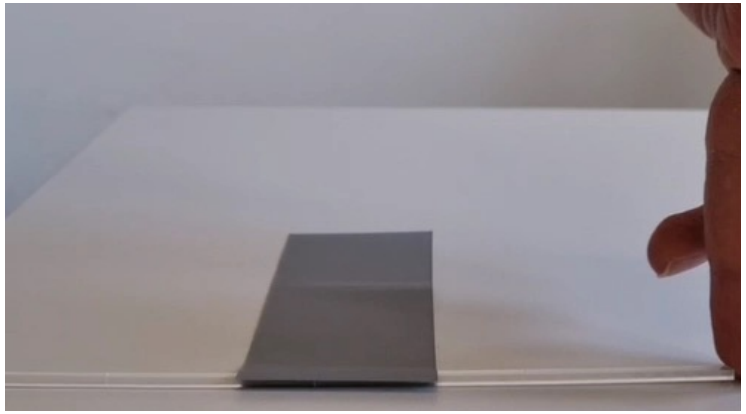
Splitting the HAXEL electrodes allows for in-plane motion: can generate shear force and skin stretch

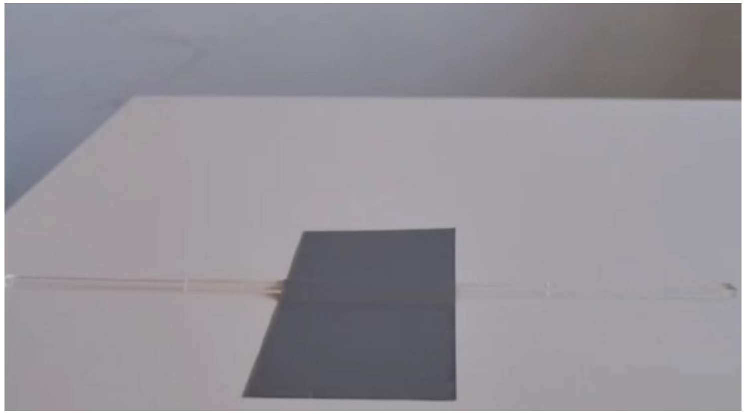




What limits the force a HAXEL can hold? Peeling

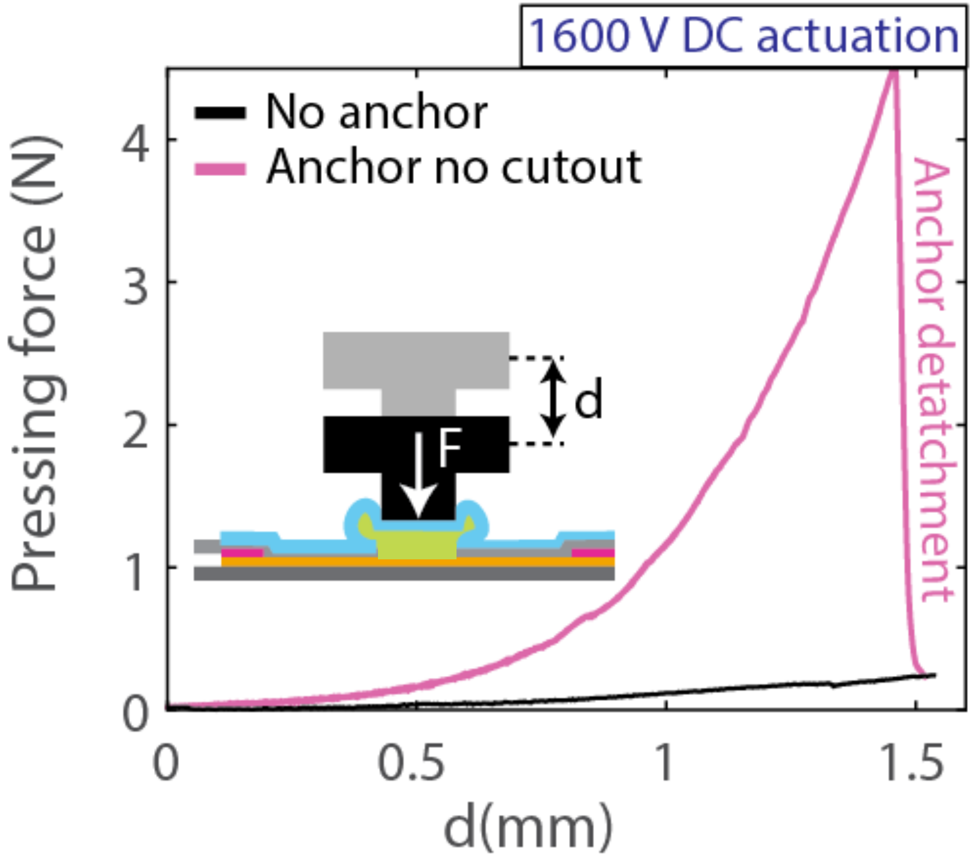






Firouzeh *et al*, manuscript under preparation

Improved design holds 4 N, then rapidly unzips, Feels like a button click



Dr. Amir Firouzeh

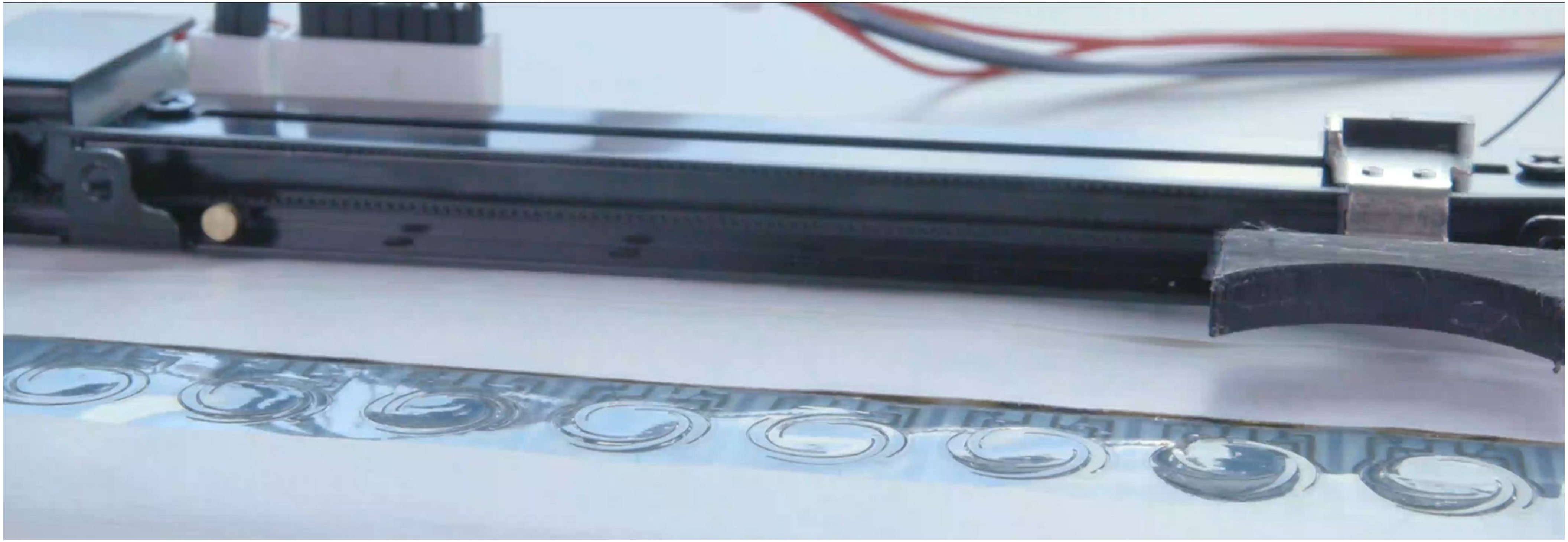
Firouzeh *et al*, manuscript under preparation

Sensorized PopTouch reconfigurable user interface, with intuitive haptic feedback, on surfaces such as back of a smart phone.

Video – real time

Firouzeh *et al*, manuscript under preparation

Buttons follow the slider…. but the slider can also follow button



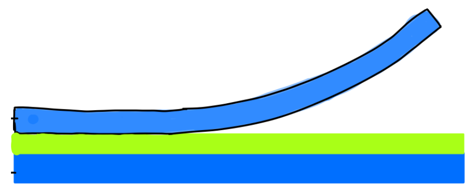
Video – real time

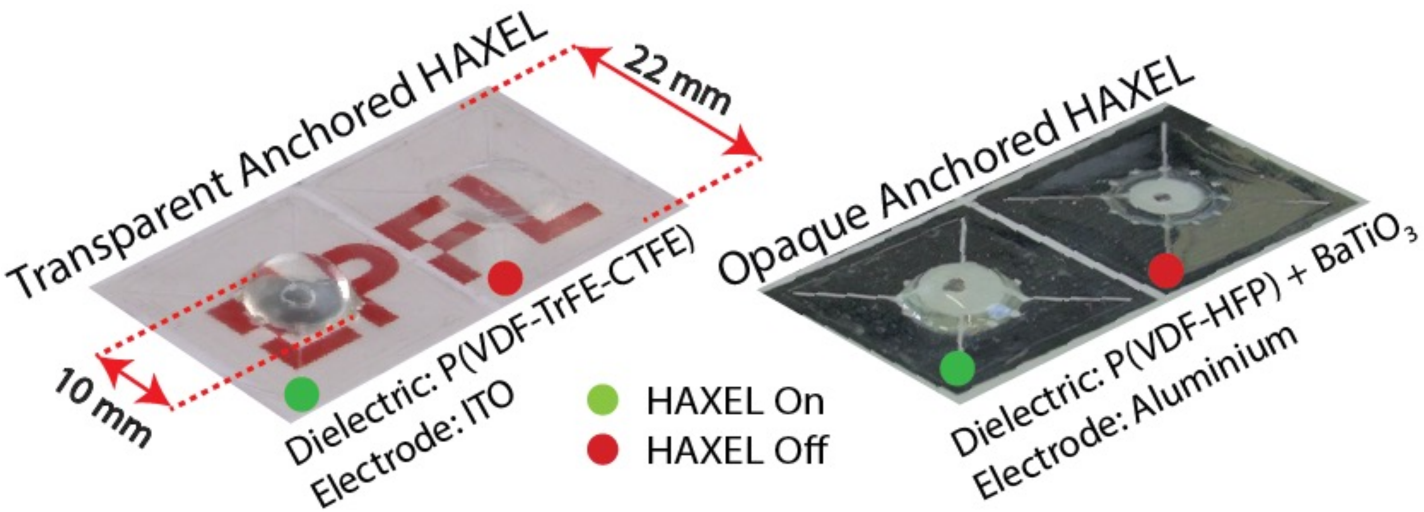
Transparent HAXELs !

Zipping actuator needs only flex, not stretch!

We developed a transparent version of Anchored-HAXELs by:

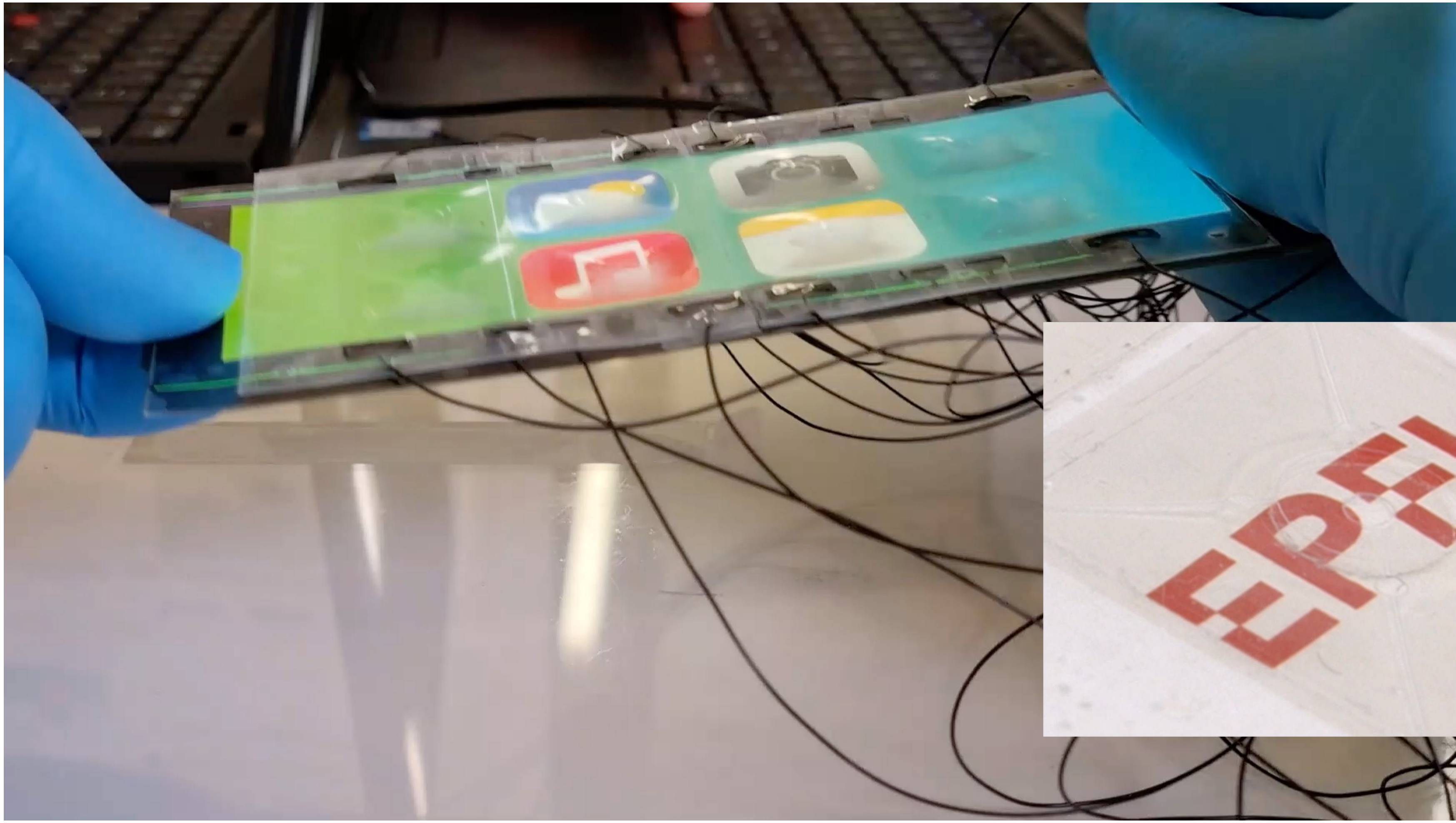
- Replacing the aluminum electrodes with a transparent layer Indium Tin Oxide (ITO)
- Replacing the opaque dielectric layer (composite of P(VDF-HFP) and $BaTiO_3$) with transparent P(VDF-TrFE-CTFE)





Firouzeh *et al*, manuscript under preparation

Transparent HAXELS: buttons pop up on touchscreens!

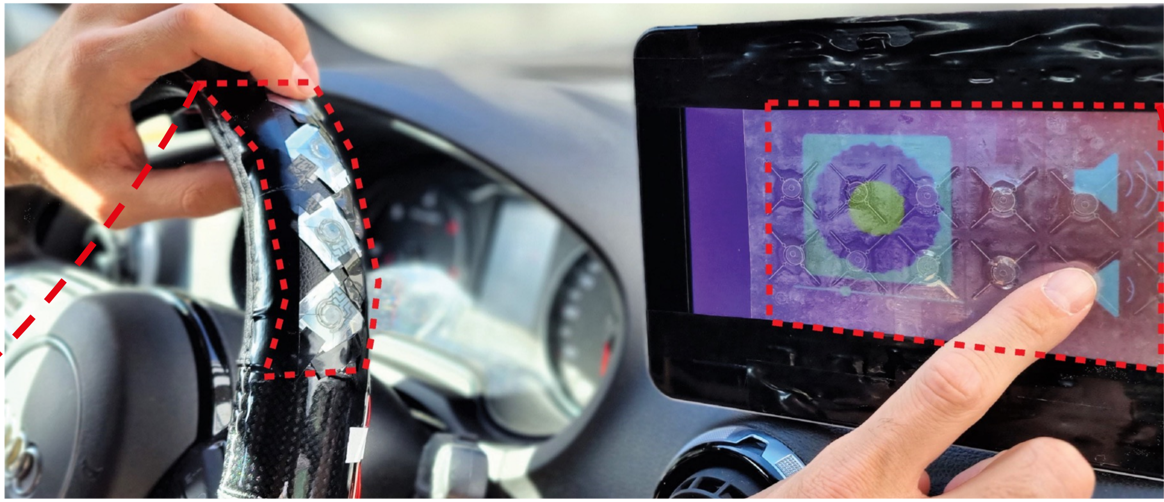


Ayana Mizutani

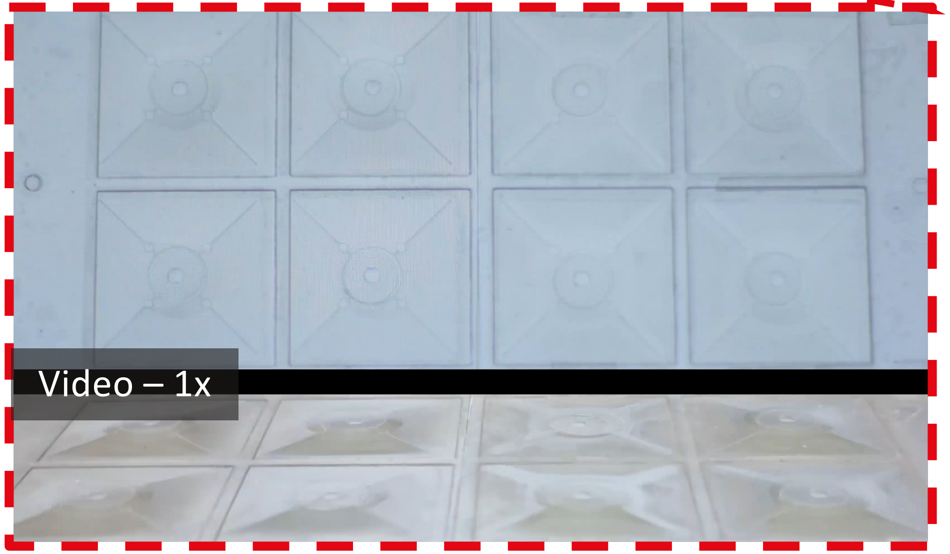
Firouzeh, Mizutani, et al, under preparation

PopTouch – In-vehicle application example

Sensorized PopTouch creates buttons where the user hand is to make interactions convenient

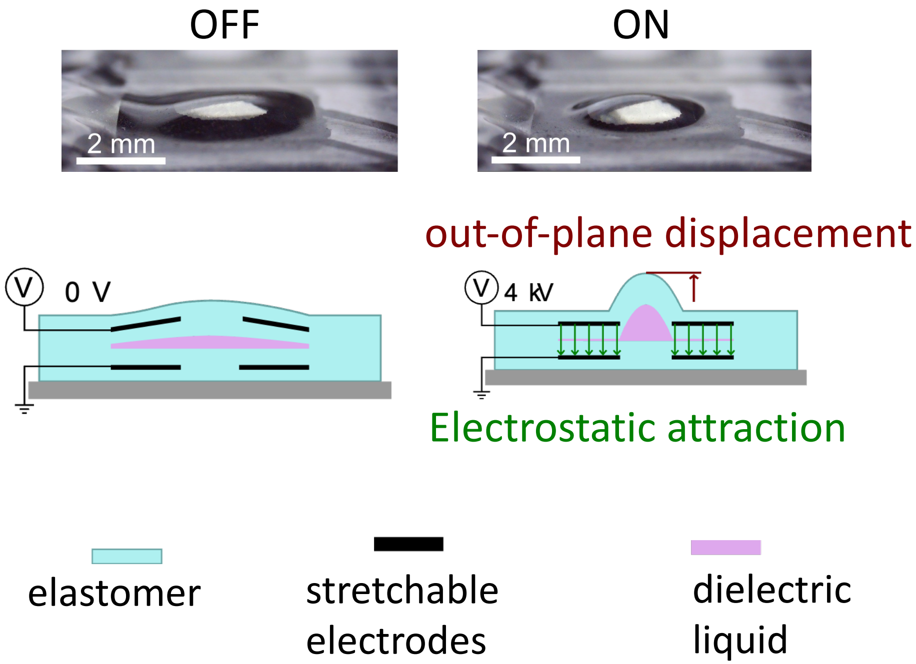


Transparent PopTouch add physical buttons on touchscreen for low-attention interaction



To make a HAXEL *stretchable, so can fit on a fingertip*: make is all silicone based

HAXELs: Hydraulically Amplified TaXELs

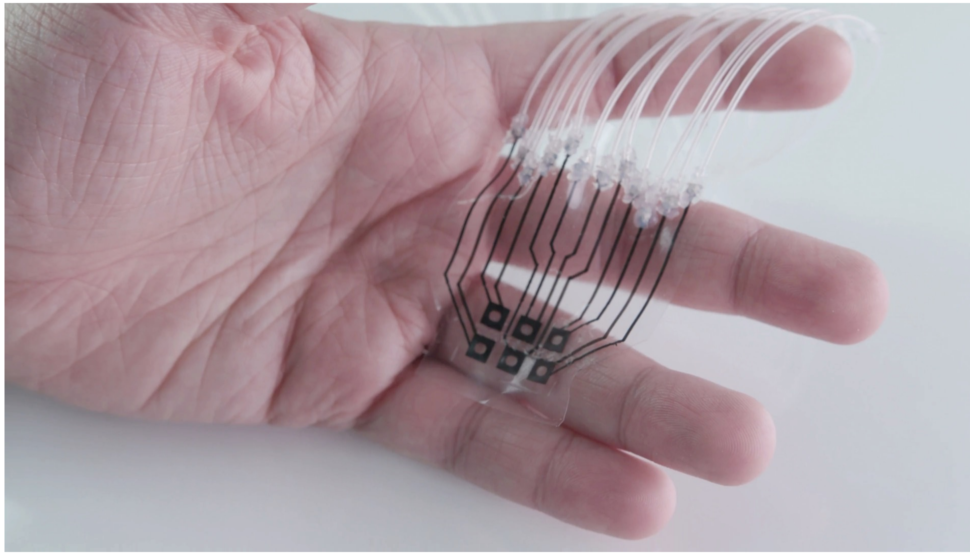


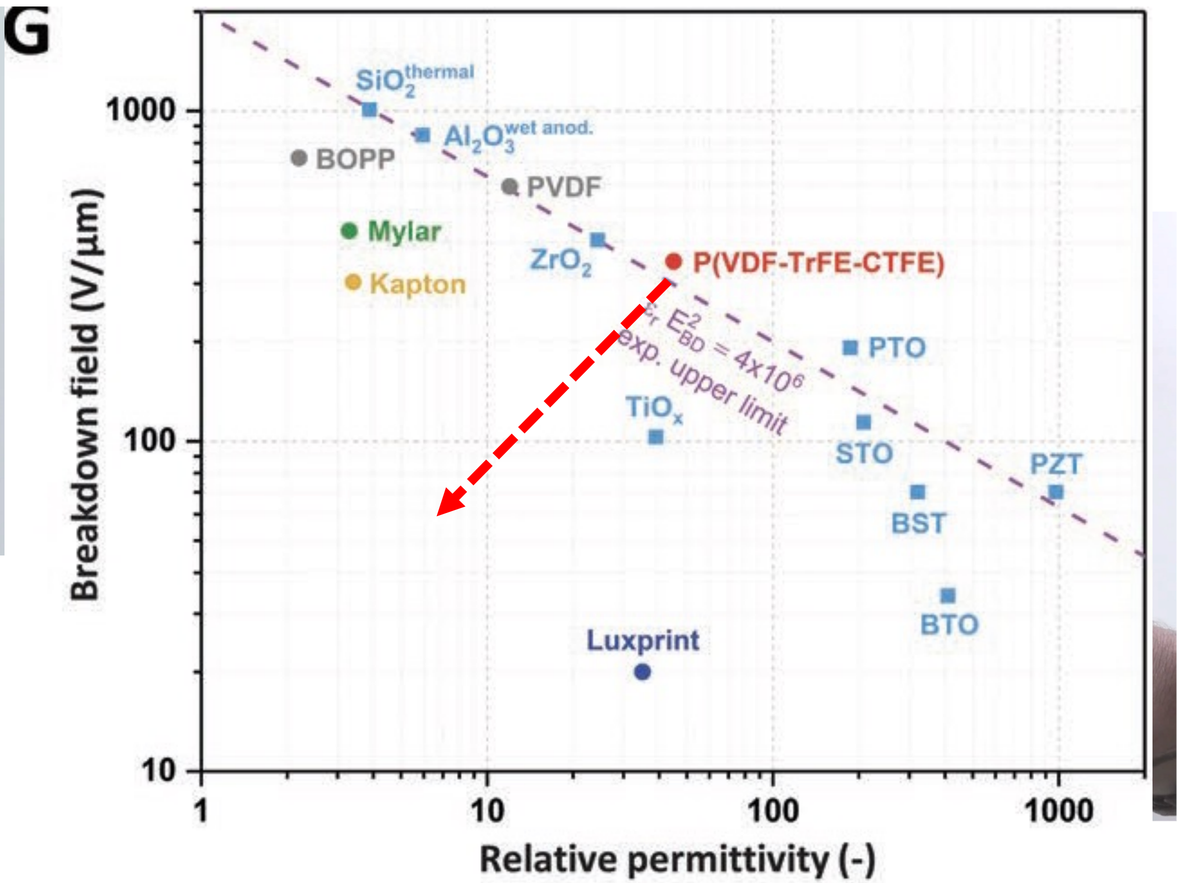
Giulio Grasso

Thus fully printed "feel-through" haptics on fingertips is *stretchable*, but lower electrical performance than flexible HAXEL

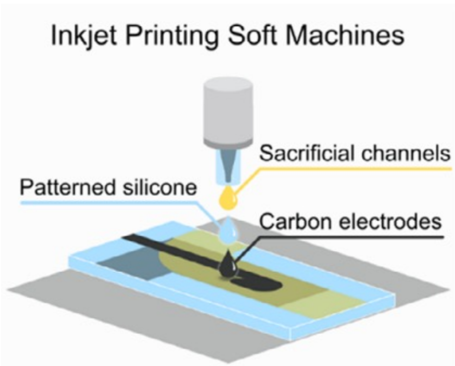
G. Grasso *et al.*, Adv. Func. Mat, 2023

To make it soft: all-printed for "feel-through" haptics on fingertips all silicone based (soft, but lower electrical performance)



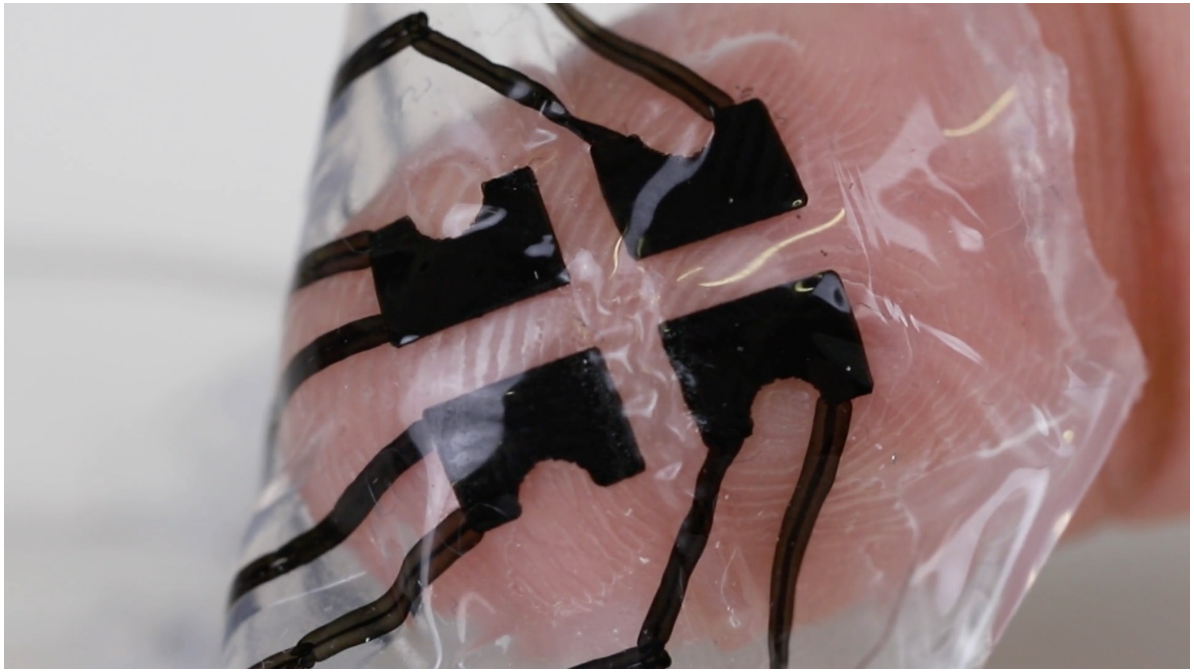


Giulio Grasso



G. Grasso *et al*, Adv. Func. Mat. 2023

Users easily correctly identify the actuated quadrant



30 mN, 200 µm stroke

Confusion matrix - Single Actuators

Active HAXEL \ User Response	Act.1	Act.2	Act.3	Act.4	No Act.
Act.1	78.2%	10.2%	0.5%	4.2%	6.9%
Act.2	13.0%	76.4%	0.5%	0.9%	9.3%
Act.3	0.0%	1.4%	92.6%	5.1%	0.9%
Act.4	3.2%	0.0%	3.2%	92.6%	0.9%
No Act.	0.0%	0.0%	0.0%	0.0%	100.0%

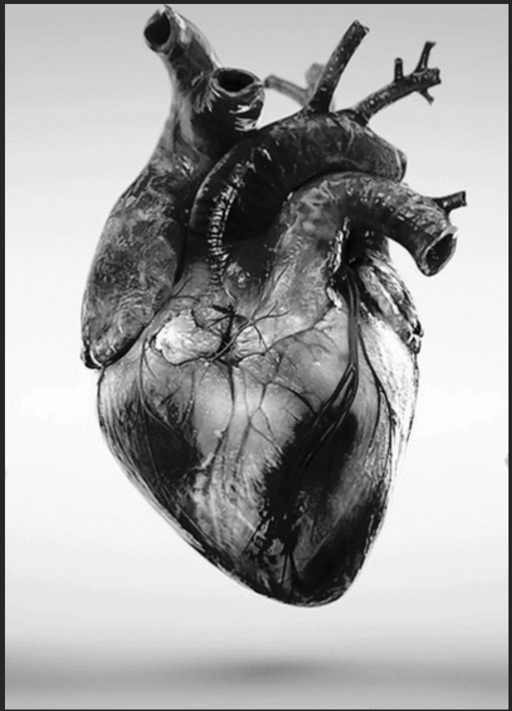
G. Grasso *et al*, Adv. Func. Mat. 2023

4. ELECTRO HYDRO DYNAMICS

Pneumatics are great, but they are tethered

Meta / Facebook reality labs

Soft pumps in nature



10 kPa

10 kPa [1]

5-60 kPa [2]

[1] 1.Anderson, J. F. & Prestwich, K. N. The fluid pressure pumps of spiders (Chelicerata, Araneae). Z. Morph. Tiere, 1975.
[2] Wainwright, P. C., Turingan, R. G. & Brainerd, E. L. Functional Morphology of Pufferfish Inflation: Mechanism of the Buccal Pump. *Copeia* 1995

How to generate fluid pressure and flow ?

External Compressor

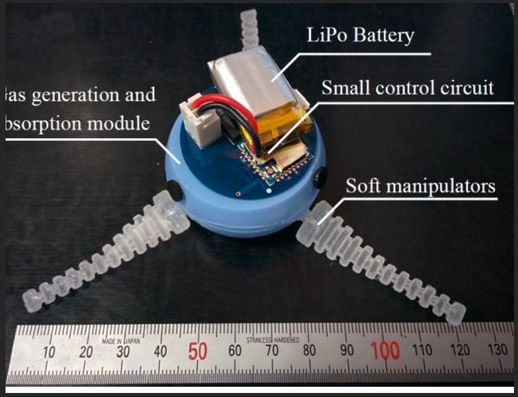
Soft Robotics Inc.

Chemical reaction to generate pressure

M. Wehner et al, Nature, 2016.

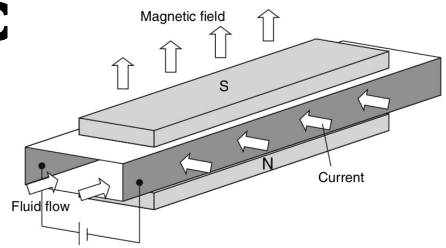
Miniature mechanical pump

M. Tolley et al, Soft Robotics, 2014.



T. Kitamori et al, IROS 2016.

Moving liquids with electric



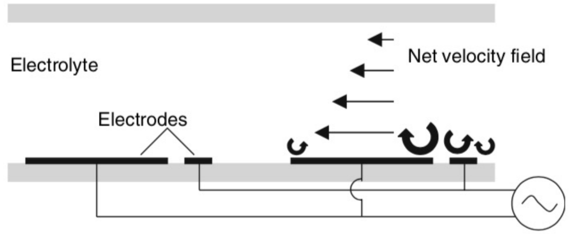
MagnetoHydroDynamic

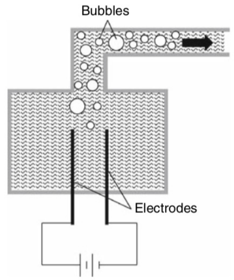
Broad field:

- Dielectrophoresis
- Electrostriction
- ElectroOsmosis
- Magnetohydrodynamics
- (even Combustion…)

But generally not soft…

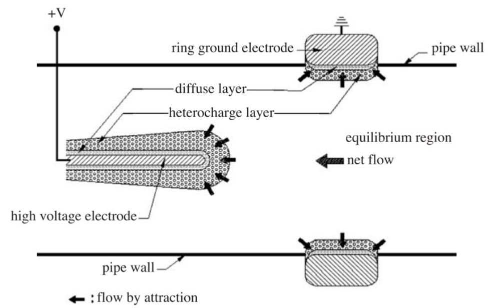
ElectroOsmotic





Phase change

ElectroHydroDynamic (EHD)

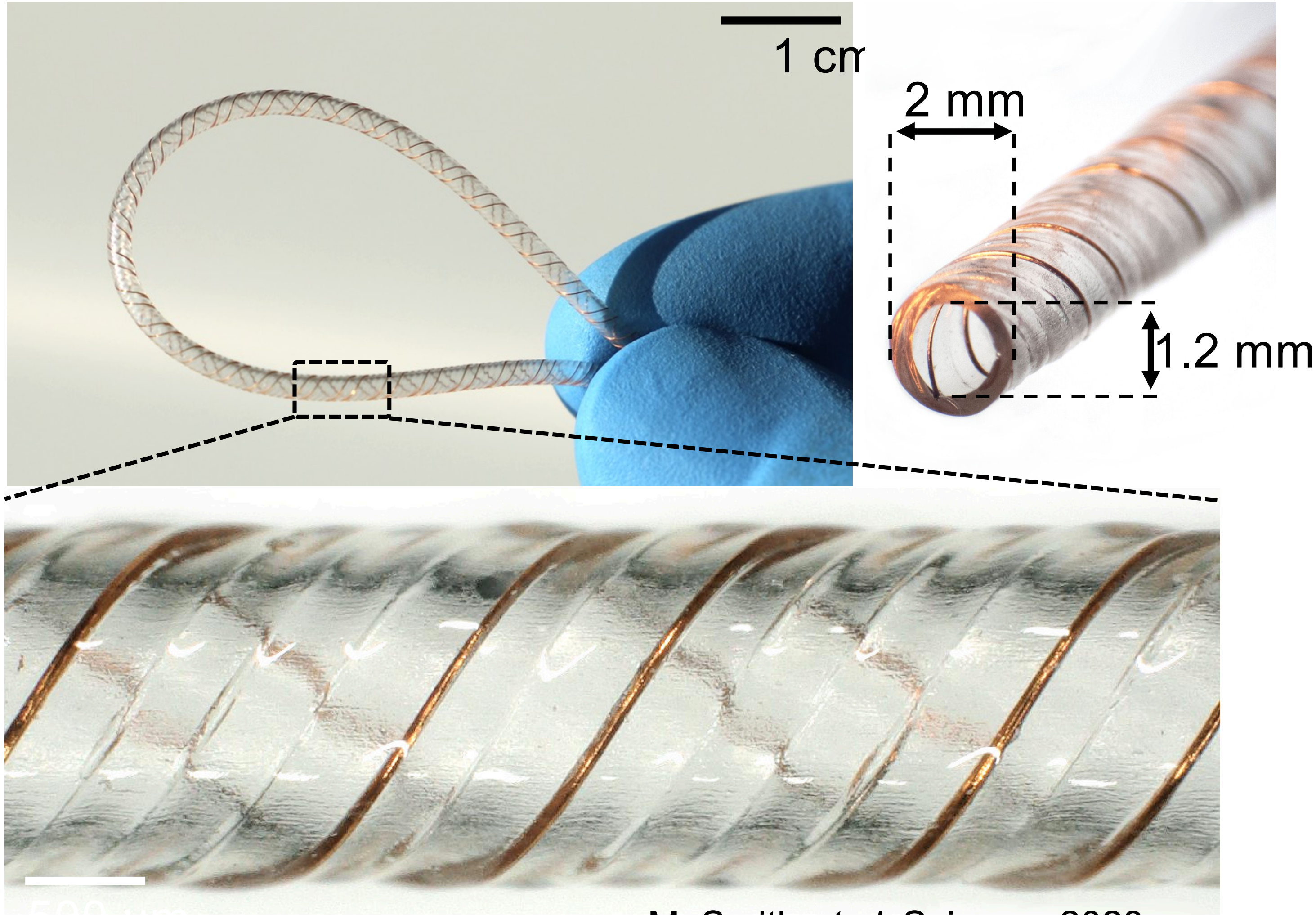


Iverson, B. D. & Garimella, S. V. Recent advances in microscale pumping technologies: a review and evaluation. *Microfluidics and Nanofluidics,* 2008.

J. Seyed-Yagoobi, “Electrohydrodynamic pumping of dielectric liquids,” J. Electrostat., 2005.

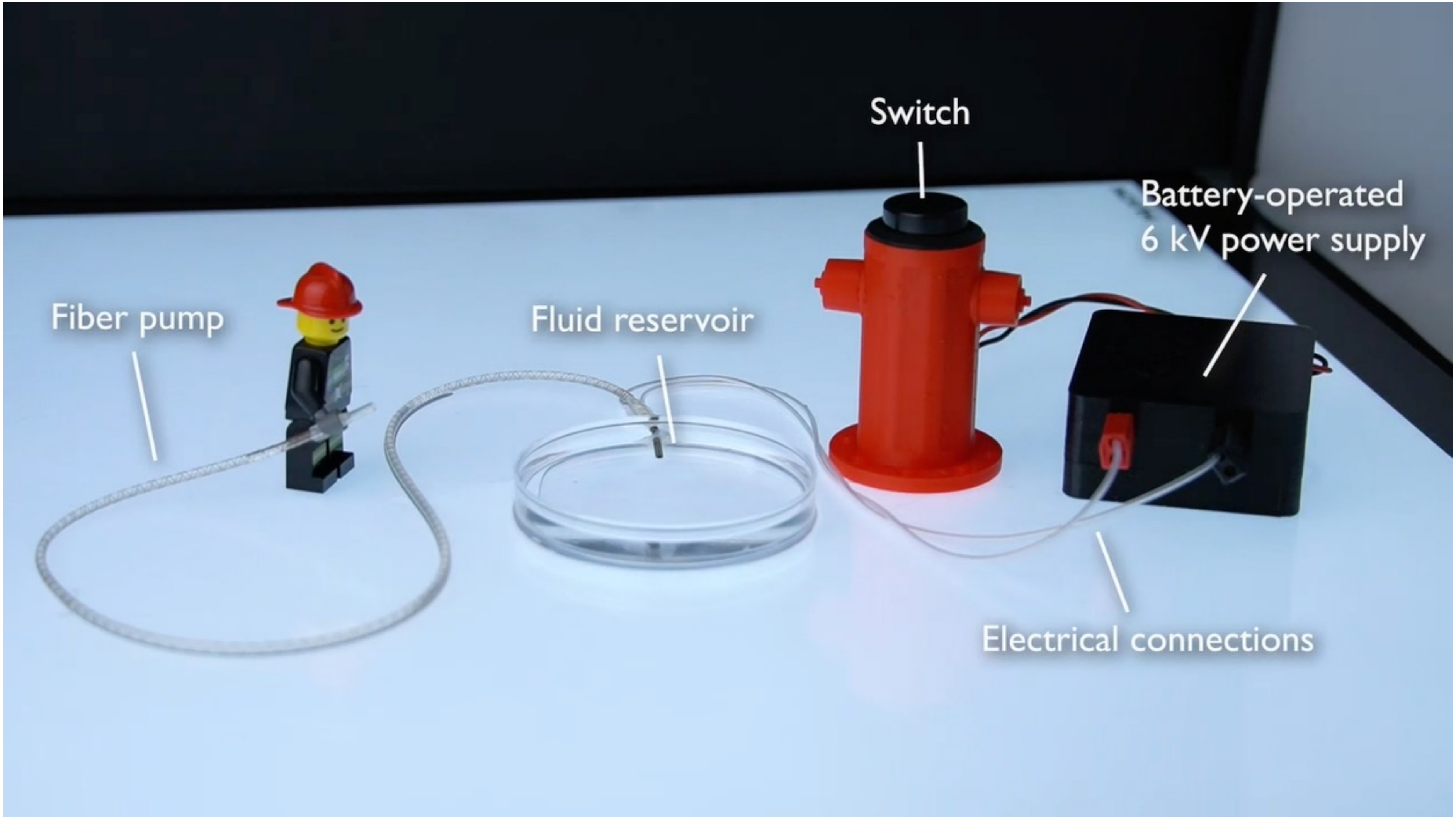
Fiber pumps for wearable fluidic systems

- 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**



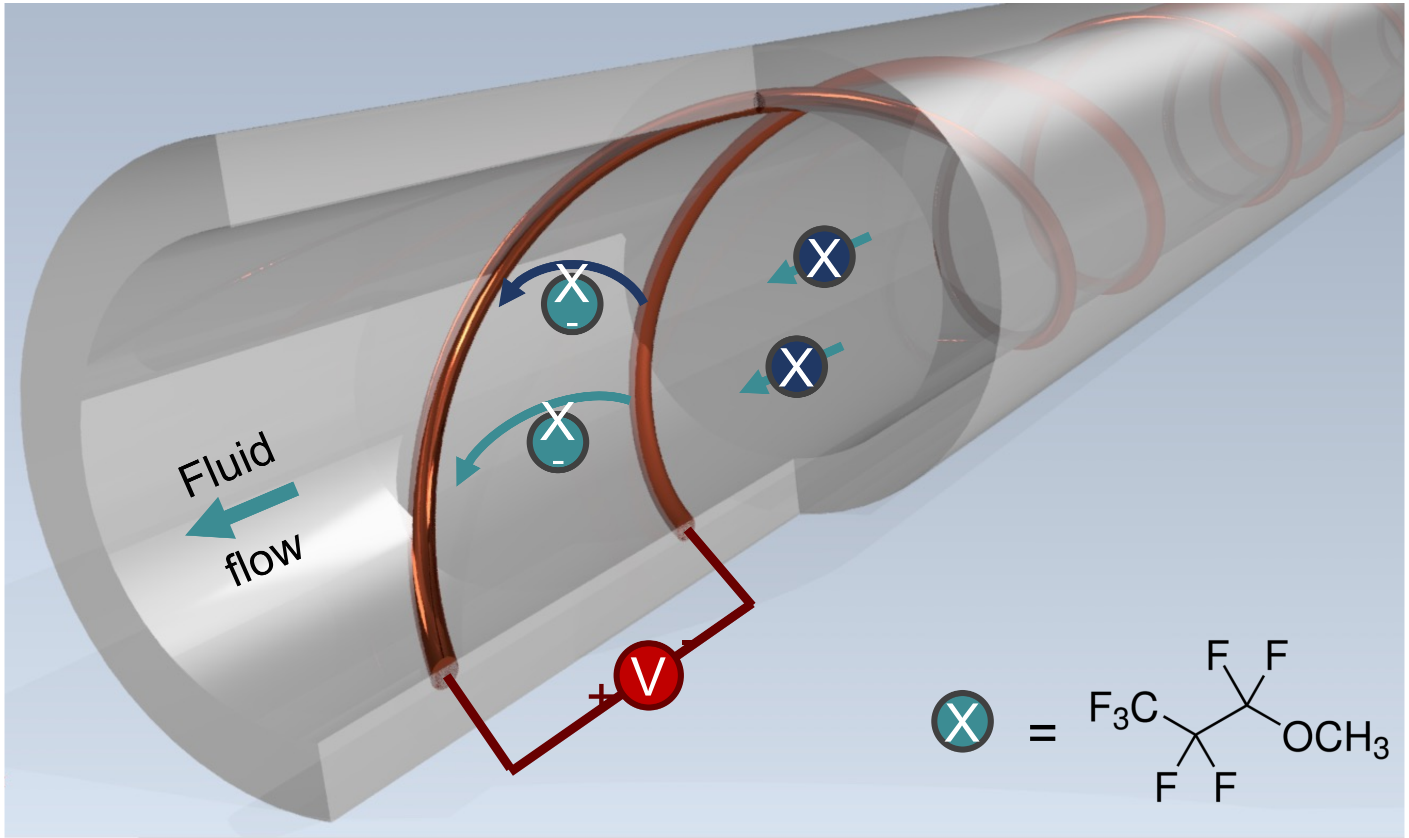
M. Smith *et al*, Science, 2023

Fiber pumps: the tube is the pump!



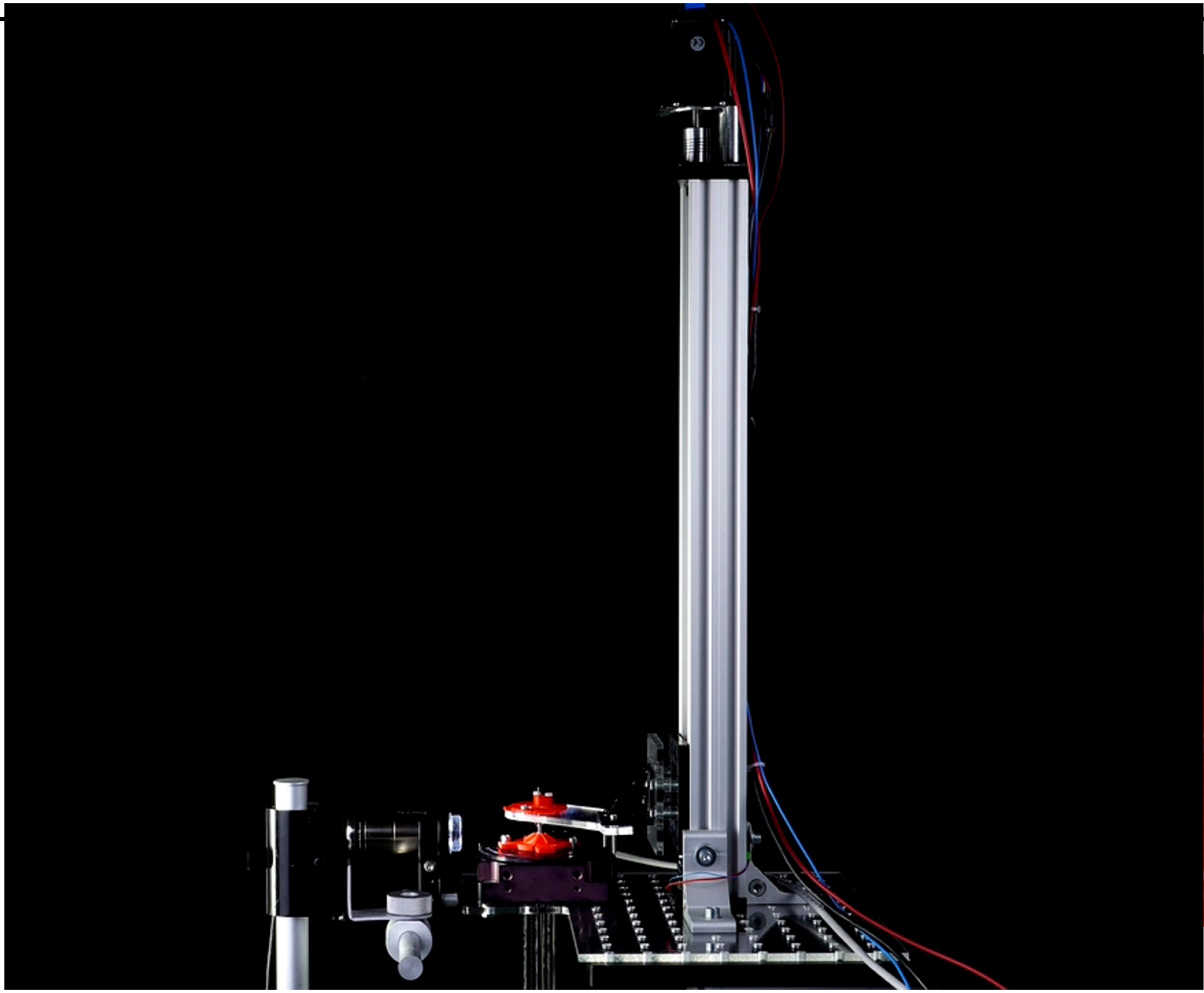
Charge injection electrohydrodynamics (EHD)

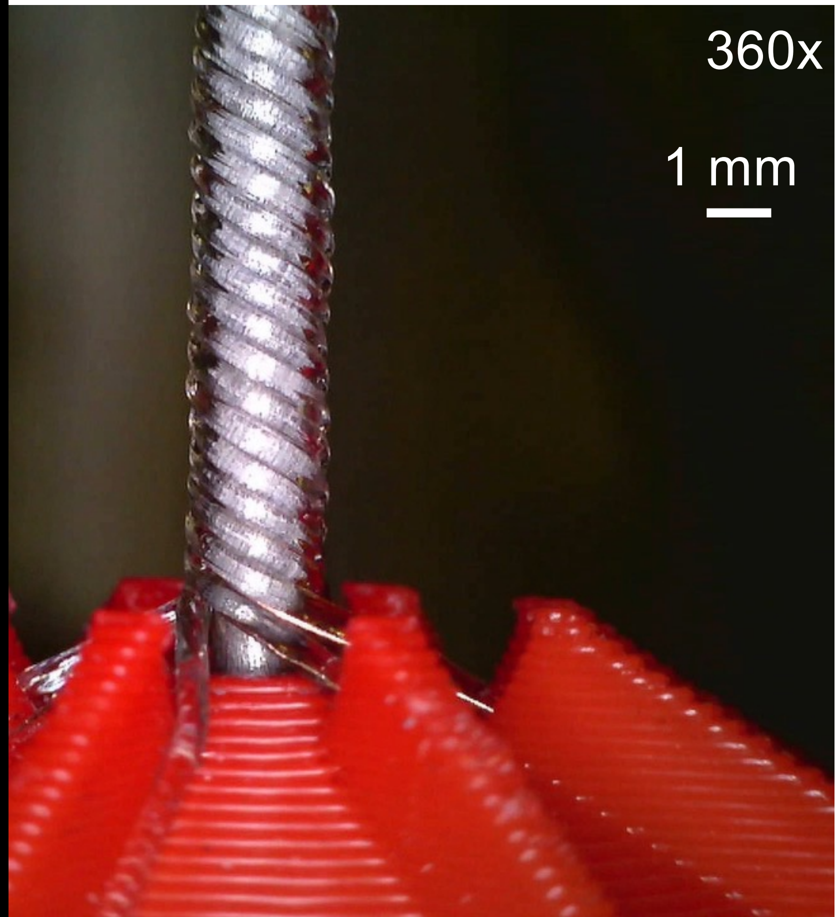
- Dielectric fluid becomes ionised at the negative electrode
  - Novec 7100 fluid
  - (or other insulating liquids)
- Ions are accelerated by electric field
- Asymmetrically spaced electrodes generate a net flow in chosen direction
- High voltage (kV)
- Low current (μA)
- Low power consumption (sub-W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



M. Smith *et al*, Science, 2023

Scalable filament winding fabrication method





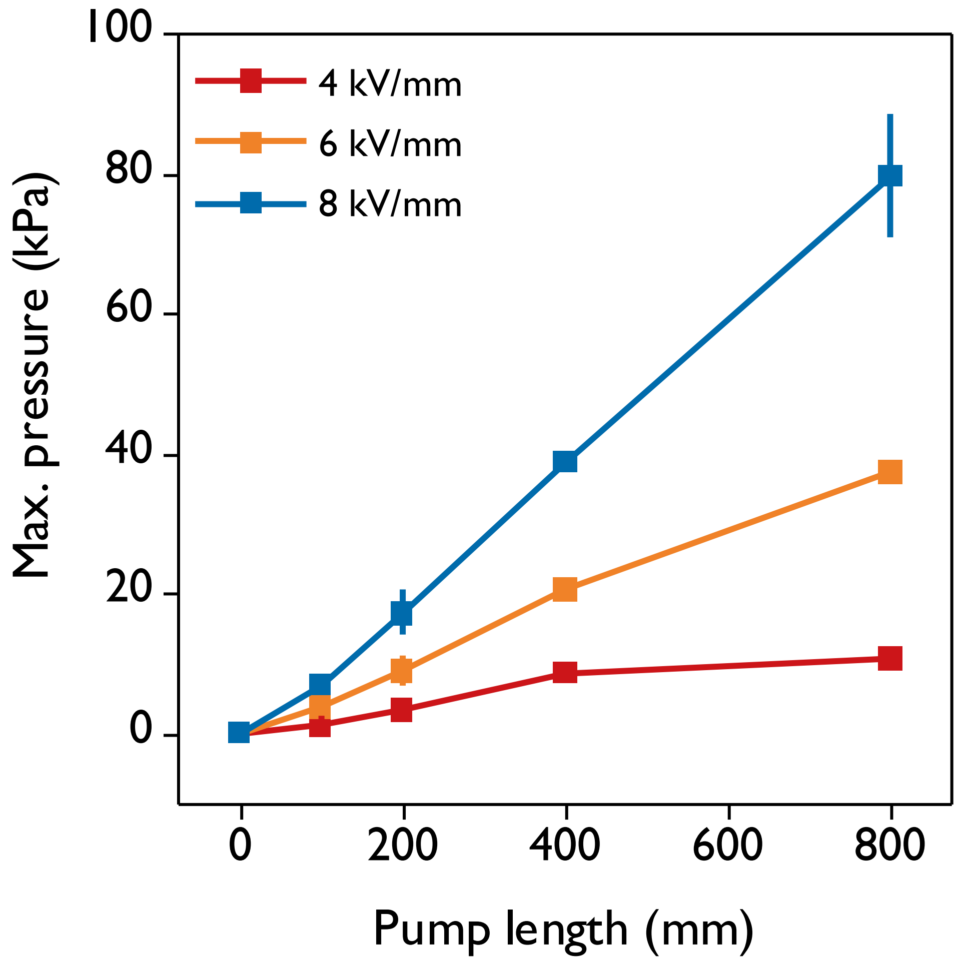
M. Smith *et al*, Science, 2023

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 / m^3
  - 27 W / kg
  - Equal to or greater than that of any other ‘soft’ pump
  - (But 10x lower than electrostatic zipping devices…)



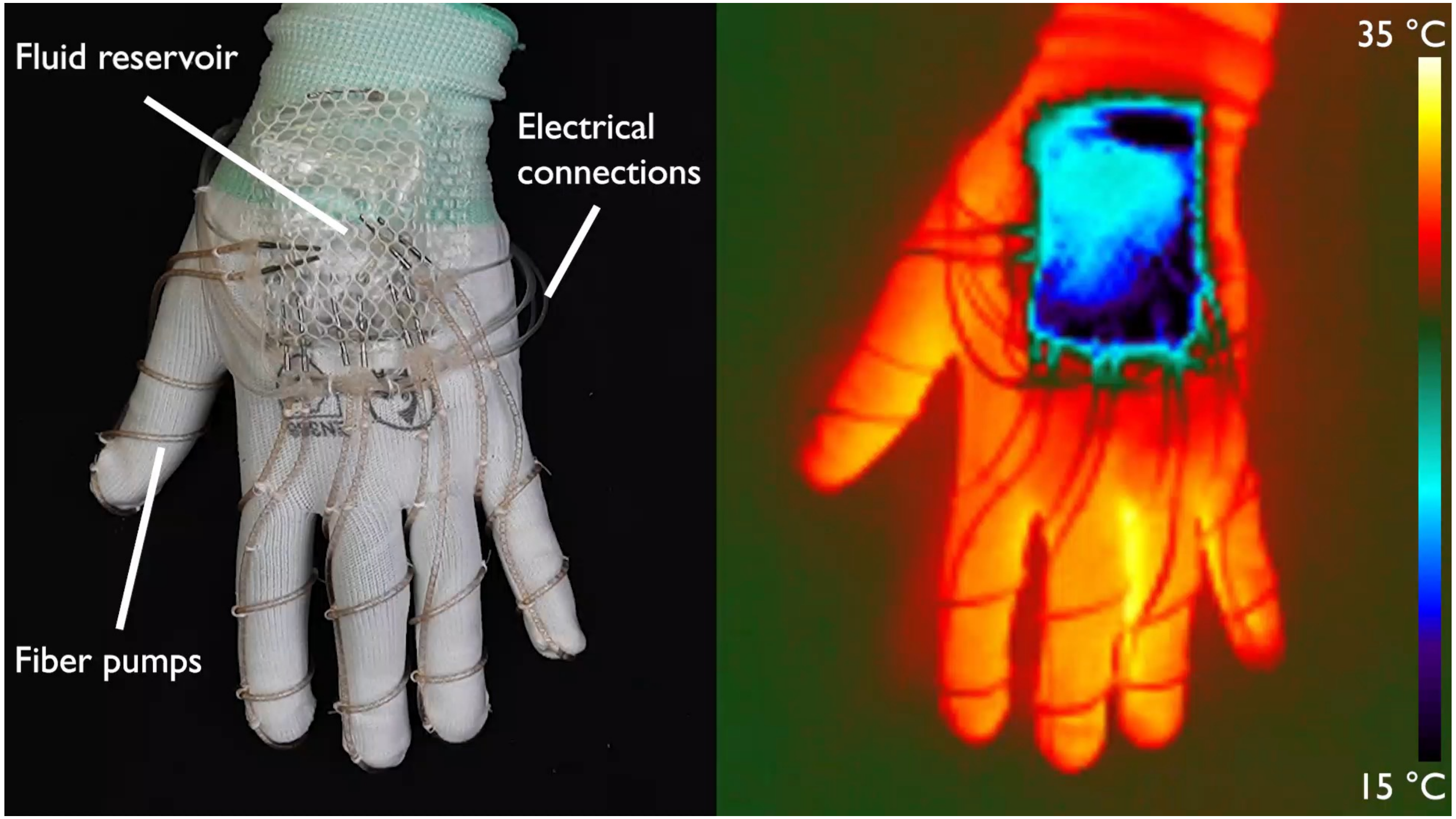
Fiber performance is broadly unaffected by deformation

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

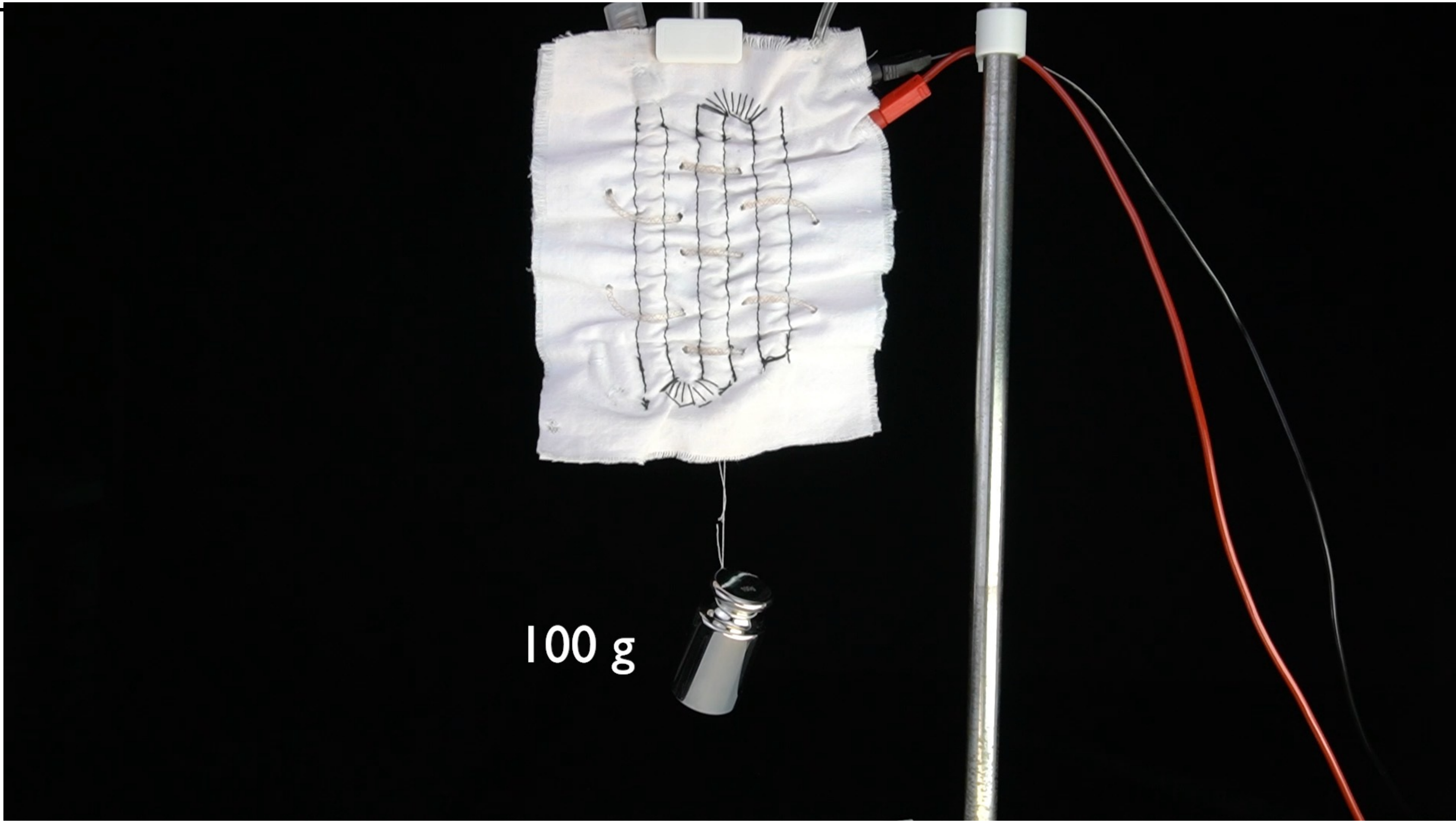
- Difficult to achieve using conventional pumps and equipment



M. Smith *et al*, Science 2023

EPFL

Integrating our pump into Fabric actuators (similar to IPAM)



servoir

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lastic fabric

Supplementary video 10

Washability of fiber pumps and fabric actuator

Fiber pumps for wearable fluidic systems

Michael Smith, Vito Cacucciolo, Herbert Shea

M. Smith *et al*, Science 2023

High performance fiber pumps will enable many applications in untethered wearable soft robotics

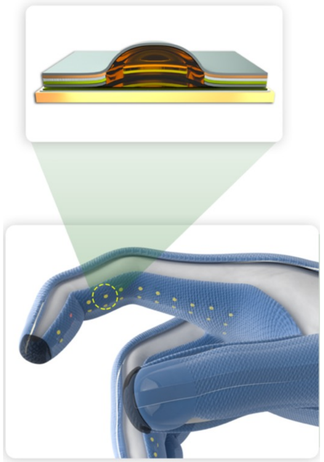
Suzumori lab, Tokyo Tech

- **The tube is the pump**: Generate pressure in distributed manner on body to locally actuate soft exoskeletons. What is the best architecture?
- Scales: longer fiber, higher pressure !
- But efficiency is still only 3% …

TOWARDS *SMART* SOFT MACHINES WITH DIRECT ELECTRICAL CONTROL

- Electrostatics and elastomers combine well to form soft efficient actuators.

- These compliant actuators can be placed on the body to create realistic and immersive haptic illusions



Challenges remain on soft actuation, integration, control, and system architecture

Bright future with a wide range of applications:

- Haptics
- Soft exoskeletons
- Gripper + Smart manipulation
- Implantable devices
- …

EPFL

Thanks to my LMTS team

Many thanks to you, for your attention!

Contact Info:

Herbert Shea (herbert.shea@epfl.ch)
Details & movies: https://www.epfl.ch/labs/lmts/