ENG-615: Topics in Autonomous Robotics

April 29 2025

Electrostatic actuators for soft or wearable robotics

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Suzumori lab, Tokyo Tech

EPFL-LMTS

A. Intro: Actuators for soft robots

B. Electrostatic actuation

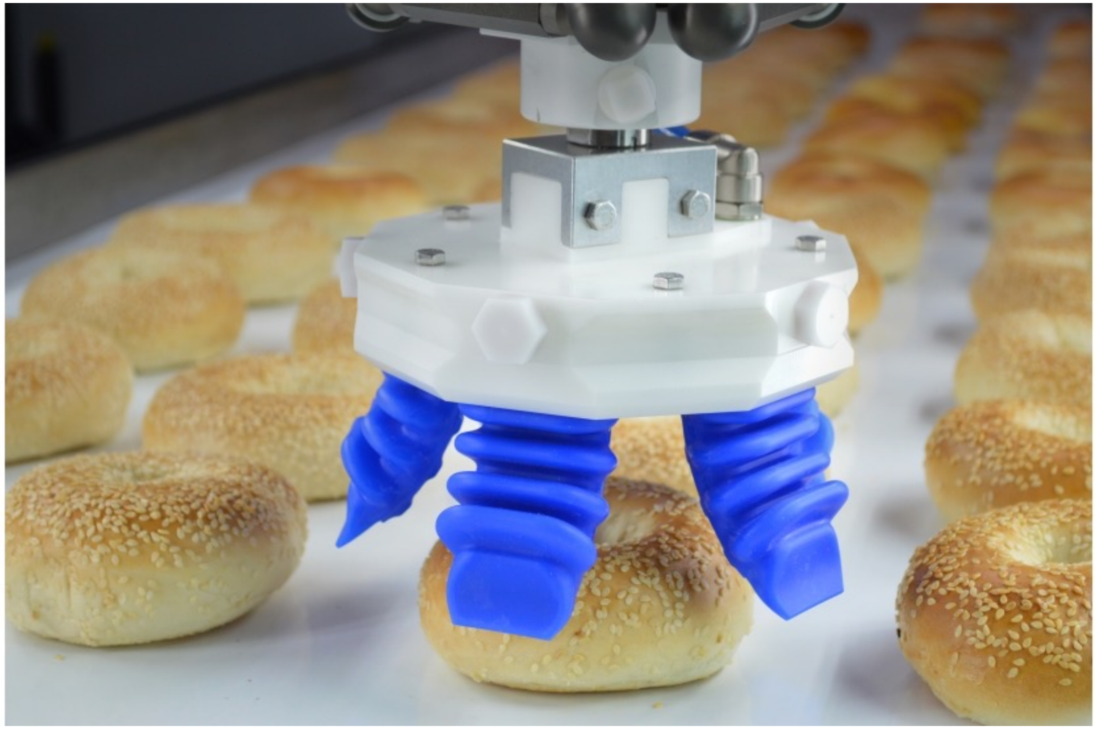
1. ES clutches & ElectroAdhesion
2. DEA
3. Zipping actuators
4. ElectroHydroDynamic (EHD) pumps

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

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

Ideally:

- Adapt their shape to match desired geometry
- Yet have sufficient mechanical stiffness to manipulate objects
- Hold their shape using zero power
- Are energy efficient when moving
- Fast
- Simple to control
- Untethered / Autonomous



Soft Robotics Inc.

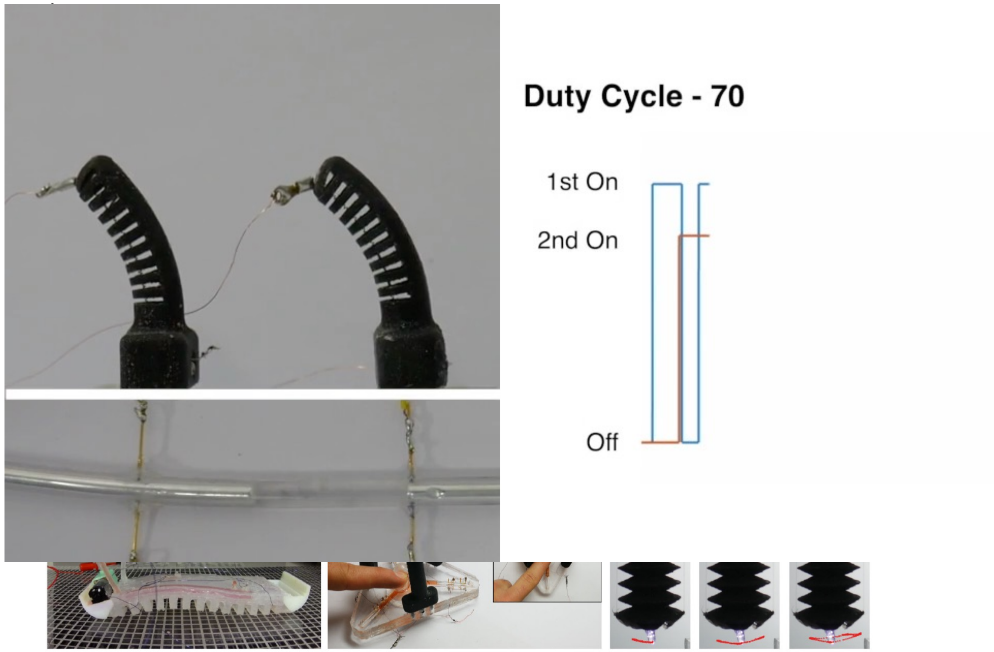
WHAT IS NEEDED TO MAKE A MACHINE SOFT, SMART, AND AUTONOMOUS?

EPFL

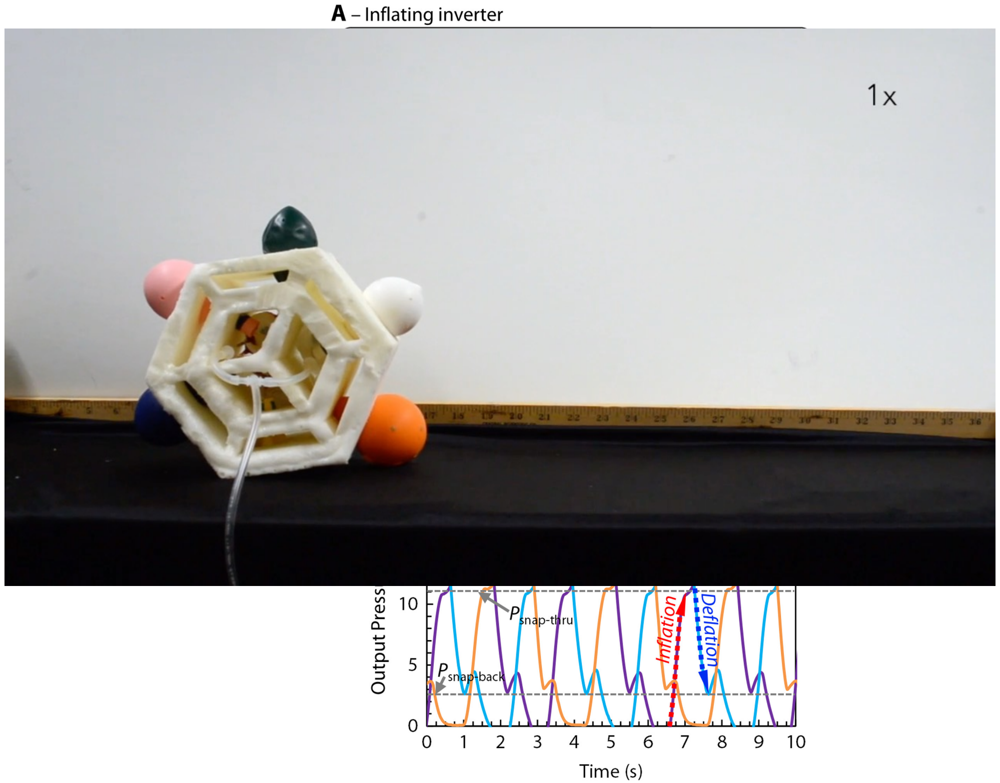
- Soft Distributed Sensors
- Soft Energy storage
- Soft Actuators
- Soft Control & Computation

Soft Computing

Include a nice Silicon CPU, or go all soft?
Also need relays, valves, etc…

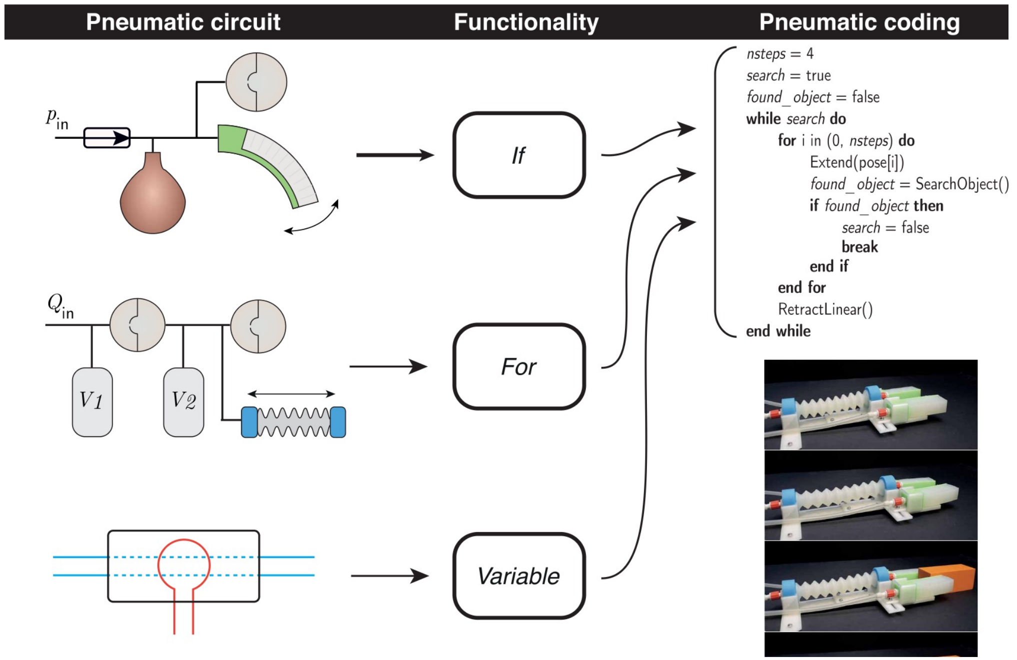


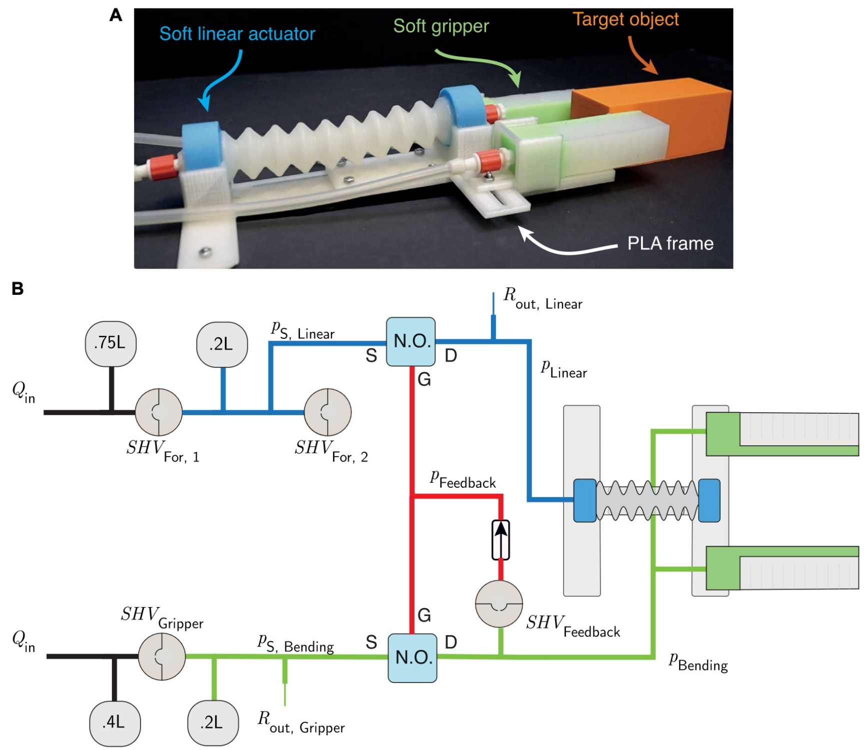
"Soft Matter Computer"
Garrad *et al*, Science Robotics 2019
Garrad et al, IEEE Robotics and Automation Letters 2021
https://doi.org/10.1109/LRA.2021.3068118



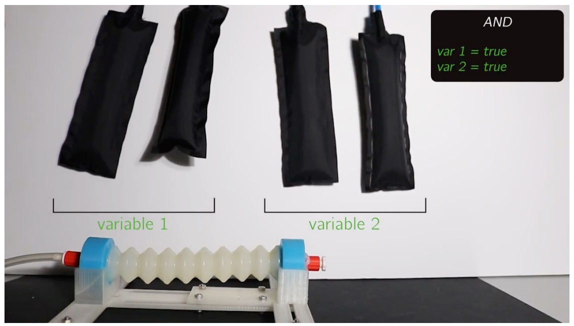
"A soft Ring Oscillator"
Preston et al. Sci. Robotics 2019

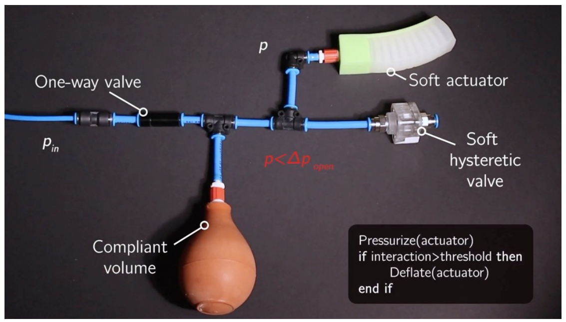
Programmable Soft Computing





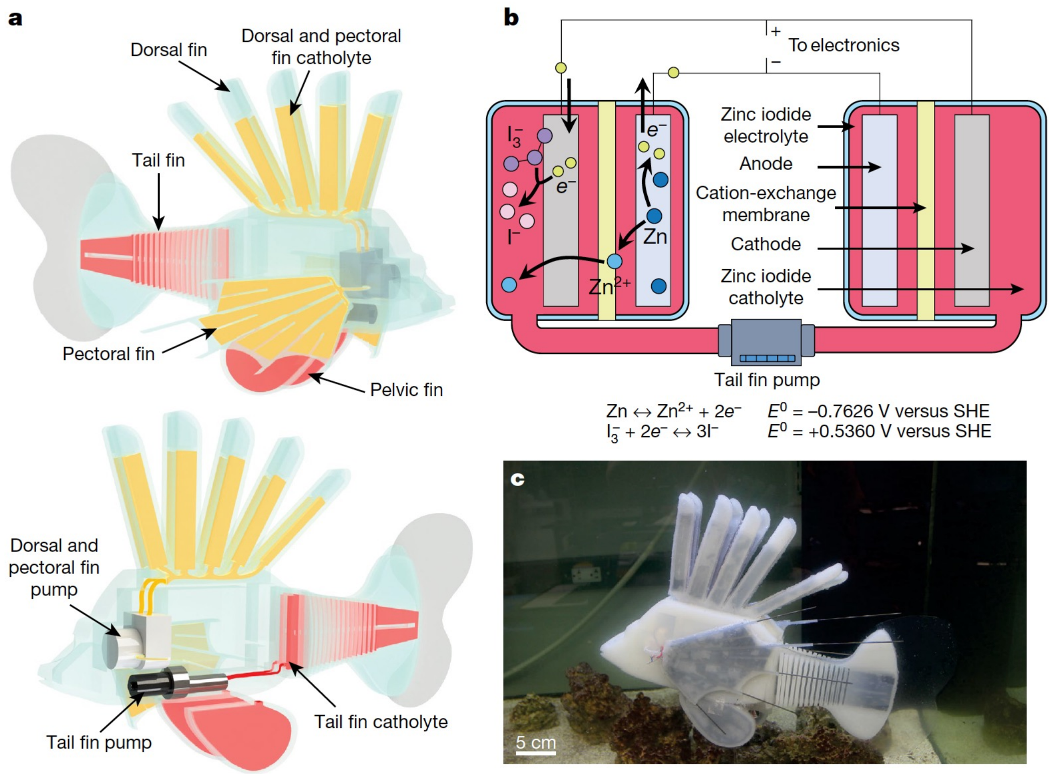

```
nsteps = 4
search = true
found_object = false
while search do
    for i in (0,nsteps) do
        Extend(pose[i])
        found_object = SearchObject()
        if found_object then
            search = false
            break
        end if
    end for
    RetractLinear()
end while
```



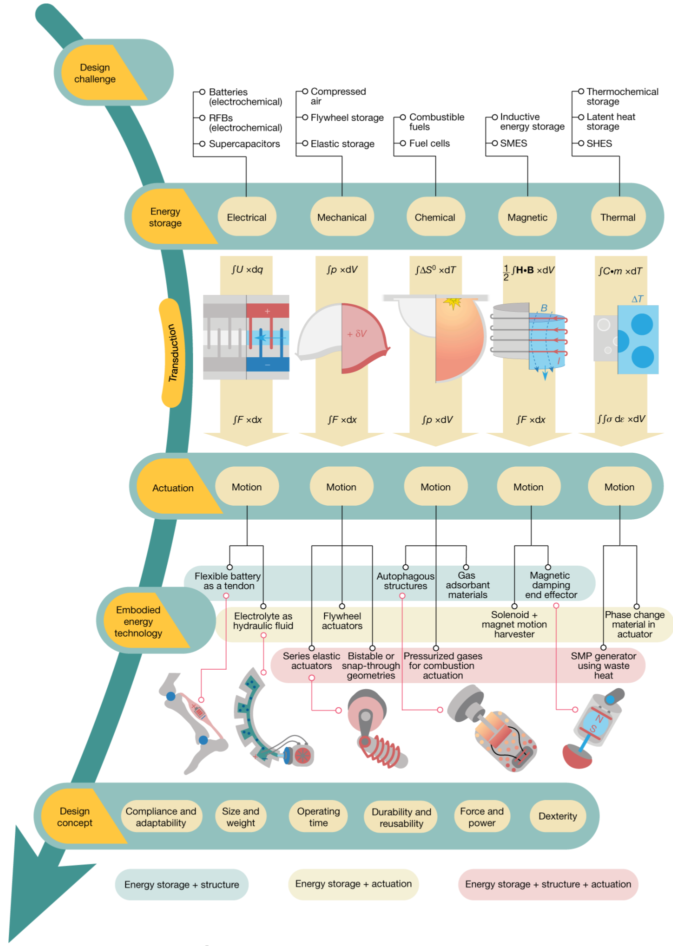


S. Picella, C. M. van Riet, J. T. B. Overvelde, Pneumatic coding blocks enable programmability of electronics-free fluidic soft robots. *Science Advances* **10**, eadr2433 (2024).

Soft & distributed Energy storage



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

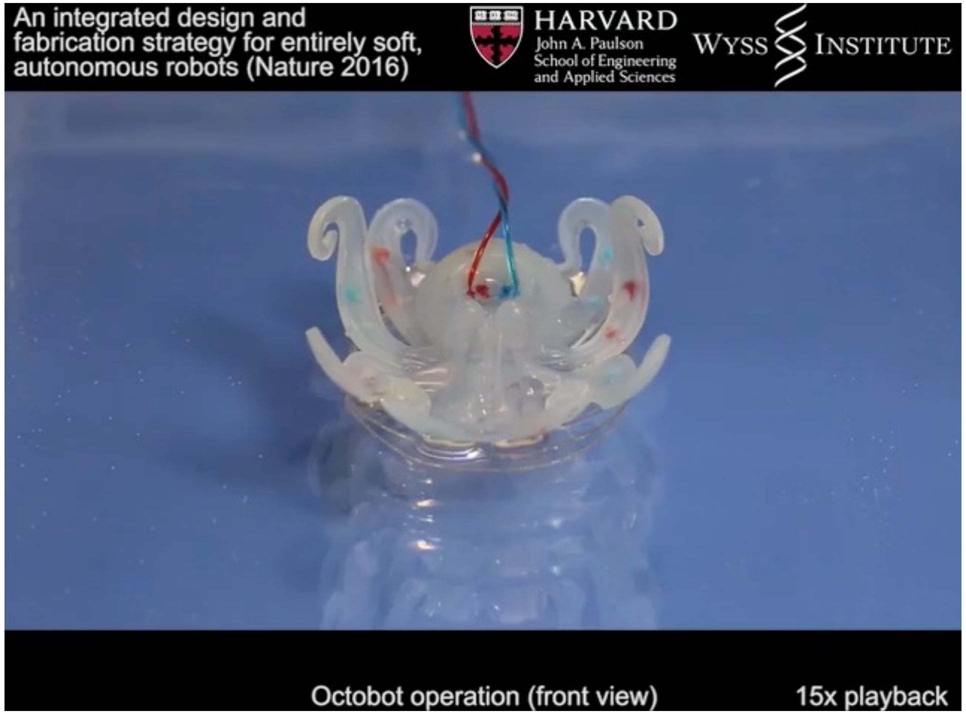


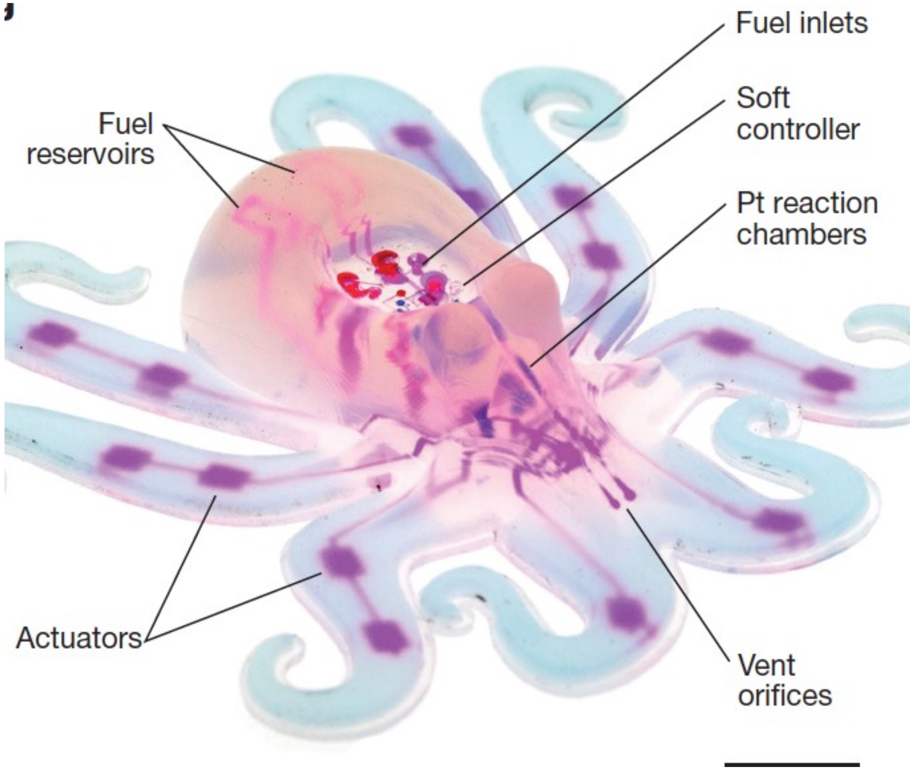
C. A. Aubin, .., R. F. Shepherd, Towards enduring autonomous robots via embodied energy. *Nature* **602**, 393–402 (2022).

"synthetic vascular system combines the functions of hydraulic force transmission, actuation and energy storage into a single integrated design"

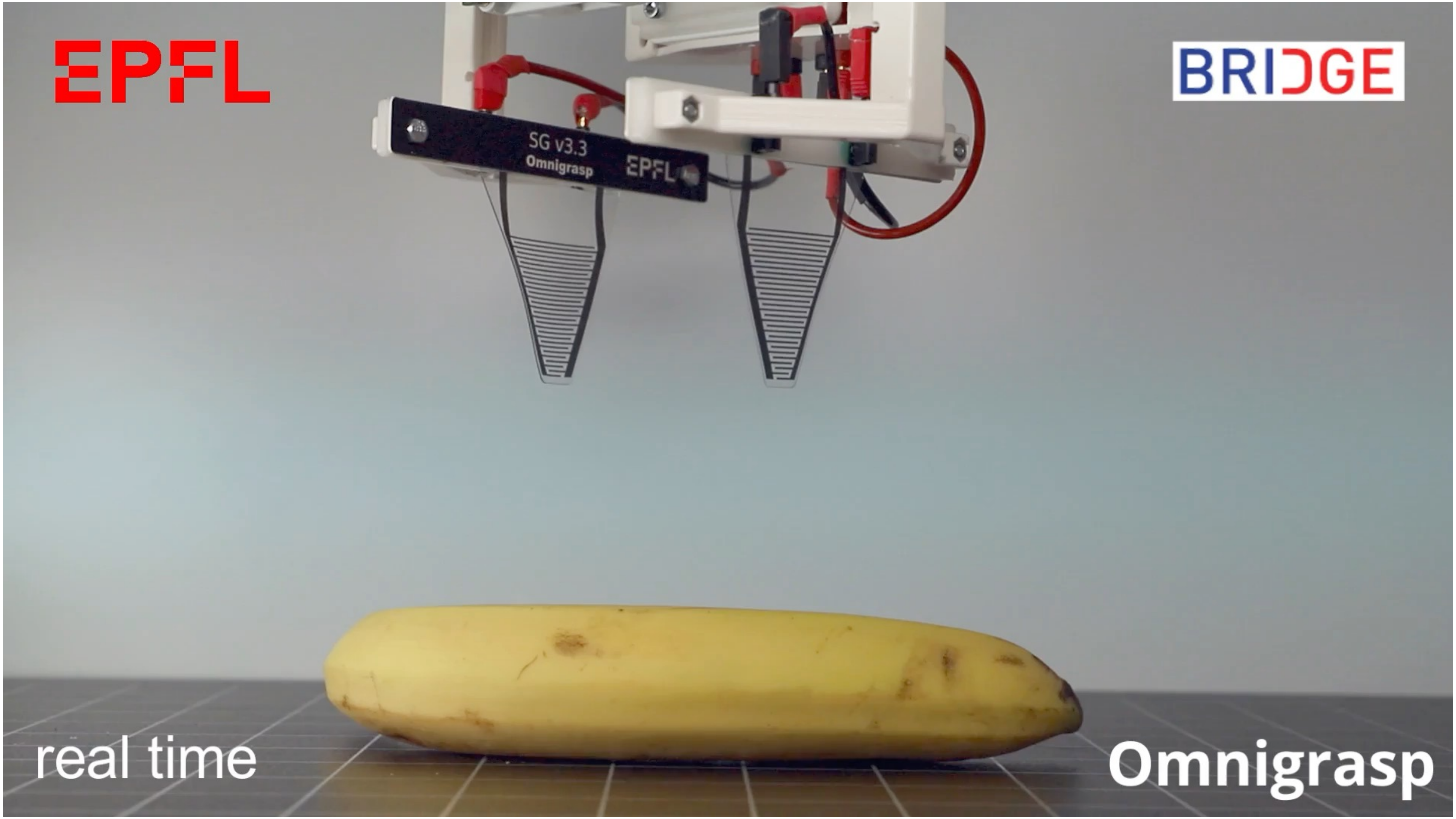
"Whereas most untethered robots use batteries to store energy and power their operation, recent advancements in energy-storage techniques enable chemical or electrical energy sources to be embodied directly within the structures and materials used to create robots, rather than requiring separate battery packs"

One of the first "all-soft" robots:
Fuel, control, actuators: all soft





"Octobot" Wehner *et al*, Nature 2016


EPFL
BRIDGE
SG v3.3
Omnigrasp
EPFL
real time
Omnigrasp

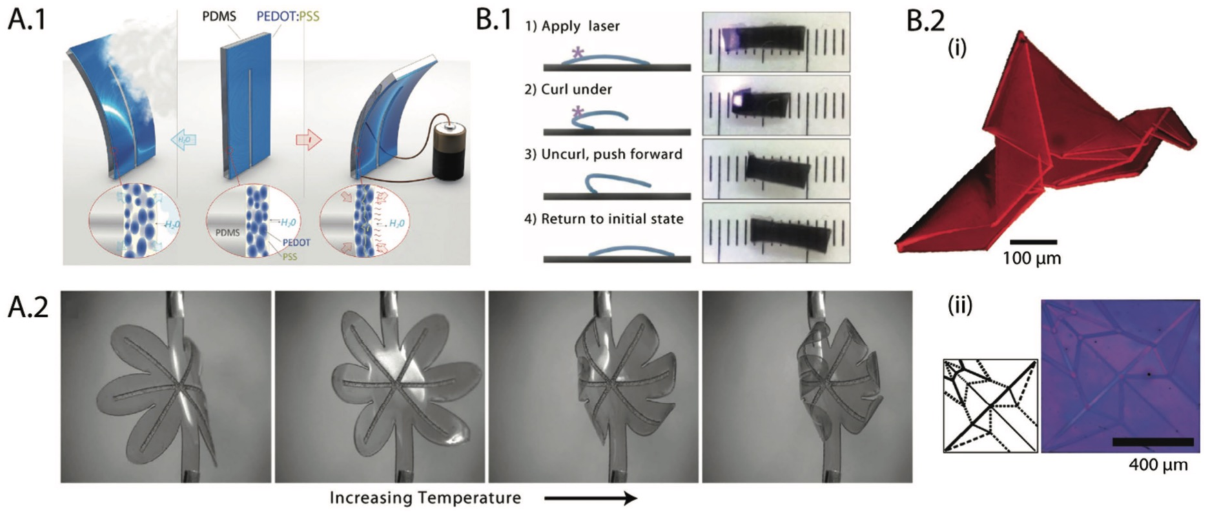
WHAT IS NEEDED TO MAKE A MACHINE SOFT, SMART, AND AUTONOMOUS?

EPFL

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

Many good (soft?) actuation principles

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



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).

Y. Jung, K. Kwon, J. Lee, S. H. Ko, Untethered soft actuators for soft standalone robotics. *Nat Commun* 15, 3510 (2024).

Some Criteria for choosing

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

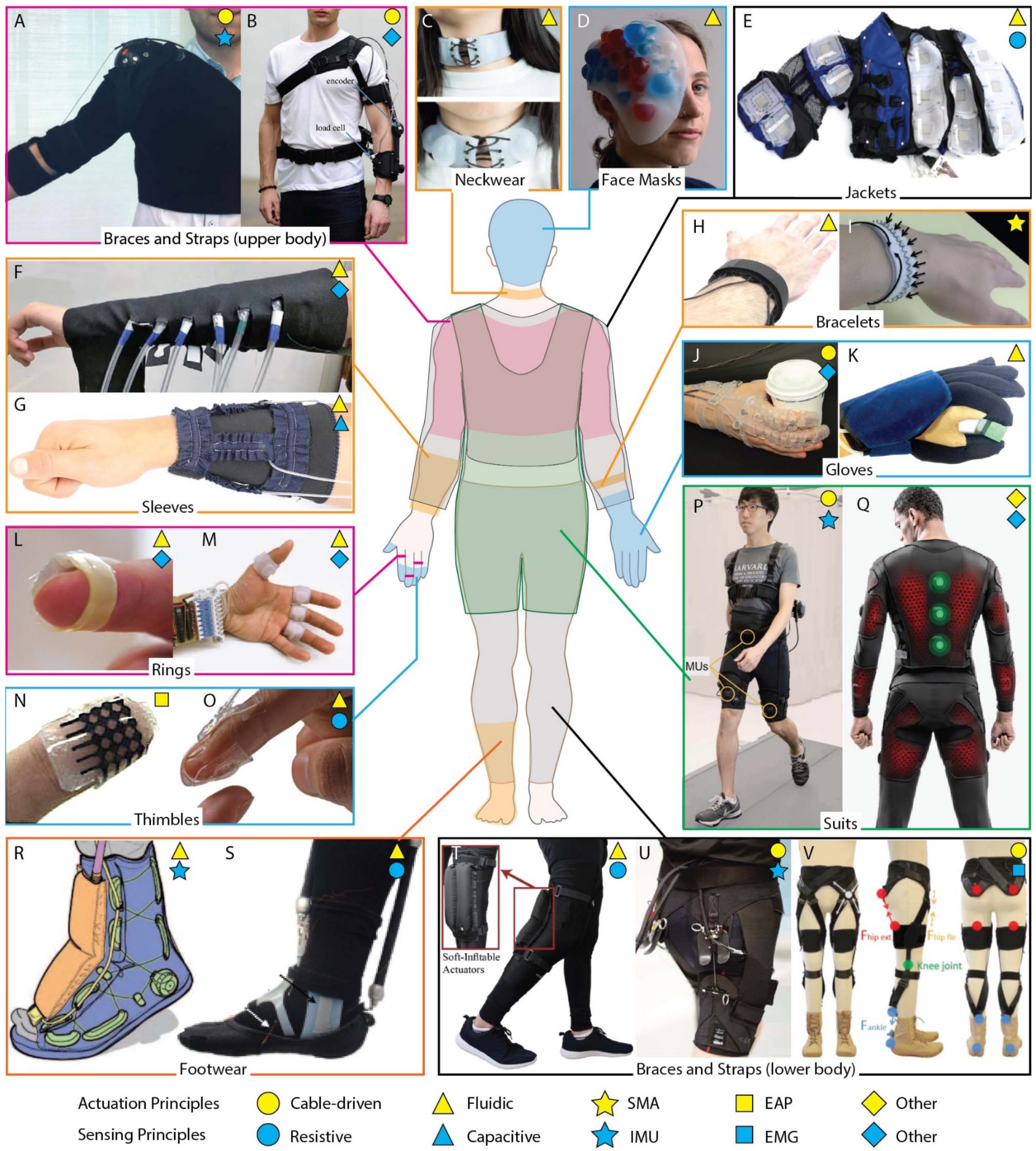
Good (now old) review on small scale soft actuators: Hines et al, Adv. Mater. 2017, 29, 1603483

How can we make effective artificial muscles?

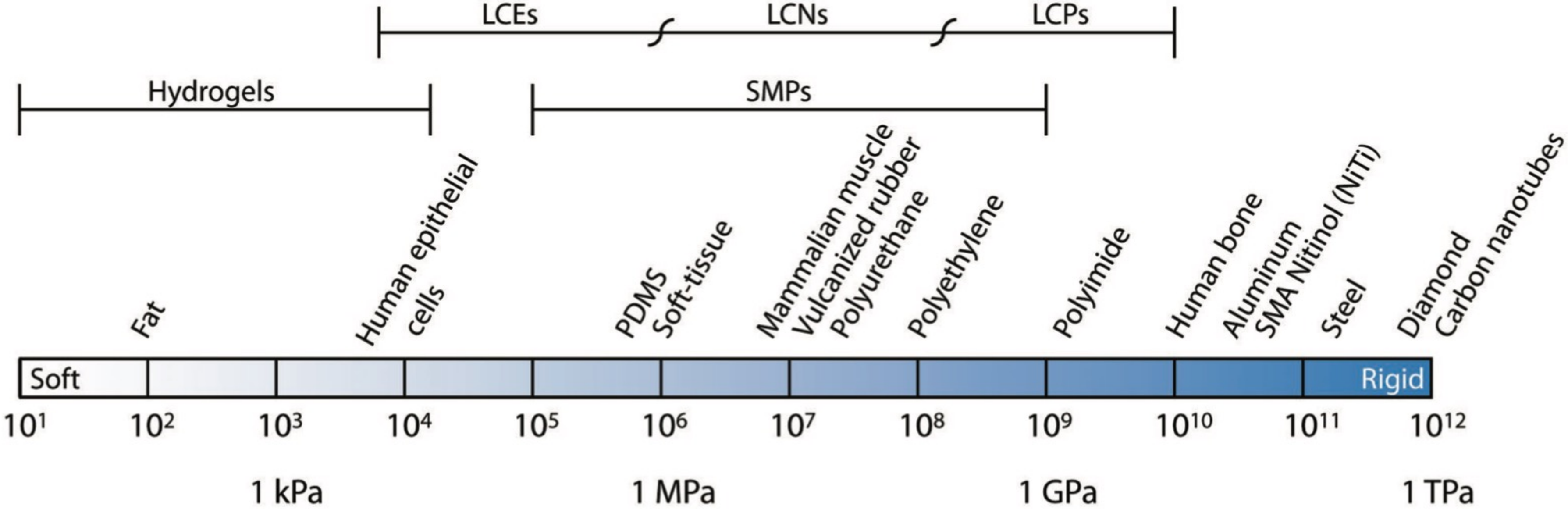
So many soft technologies !

How to compare

- Force? Stroke?
- Speed ?
- Efficiency ?
- Power density ?
- External equipment ?
- Incorporate in clothing ?
- What is suitable for untethered operation?



M. Zhu et al, “Soft, Wearable Robotics and Haptics: Technologies, Trends, and Emerging Applications”, *Proc. IEEE* (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:

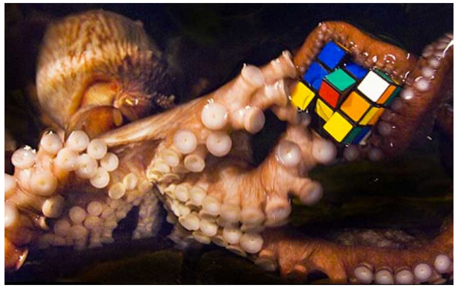
- Reliability
- Lifetime

- Energy efficiency

- Ease of integration
- Control: accuracy, simplicity

- Robust & reproducible manufacturing process

- Invisible power supply



SOFT ACTUATORS FOR SOFT MACHINES

- 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

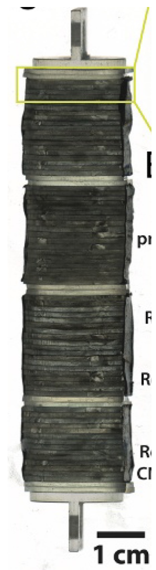
Actuation method	Strain (%)	Work density (kJ m^{-3})	Modulus (MPa)	Power density (kW m^{-3})	Strain rate (% s^{-1})	Frequency (Hz)	Auxiliary equipment
Skeletal muscle	20–40	8–40	10–60	50–300	10–50	1–10	Body metabolism
Pneumatic actuator	10–40	1–200	0.1–100	10–1,000	10–70	1–5	Pneumatic pump, valves
Liquid-crystal 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).

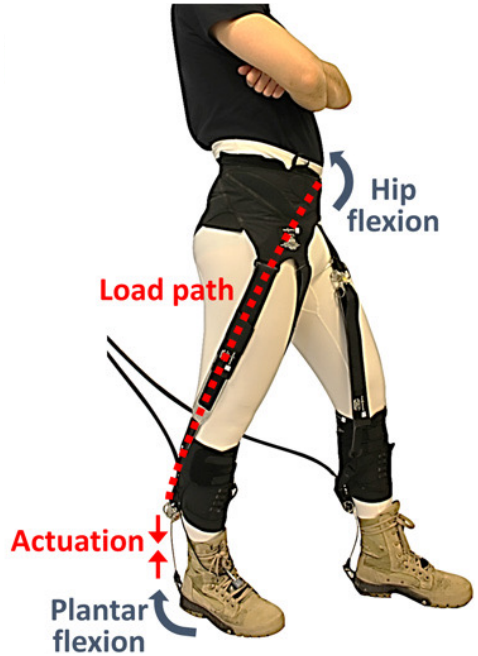
This table can be misleading!

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

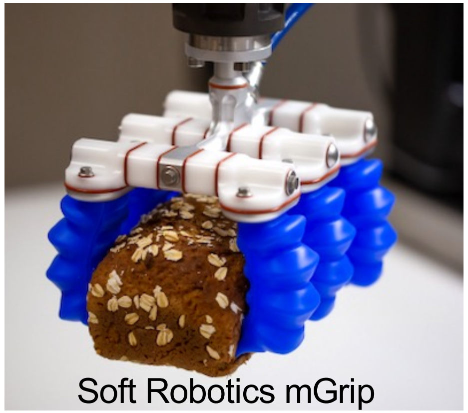


M. Duduta, Harvard



C. Walsh, Harvard

Is energy efficiency important?

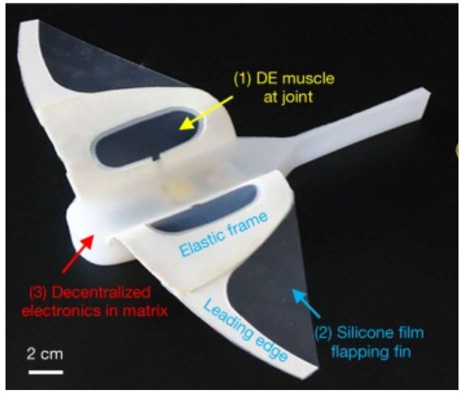


Energy efficiency is essential when untethered!

Photo: Tingshu Wang/Reuters 4-2025

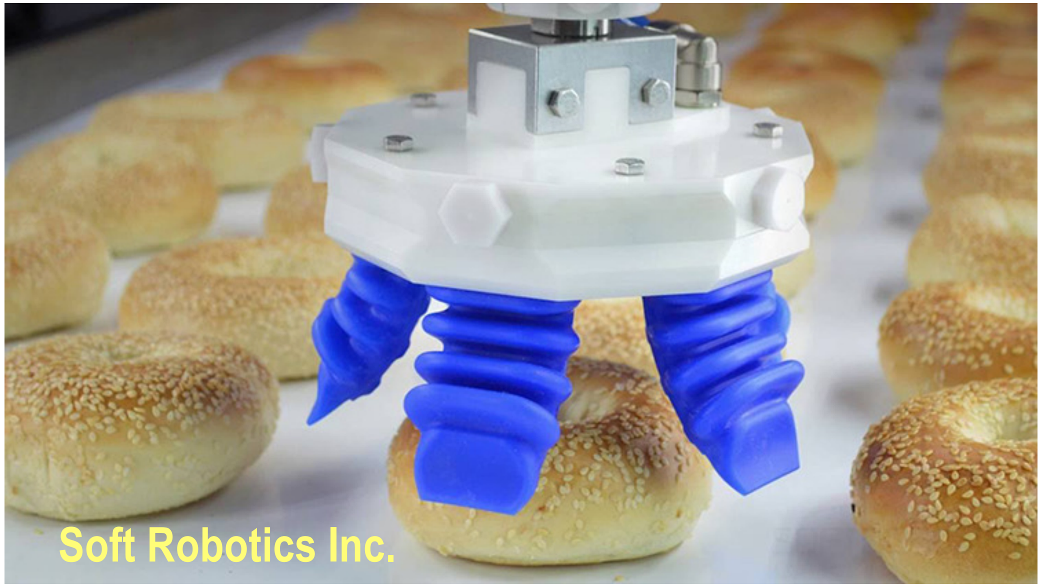
Generated with · DALL·E 3

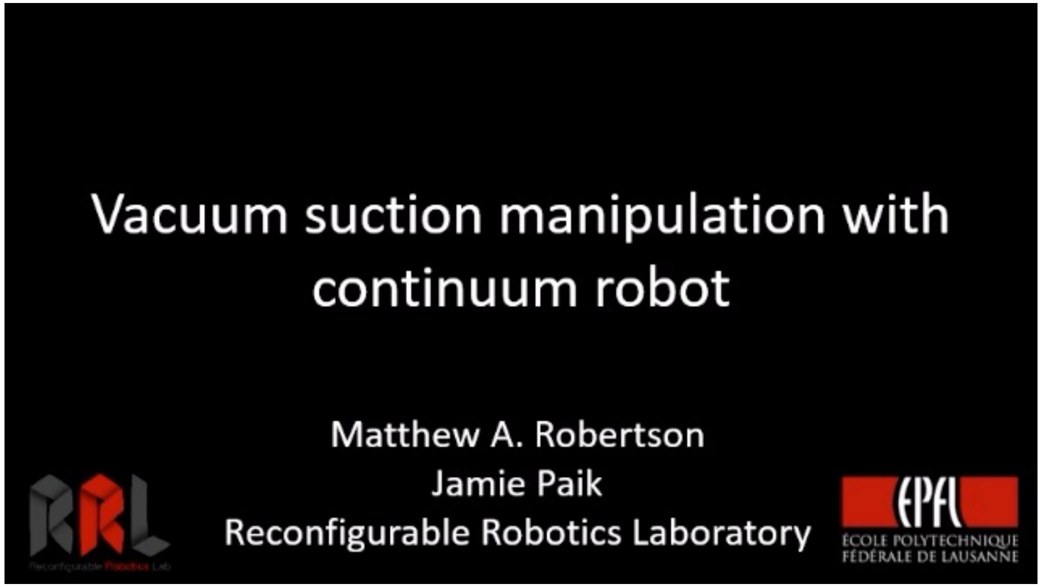
Luo et al, CHI 2022



G. Li et al. *Nature* (2021)

Most widespread soft actuation is pneumatic



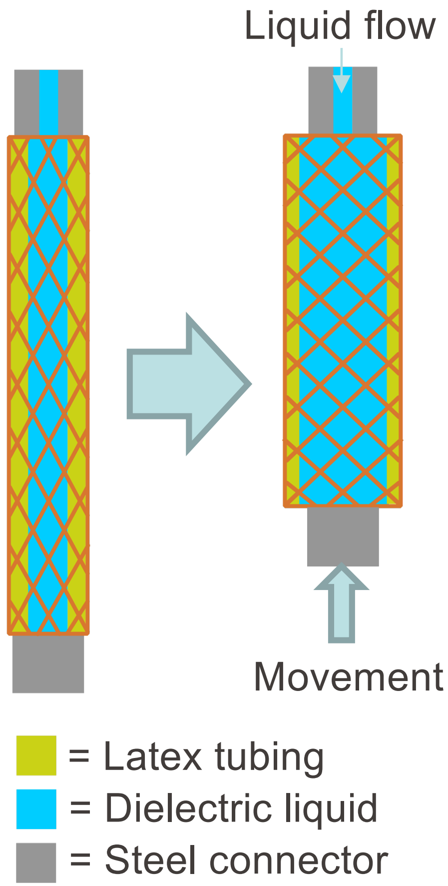


Robertson & Paik, Science Robotics (2017)

McKibben actuators are a good solution for anthropomorphic robotics

- Hydraulic McKibben actuators
  - Consists of soft tubing in a braided mesh
  - Inflating tubing causes mesh to contract
  - Produce up to 1650N of force
  - Have up to 25% percent strain
  - High energy density
  - Contraction speed similar to that of humans

Mayuko Mori et al. Advanced Robotics, 2011



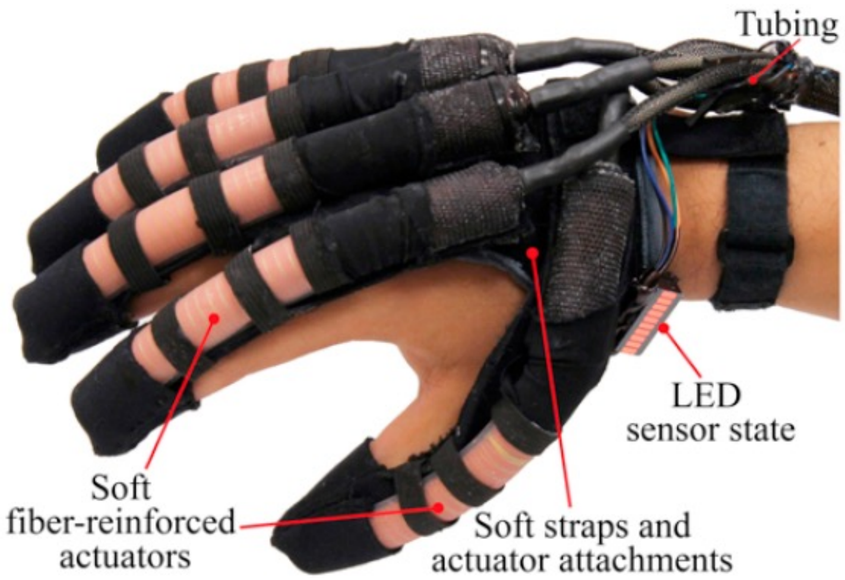
clonerobotics.com

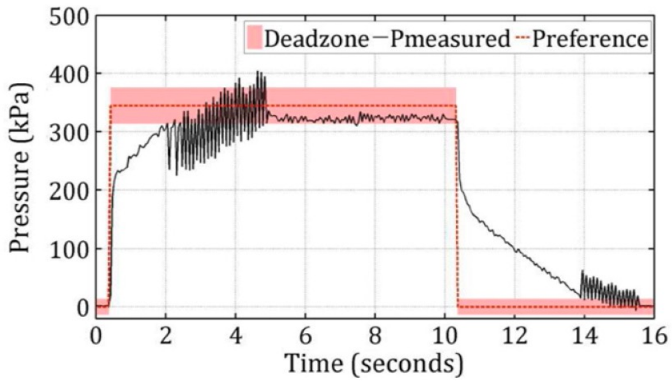
Pneumatic actuation can directly allow for high forces

Li et al, PNAS 1713450114 (2017)

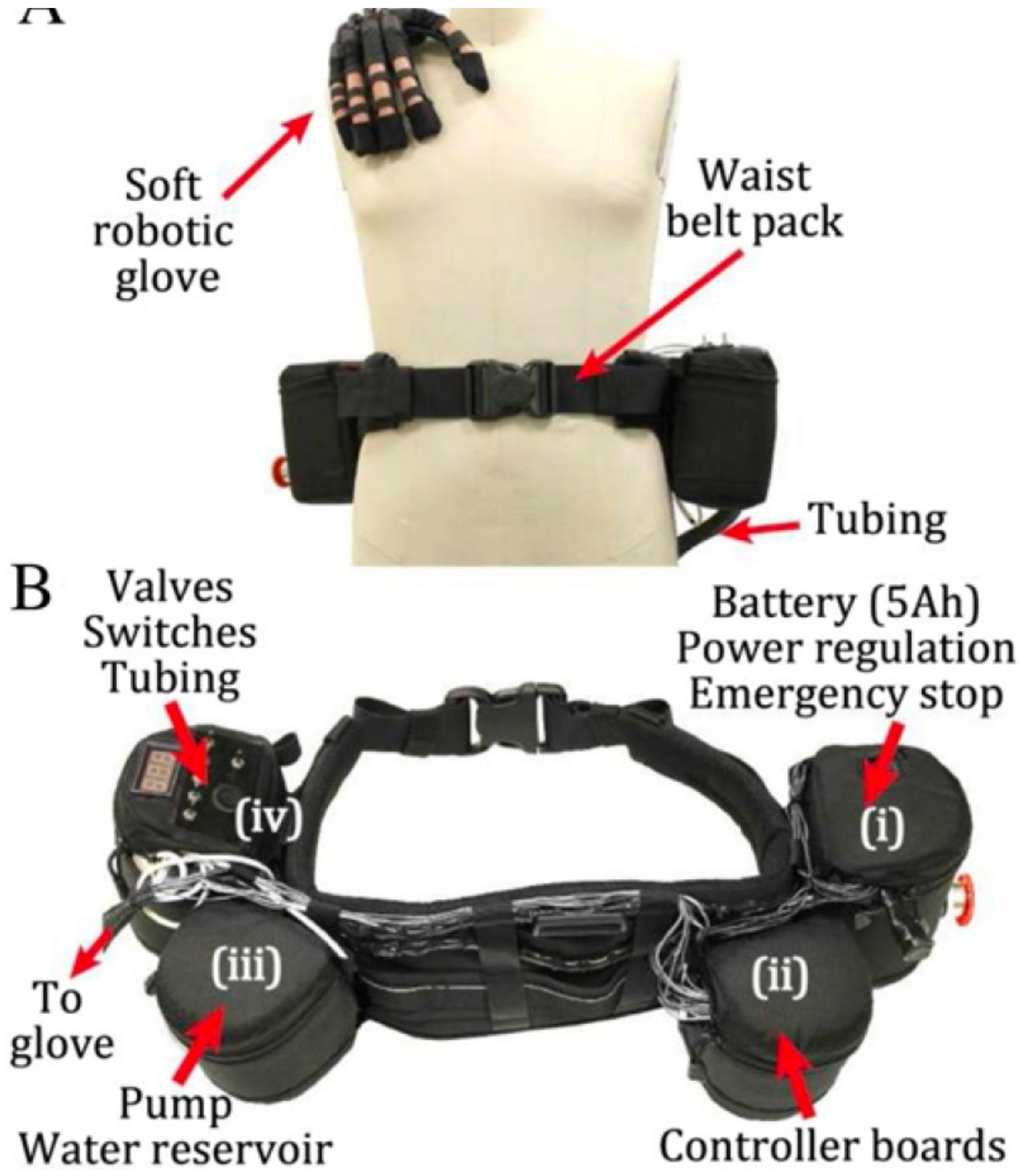
Suzumori lab, Tokyo Tech

But need to keep compressor running…



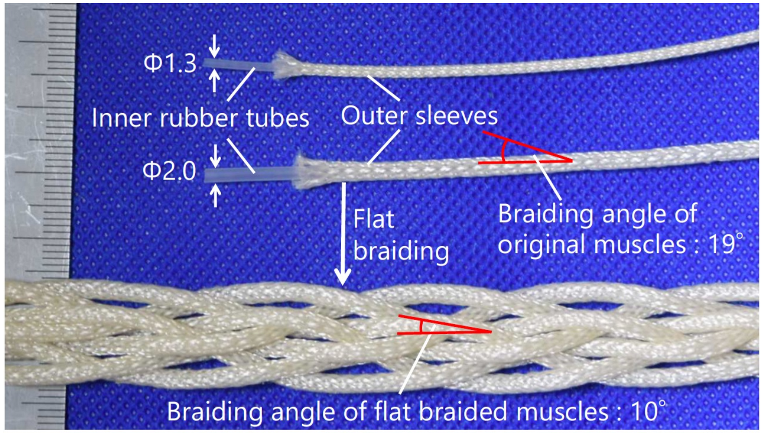


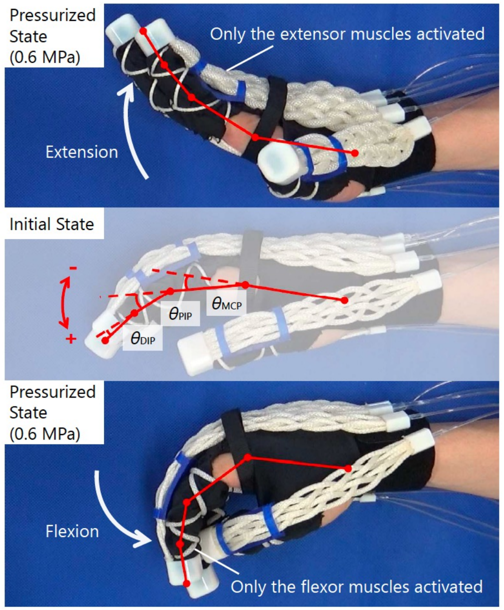
P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, “Soft robotic glove for combined assistance and at-home rehabilitation,” *Robotics and Autonomous Systems*, vol. 73, pp. 135–143, Nov. 2015



Beltpack: 3.3 kg

Thin McKibben actuators





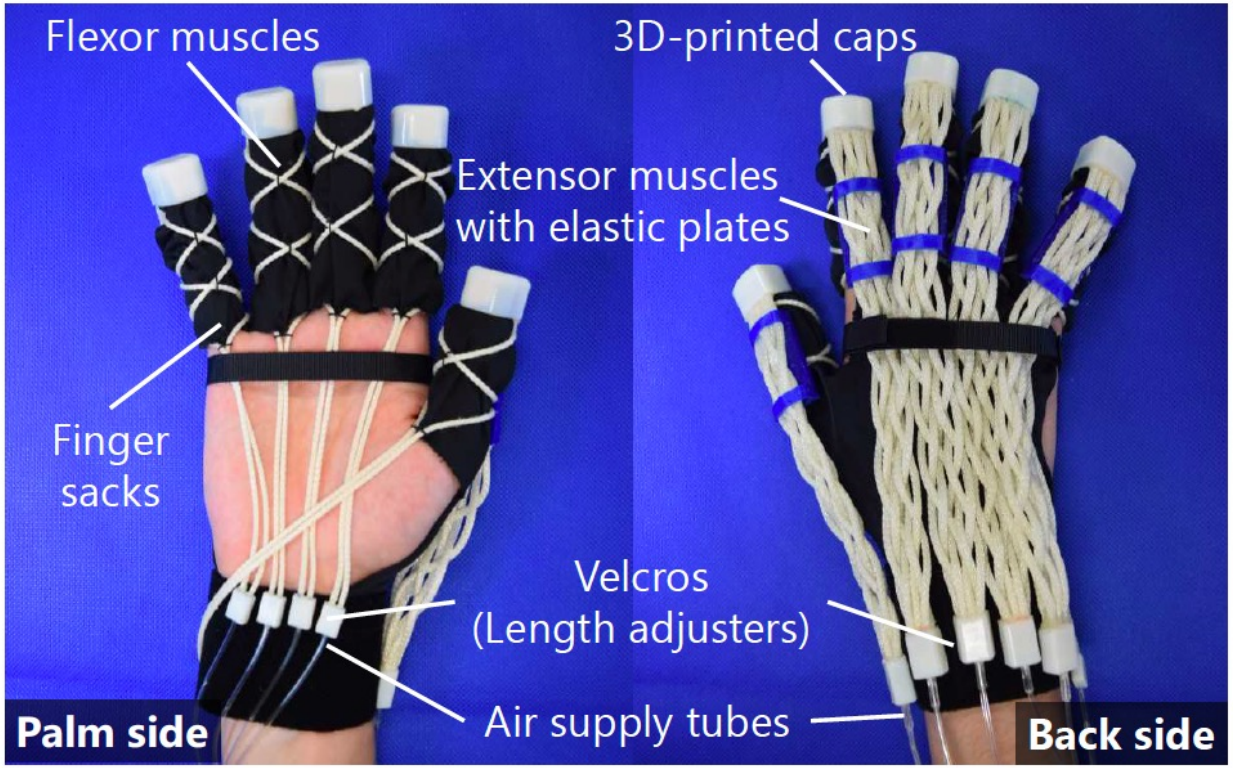
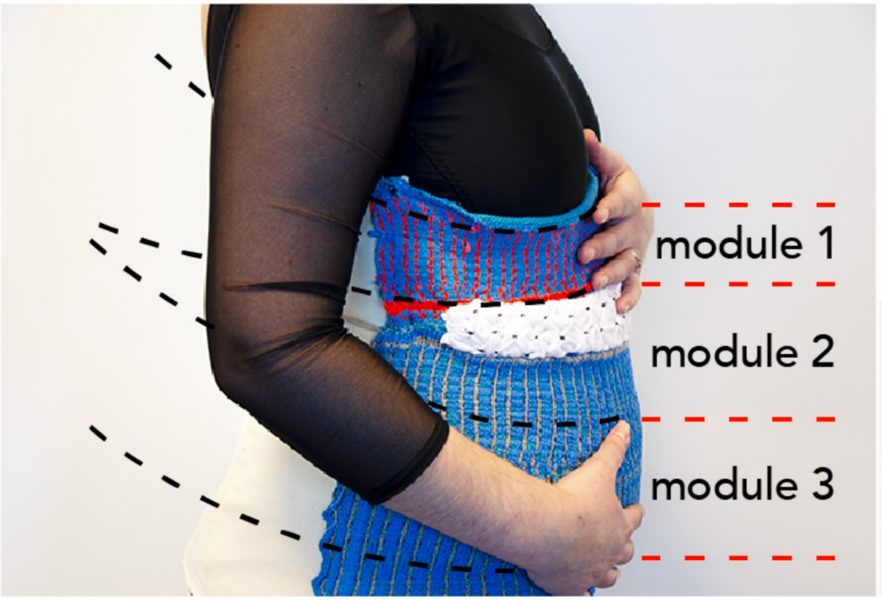
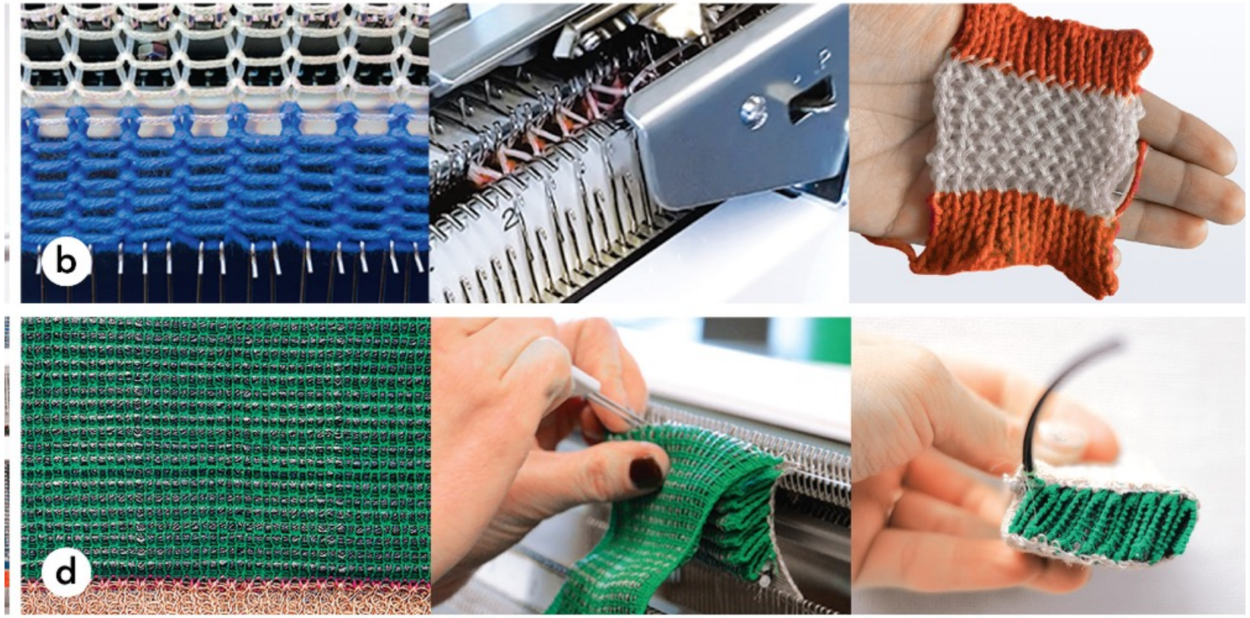


Fig. 2. Overview of soft robotic glove with thin McKibben muscles (64.7 g without air supply tubes, 10 DoF)

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.

Thin McKibben in fabric





O. Kilic Afsar, … H. Ishii, “OmniFiber: Integrated Fluidic Fiber Actuators for Weaving Movement based Interactions into the ‘Fabric of Everyday Life’”
in *The 34th Annual ACM Symposium on User Interface Software and Technology* (ACM, Virtual Event USA, 2021; https://dl.acm.org/doi/10.1145/3472749.3474802)

Pneumatics are great, but they are tethered

Meta/ Facebook Reality Labs

ELECTROSTATIC FORCES AND ACTUATORS

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

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

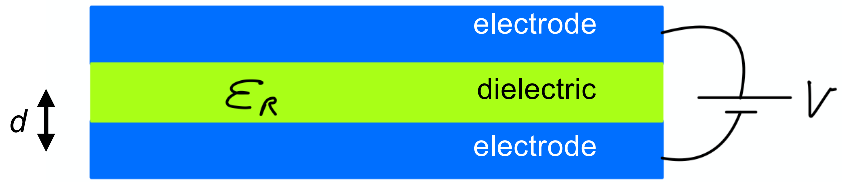
- But requires high voltages and has materials challenges

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

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

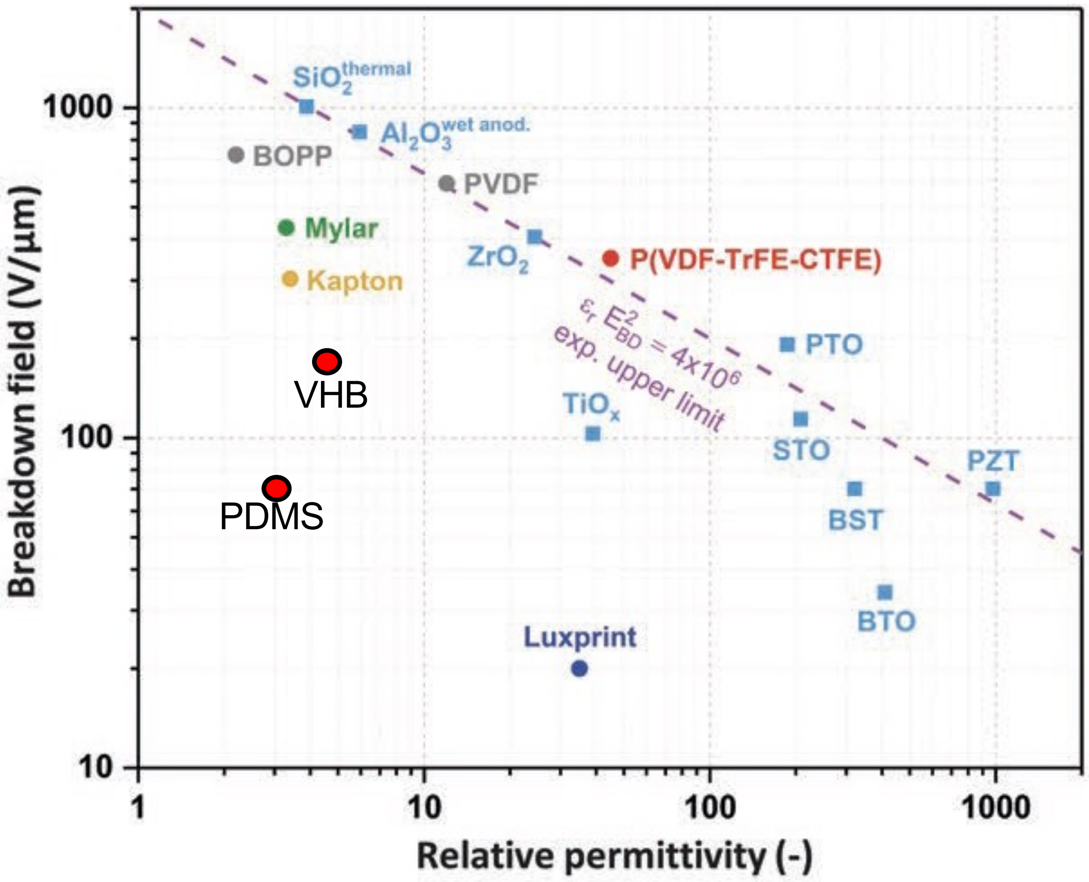
What soft materials to choose?
- Good electrical performance

and

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

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

EPFL



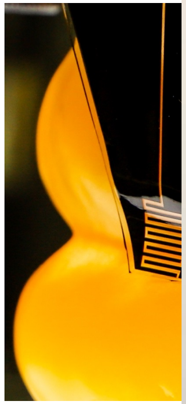
- Want materials with high ε_r and high $E_{breakdown}$
- But softer materials have lower breakdown field…
  - Elastomers typically have E_{DB} 100 V/µm,
  - SiO_2 has E_{DB} 1 kV/µm

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

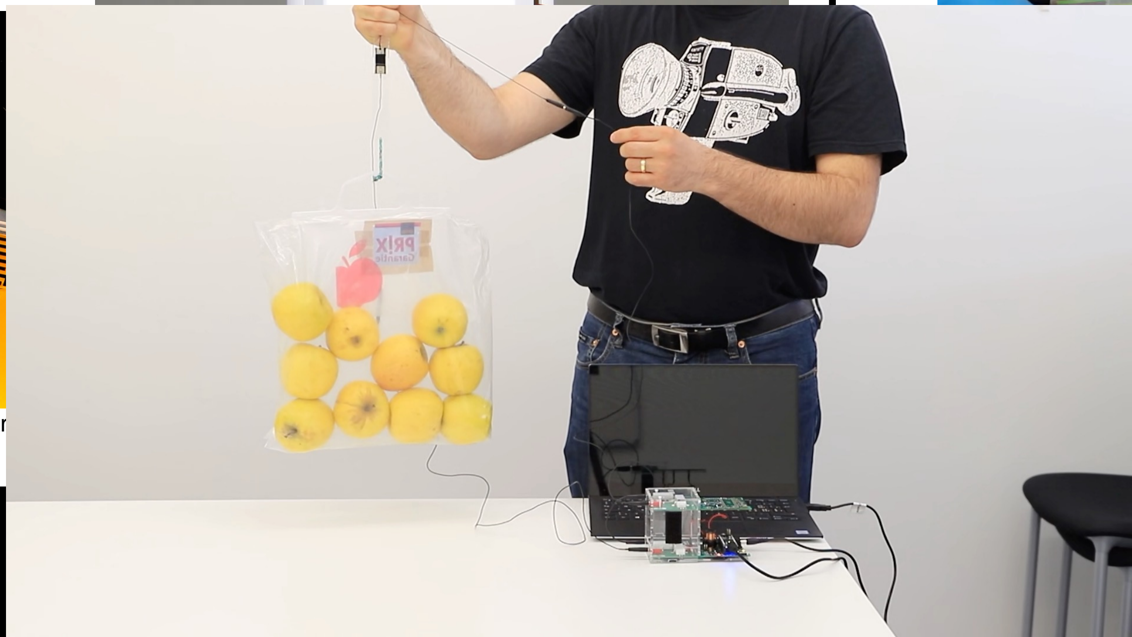
Hinchet et al. *Advanced Materials Technologies* **5**, 1900895 (2019)

Four ways we use electrostatic forces in flexible systems

- Shear Force / EA



Cacucciolo, Extr

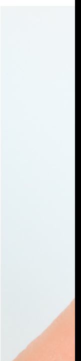


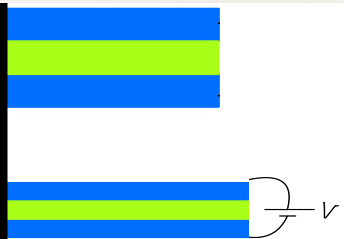
Leroy, Adv. Mat 2020

Firouzeh, Mizutani, Adv. Mat 2023

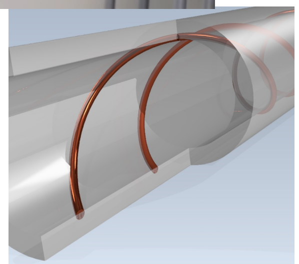
- DEA

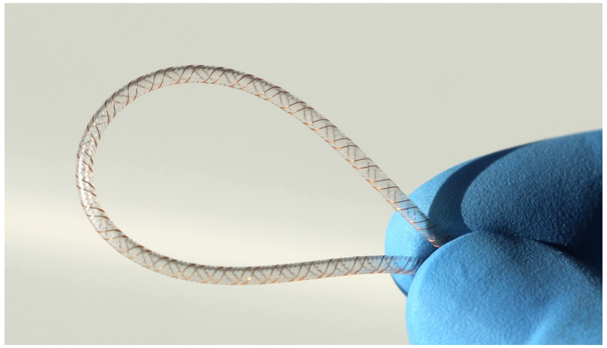
ing (EHD)





Adv. Func Mat 2021

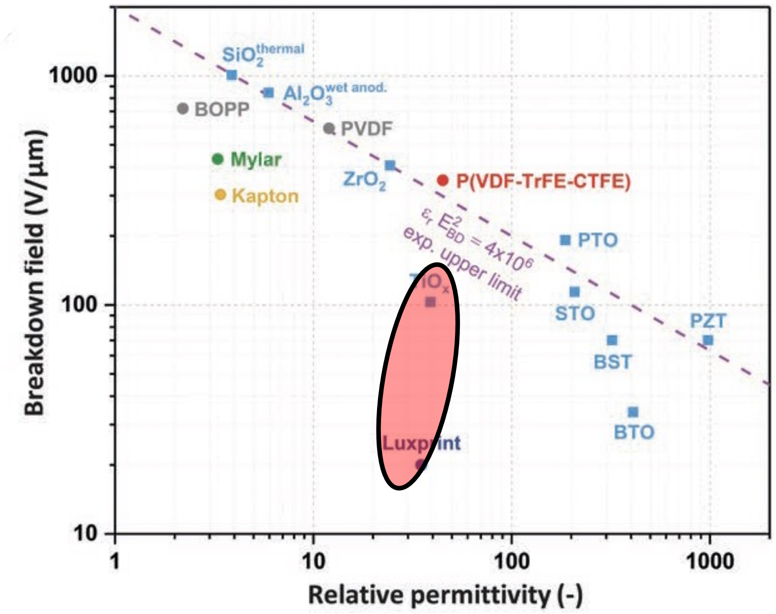


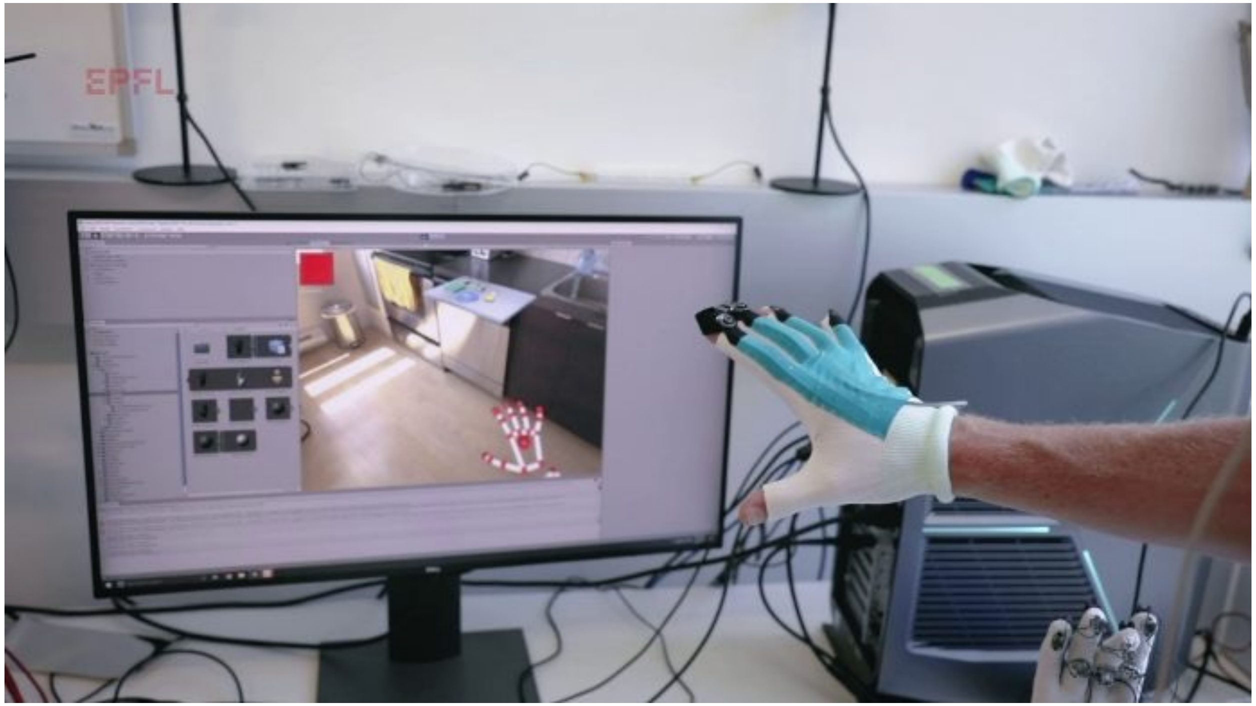


M. Smith, Science 2023

1. SLIDING ELECTROSTATICS

- 1A: ES clutches



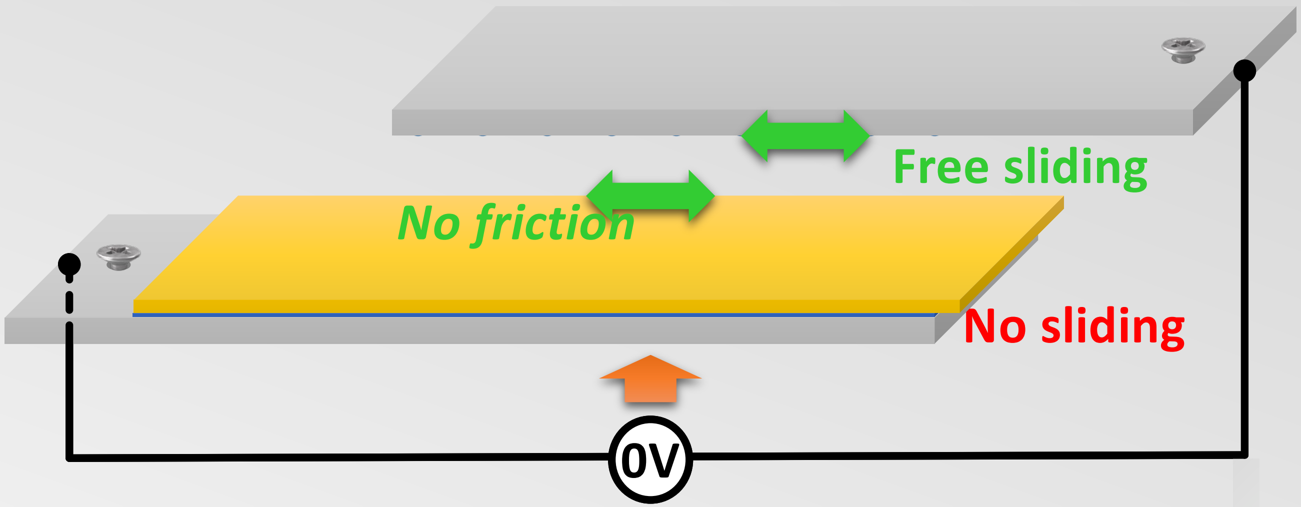


Haptic glove for VR + AR

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

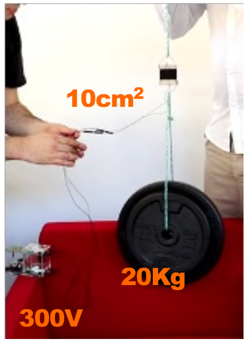
$$F_{ES} = \frac{1}{2}\varepsilon_0\varepsilon_r A E^2$$

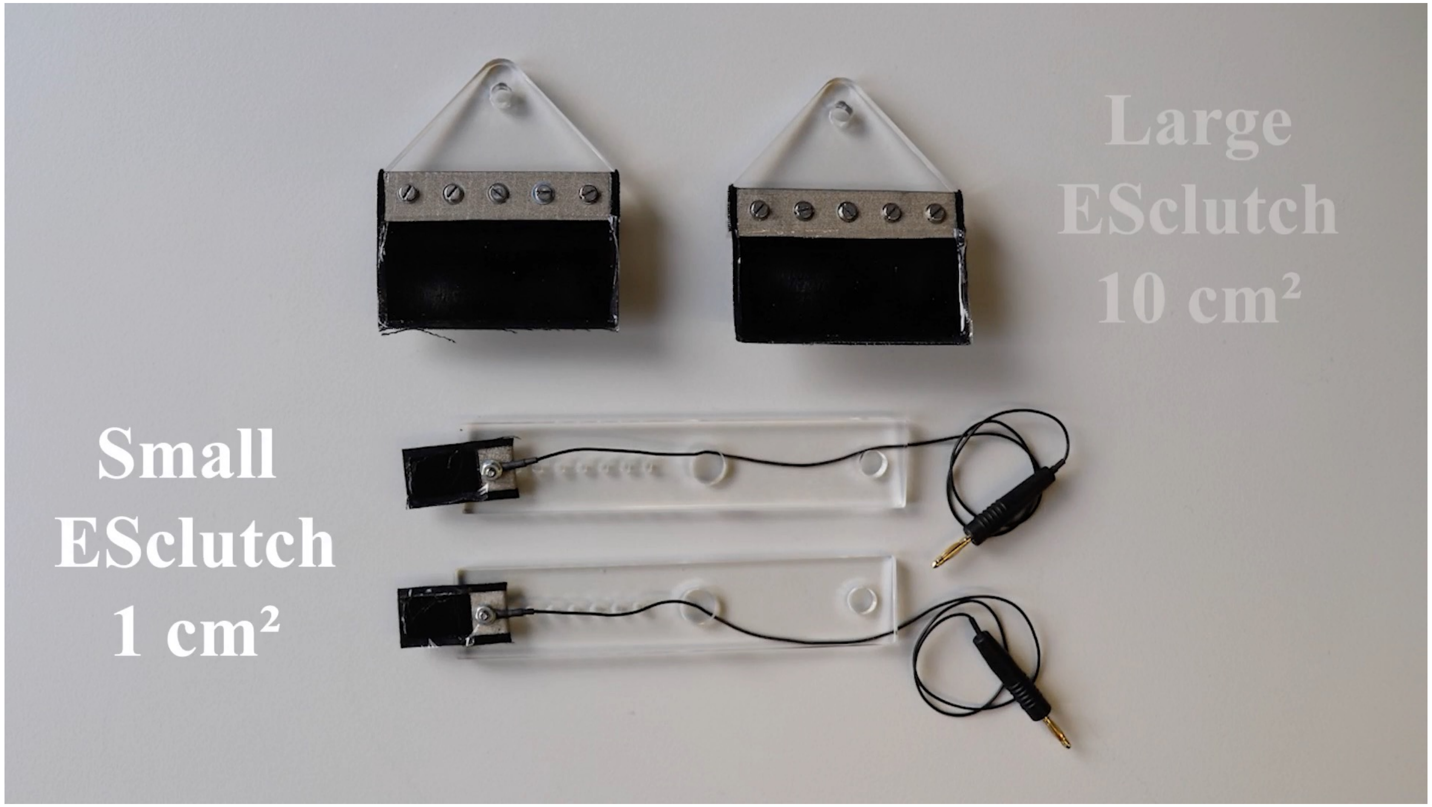
$$F_{fric} = \mu \frac{1}{2}\varepsilon_0\varepsilon_r A E^2$$

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

Small ESclutch

Large ESclutch

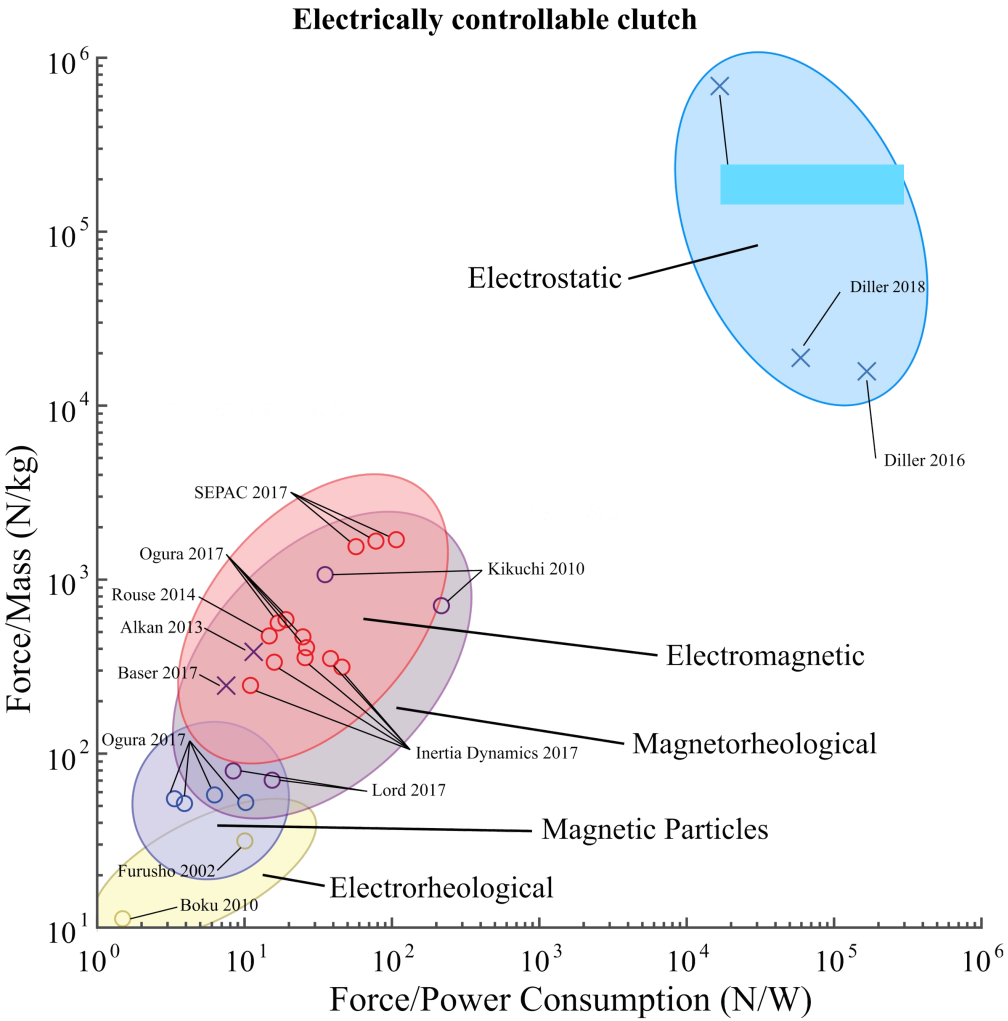




- High holding force : *20 N/cm² at 300 V*
- low power *1.2 mW/cm²*
- Flexible, Lightweight *30 mg/cm²*
- Fast *< 15 ms*
- Tuneable Stiffness

- Performance comes from use of 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

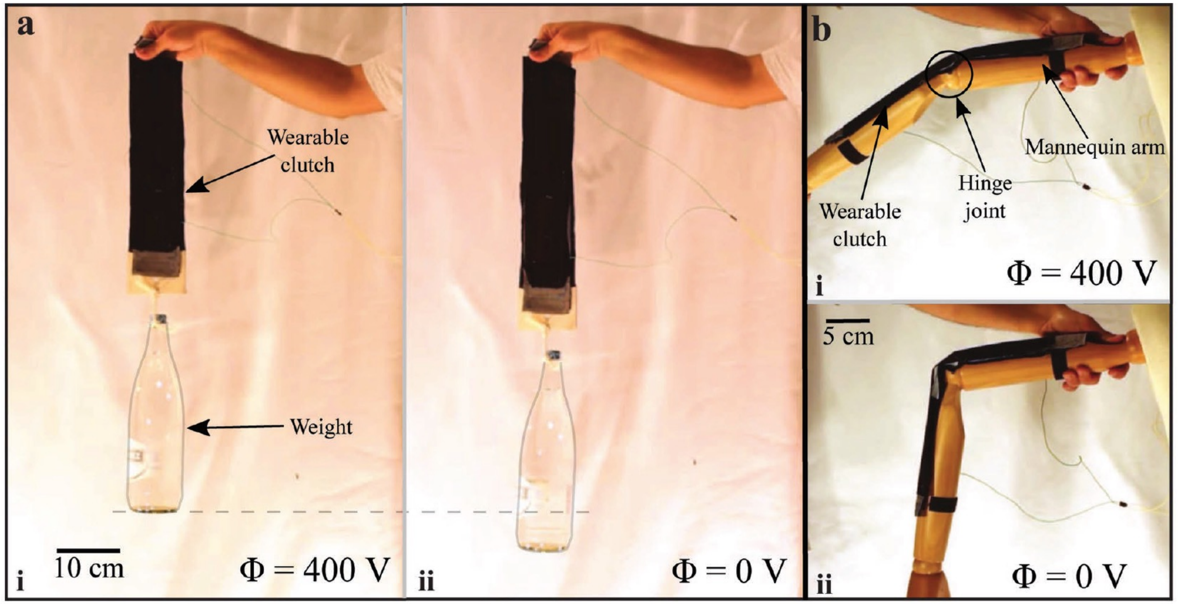


- In principle, blocking motion costs zero energy (because no motion = no work)
- ES brakes offer exceptionally low power consumption

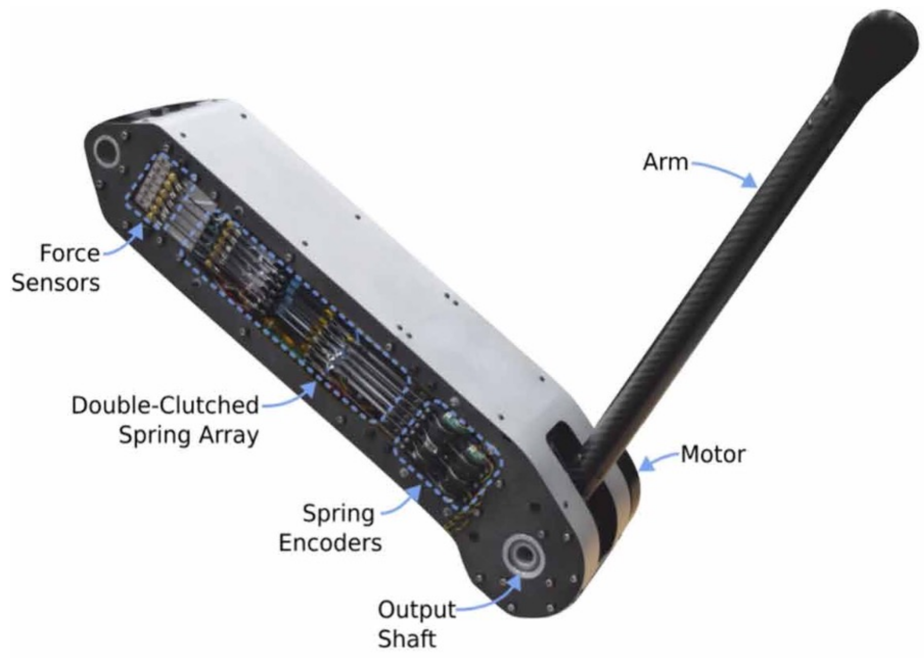
J. Levine, K. T. Turner, J. H. Pikul, Electroadhesive Clutches with Enhanced Force Capacity Using Soft Dielectric Interfaces. *Advanced Engineering Materials*, 2402244 (2024).

D. J. Levine, G. M. Iyer, R. Daelan Roosa, K. T. Turner, J. H. Pikul, A mechanics-based approach to realize high–force capacity electroadhesives for robots. *Science Robotics* **7**, eabo2179 (2022).

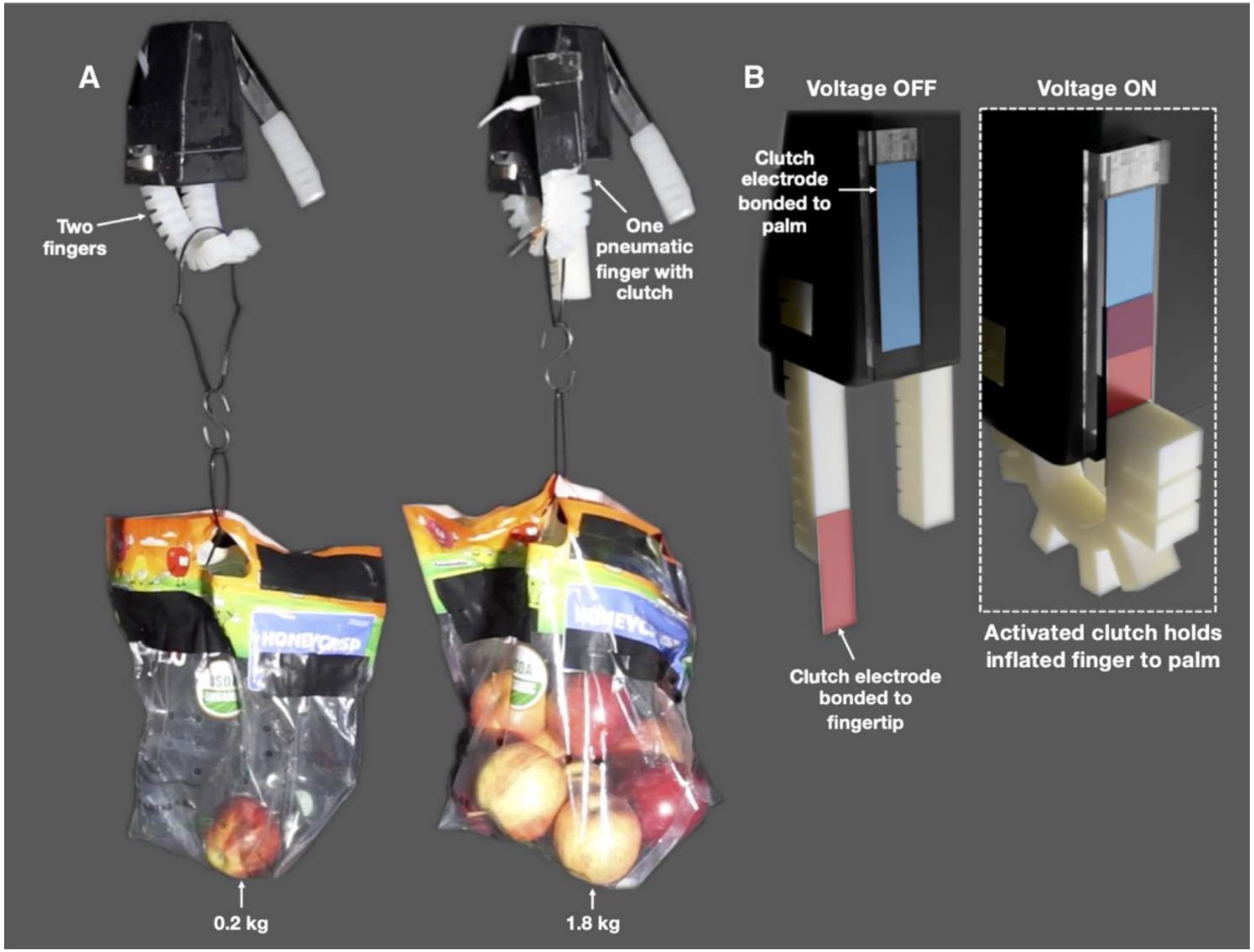
based on Diller et al, *The effects of electroadhesive clutch design parameters on performance characteristics.* Journal of Intelligent Material Systems and Structures, (2018).



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



E. Krimsky, S. H. Collins, Elastic energy-recycling actuators for efficient robots. *Science Robotics* **9**, eadj7246 (2024).



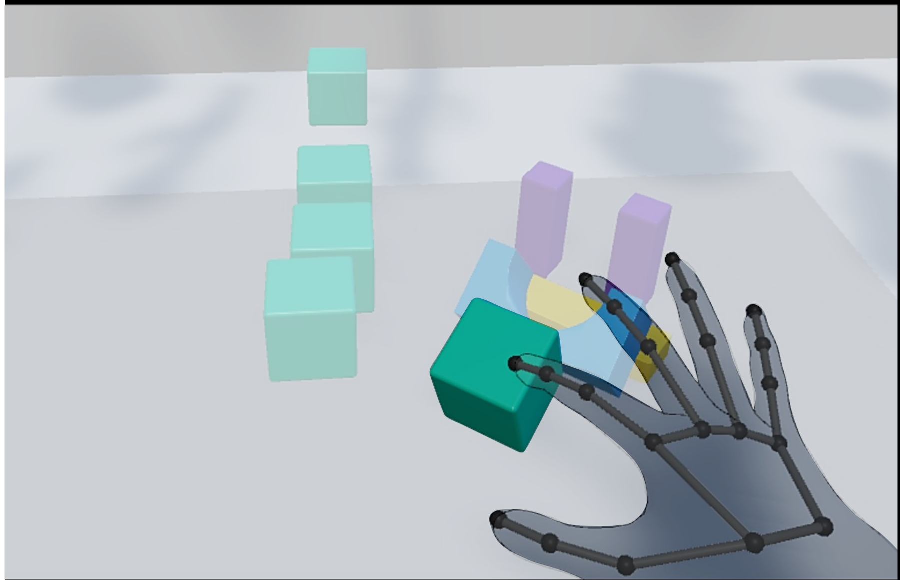
D. J. Levine, G. M. Iyer, R. Daelan Roosa, K. T. Turner, J. H. Pikul, A mechanics-based approach to realize high–force capacity electroadhesives for robots. *Science Robotics* **7**, eabo2179 (2022).

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



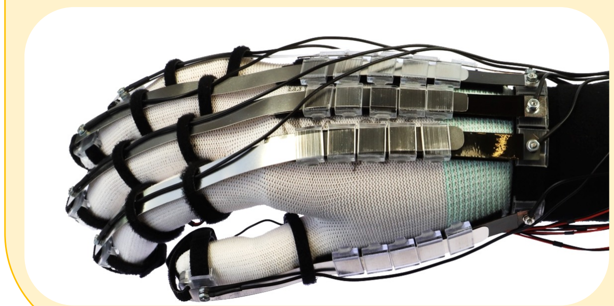
Fergal Coulter (ETHZ), Junsoo Kim (EPFL), et al., manuscript in preparation, 2025

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

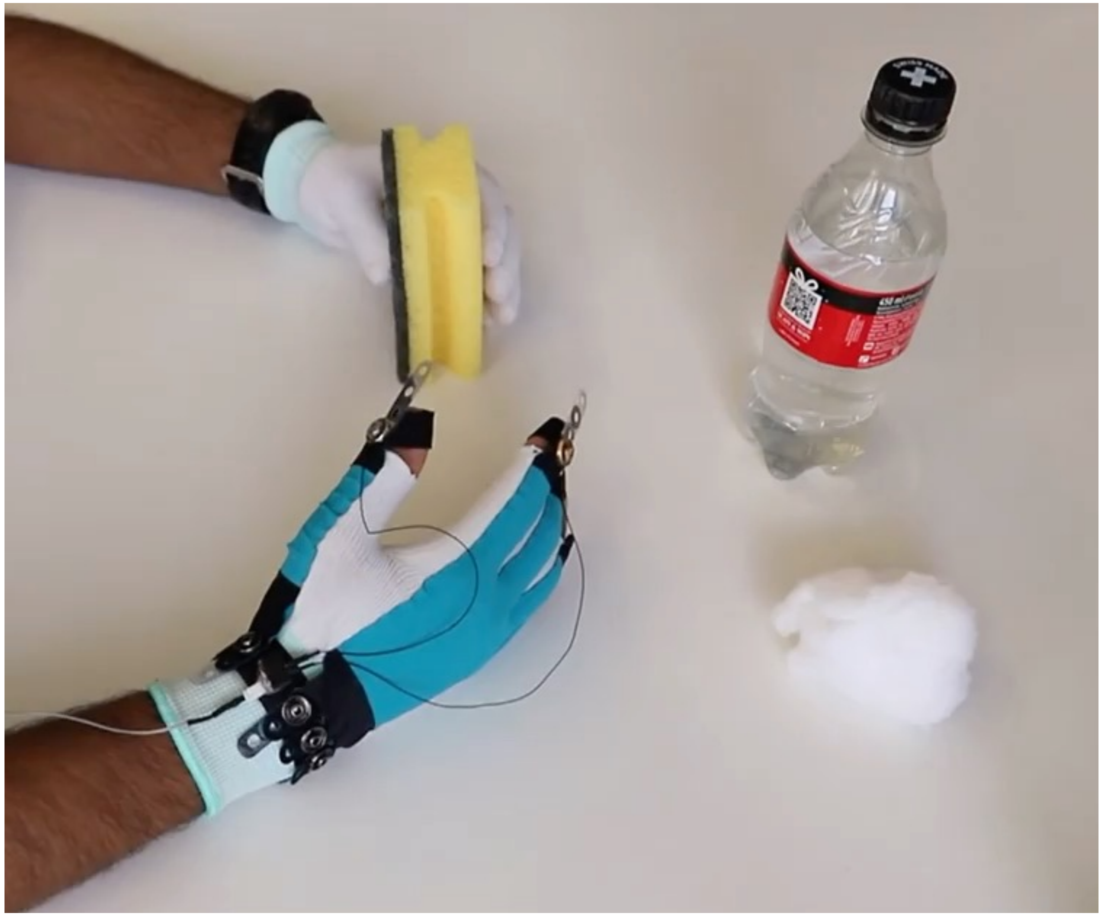
- Textile ESclutch
- High force, low voltage
- Floating elastic integration
- Takes long to put on
- Only On/Off
- Comfortable

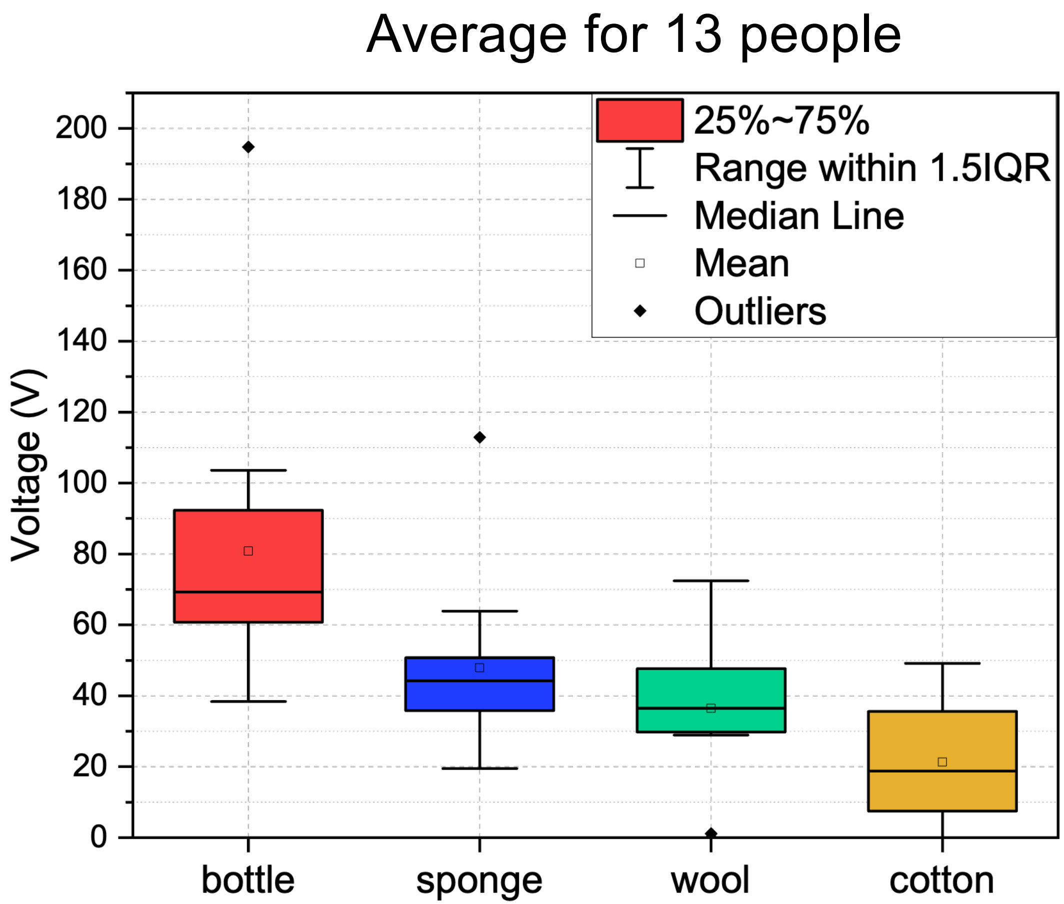
DextrES v3

Better actuators & integration

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

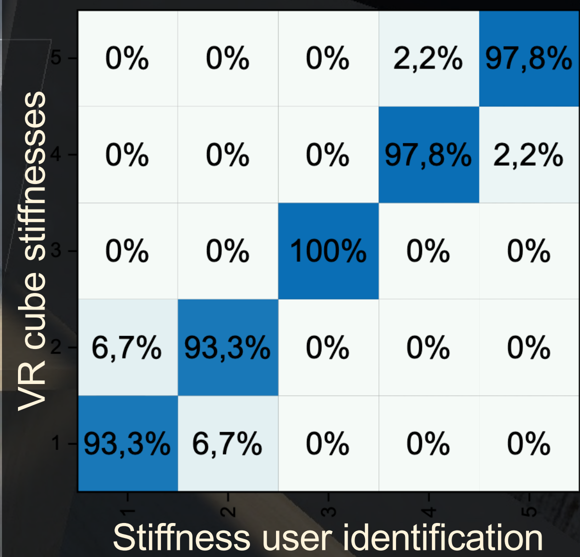
Can allow controlled sliding



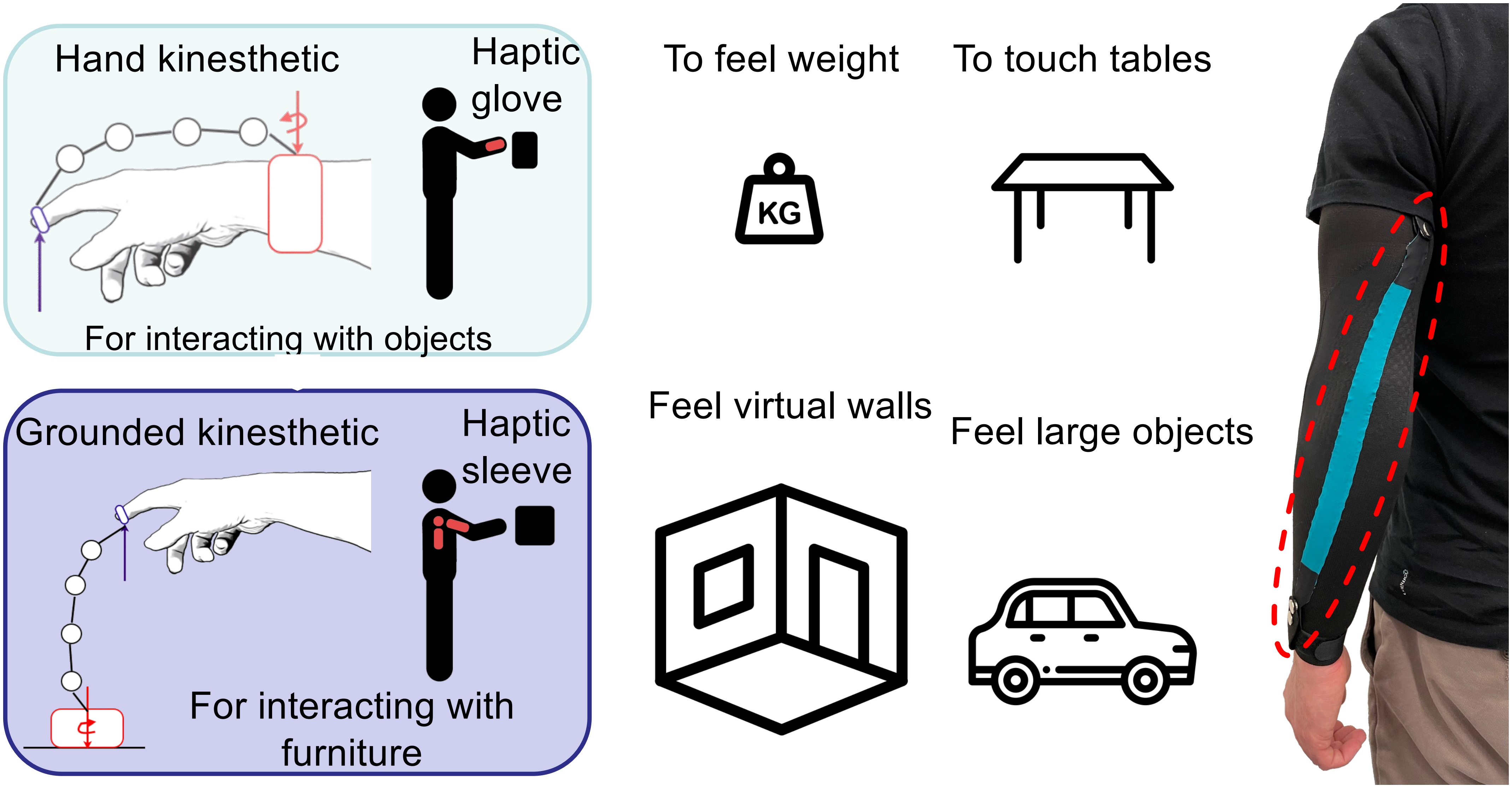


VR tests: sort cubes of different stiffnesses

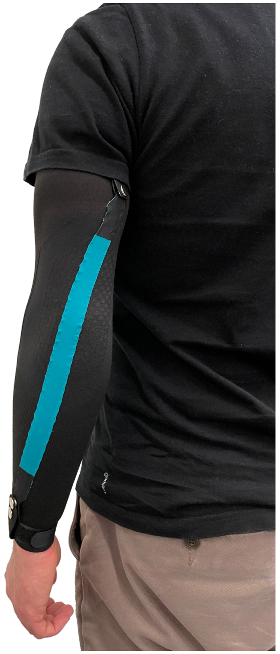
VR scenario
- 5 VR cubes of different stiffness



Extend concept to elbow and shoulder for grounded kinesthetic feedback



Feeling inertia in body-grounded haptics



DextrES

Ronan Hinchet

Herbert Shea

(hebert.shea@epfl.ch)

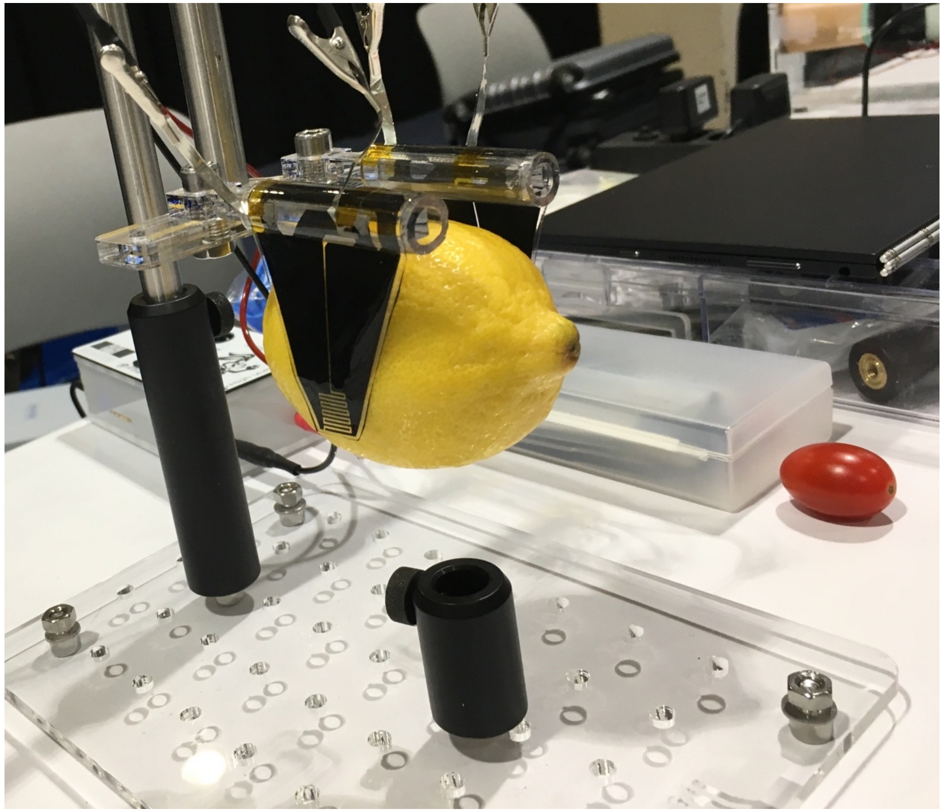
École polytechnique fédérale de Lausanne

LMTS lab 2021

Hinchet and Shea, Adv. Intell Sys, 2022

1. SLIDING ELECTROSTATICS

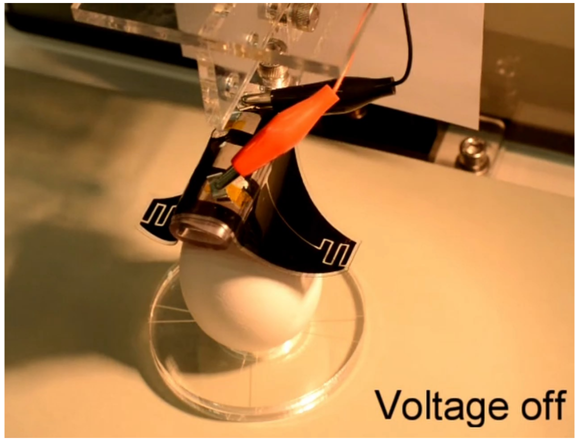
- 1B: ElectroAdhesion to generate high shear forces



Soft Electroadhesion (EA) grippers
Milestones in the past 10 years at LMTS

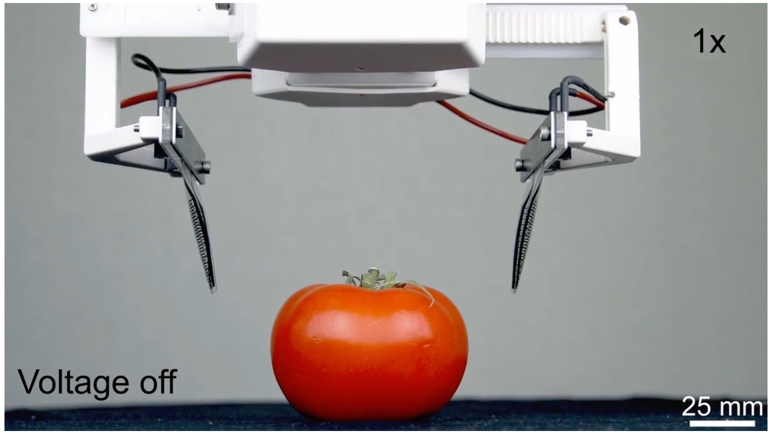
EPFL

DEA & Electroadhesion



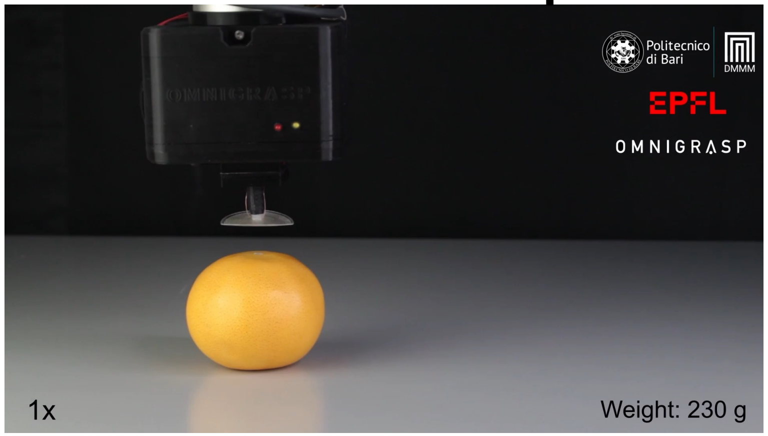
2016 [1]

Motorized fingers & Electroadhesion



2022 [2]

Electroadhesion suction cups



2024 [3]

[1] J. Shintake et al, *Advanced materials* (2016)
[2] V. Cacucciolo et al, *Extreme Mechanics Letters* (2022)
[3] F. Caruso et al, *Advanced Materials (2025)*

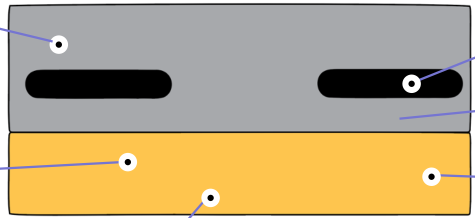
Politecnico di Bari

Jun Shintake

Vito Cacucciolo

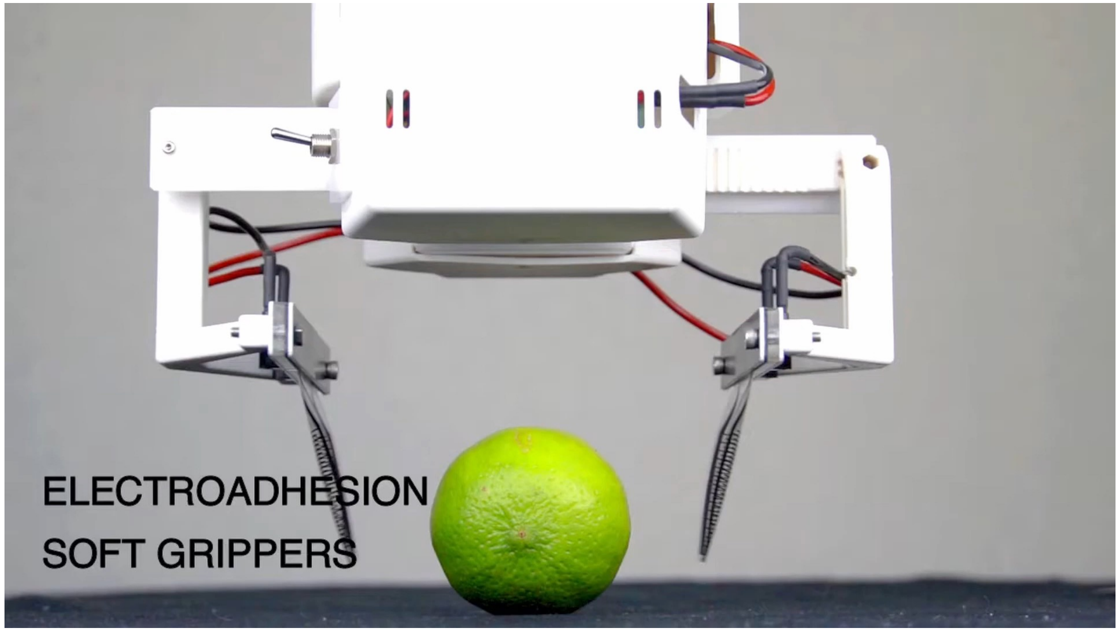
Fabio Caruso

Electroadhesion soft grippers: generate high shear forces using interdigitated compliant electrodes



$$\sigma_{EA} \sim \left(\frac{V}{t}\right)^2 \varepsilon^2$$

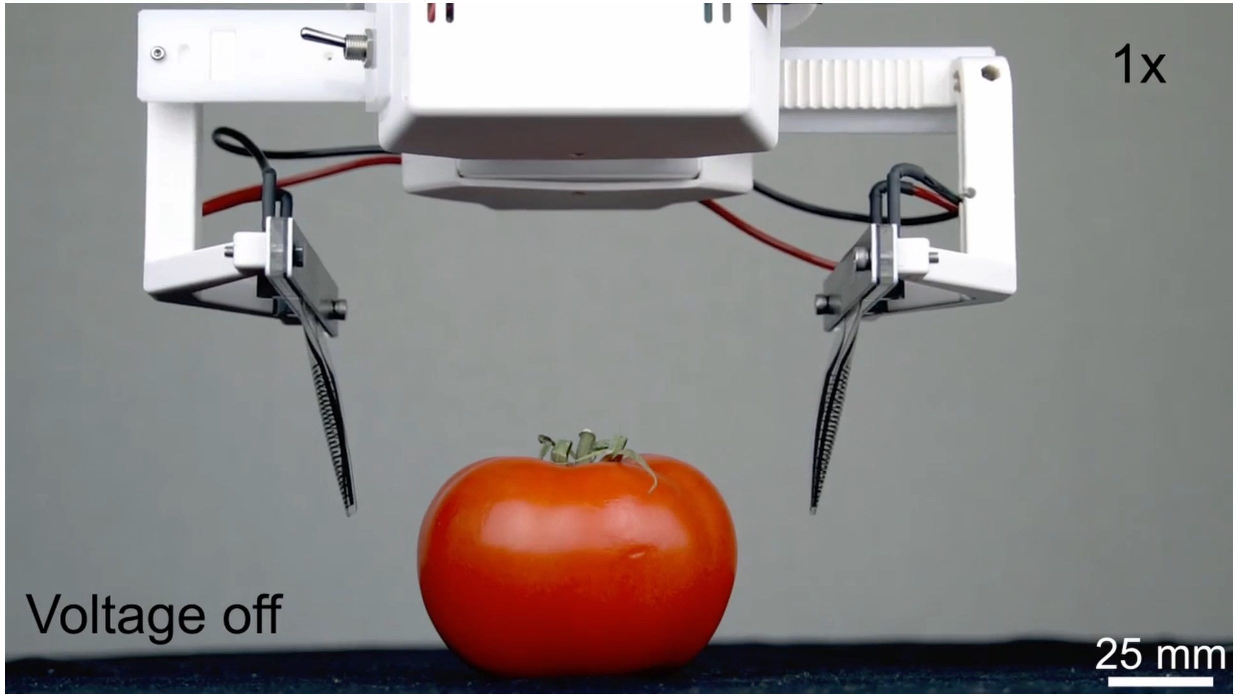
V=1-5 kV

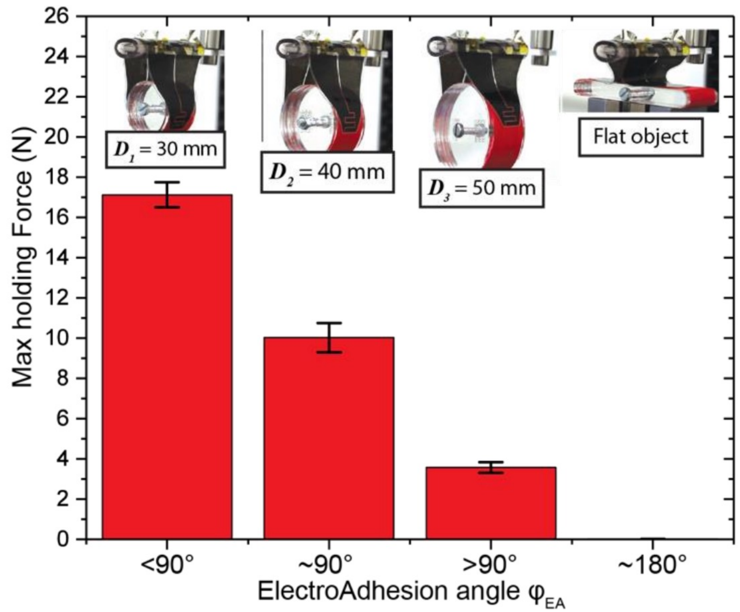


V. Cacucciolo et al, *Extreme Mechanics Letters* 2022

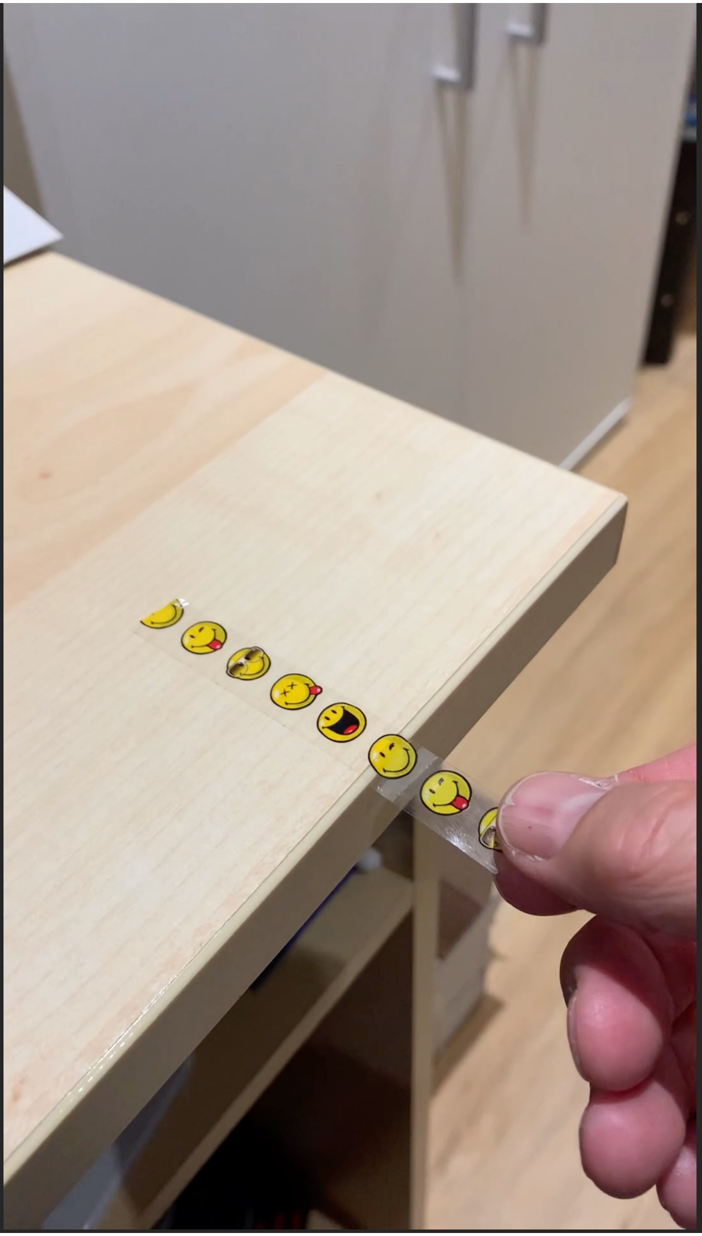
Prof. Vito Cacucciolo
(now at Politecnico di Bari)

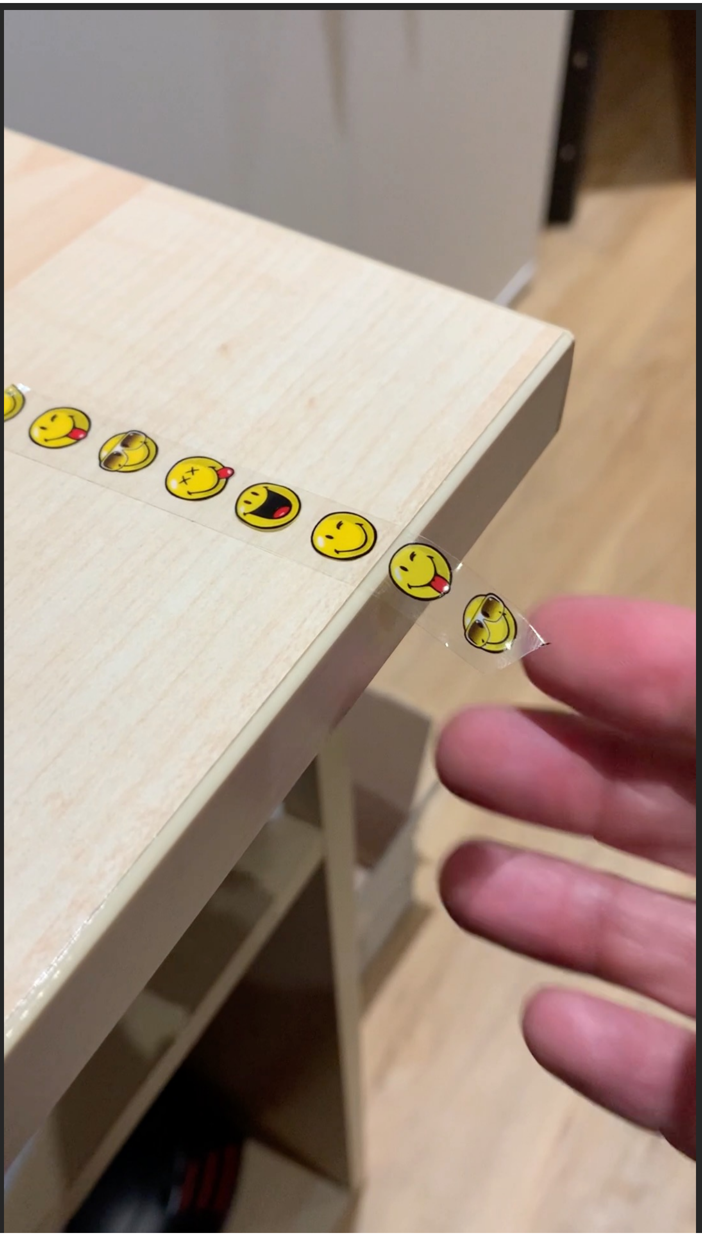
Peeling in electroadhesion soft grippers limits the holding force



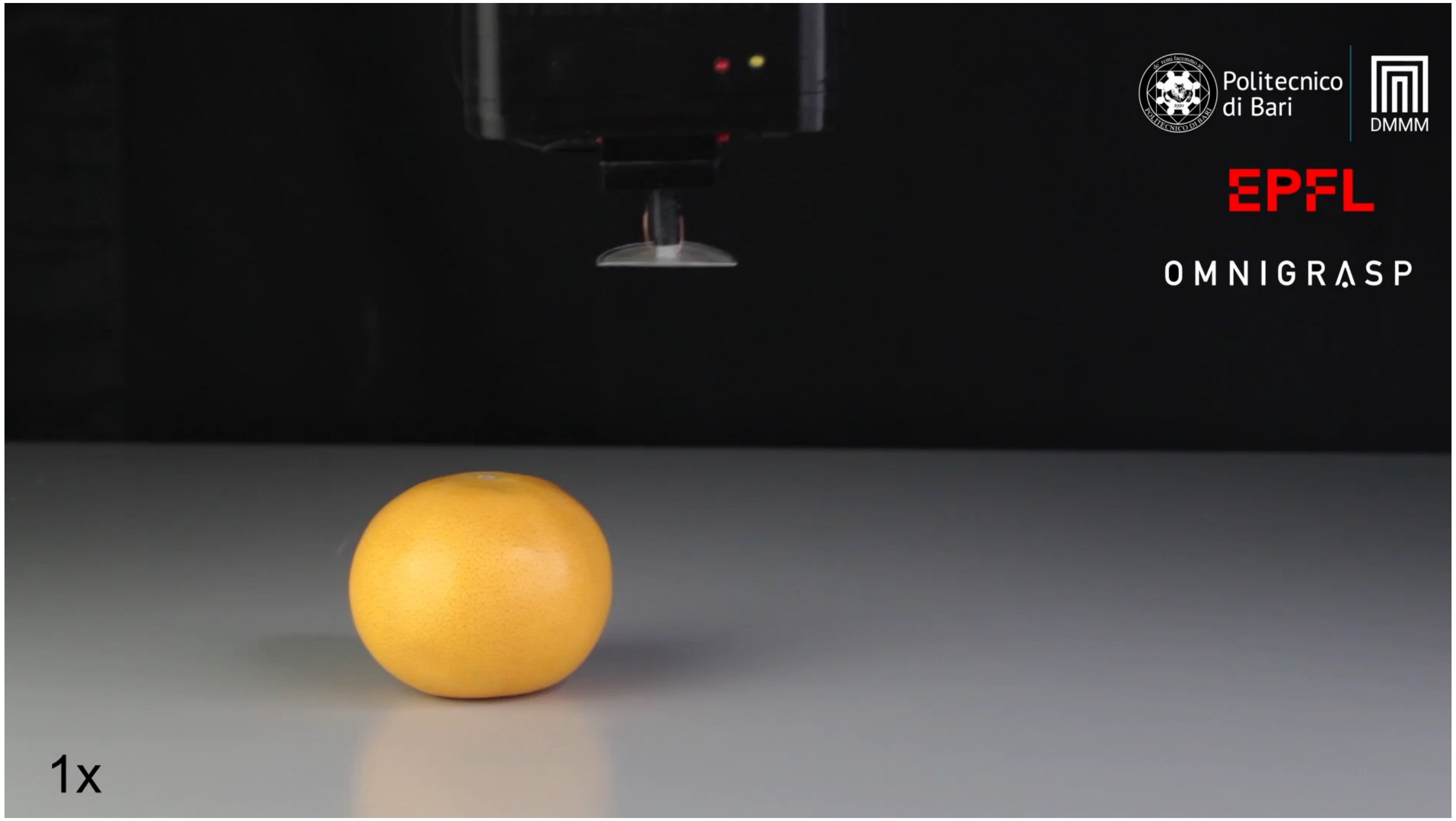


Cacucciolo, V., Shea, H., & Carbone, G. *Extreme Mechanics Letters* (2022)
Cacucciolo, V., Shintake, J., & Shea, H. *2nd IEEE International Conference on Soft Robotics (2019)*





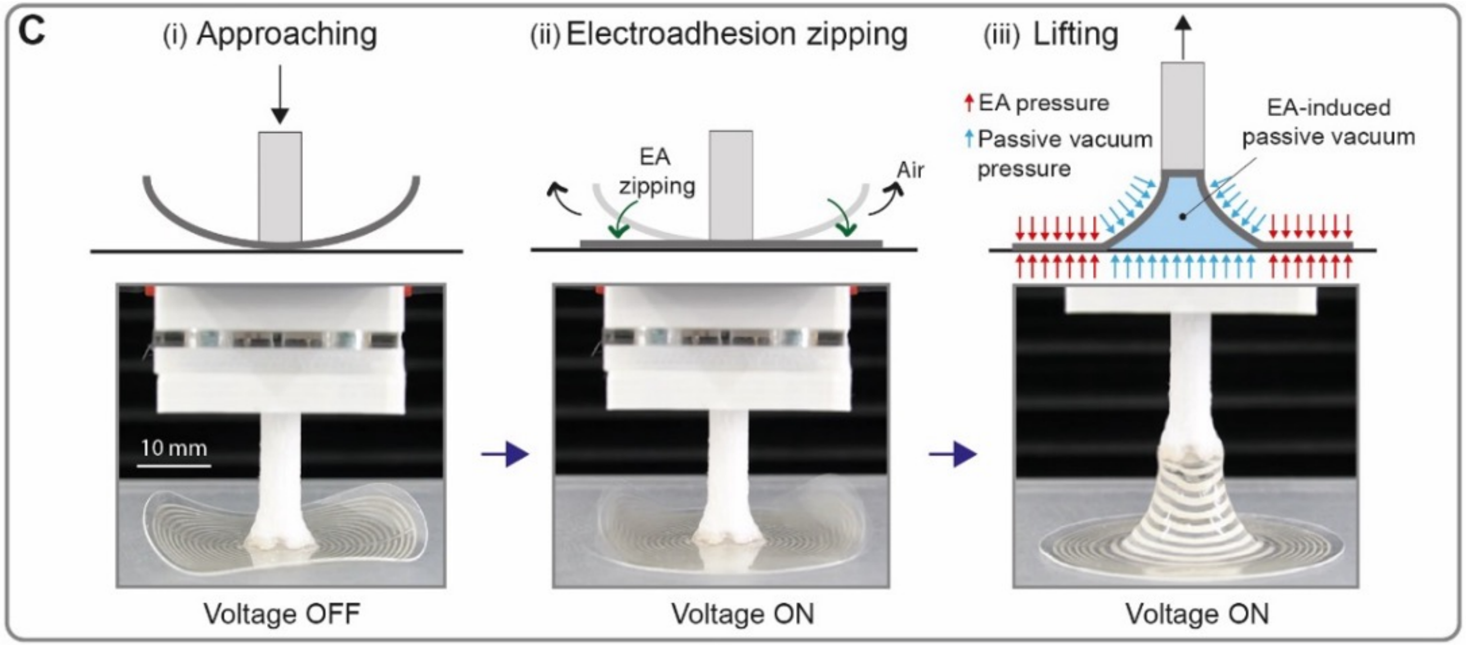
Electroadhesion (EA) suction cups enable gripping from the top

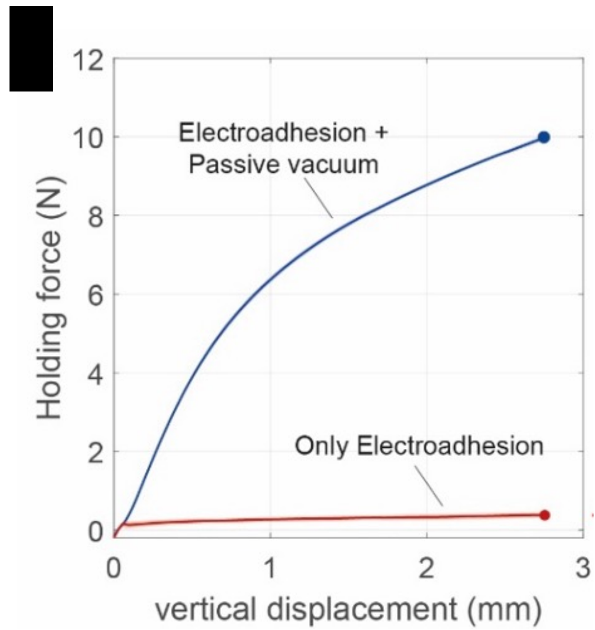


Fabio Caruso

F. Caruso, H. Shea, V. Cacucciolo. *Advanced Material* 2025

Electroadhesion suction cups: combine EA <u>and</u> passive vacuum



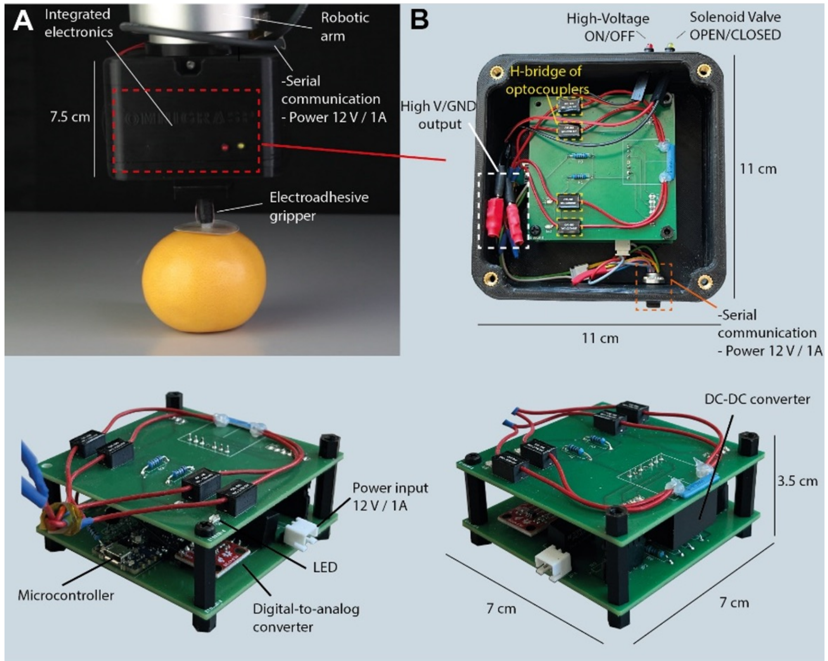


- conforms to object shape,
- EA geometry maximizes force before peeling occurs

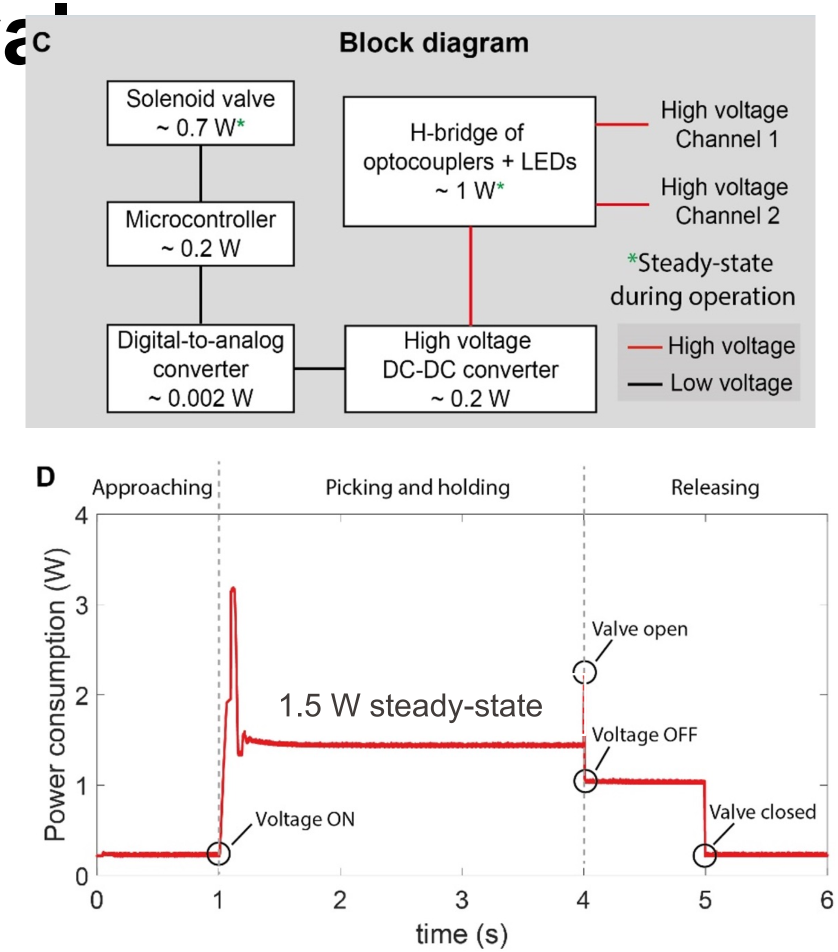
Like a vacuum suction cup, but 10-100x less power

F. Caruso, H. Shea, V. Cacucciolo. *Advanced Material* 2025

power consumption in EA suction cups from HV electronics and va



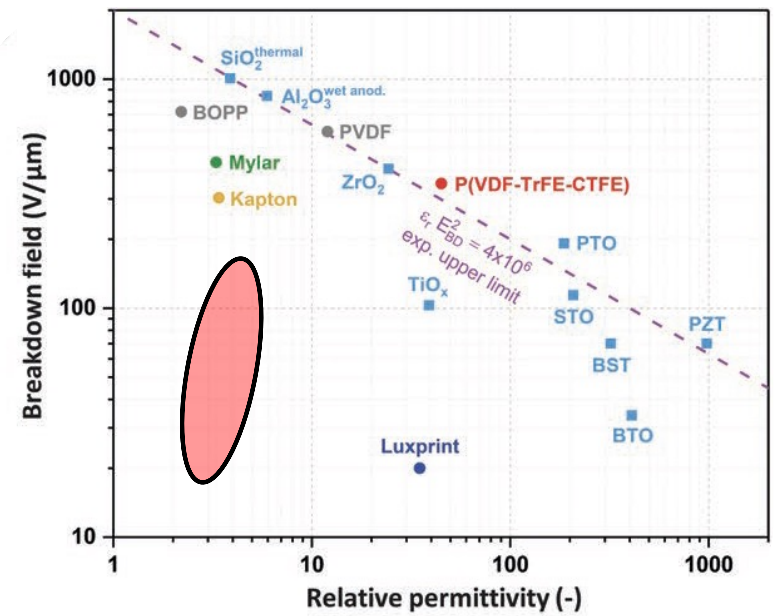
Integrated HV power supply
(can power 10 EA suction cups)



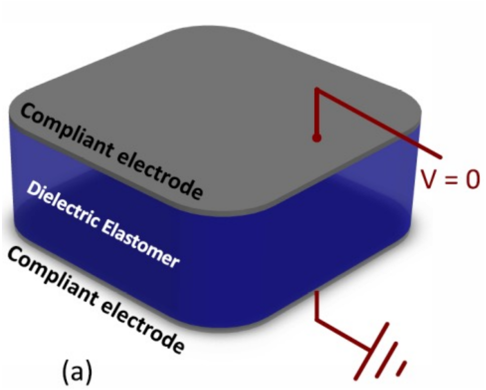
Compare 1.5 W to the power consumption for vacuum generator of roughly 10 W to 100 W

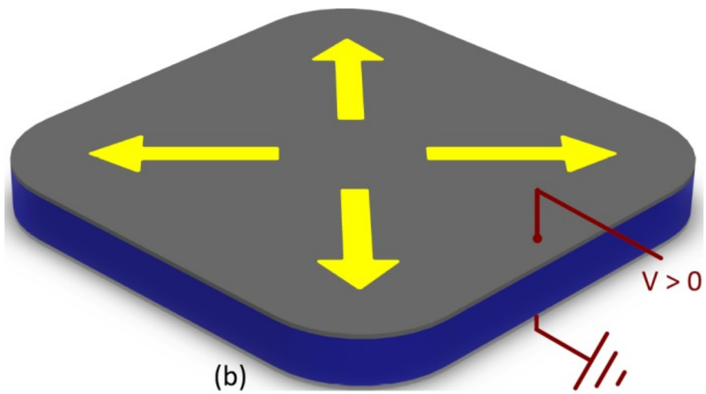
2. DEA

Dielectric Elastomer Actuators (DEAs)



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





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

Pelrine, *Science* 2000

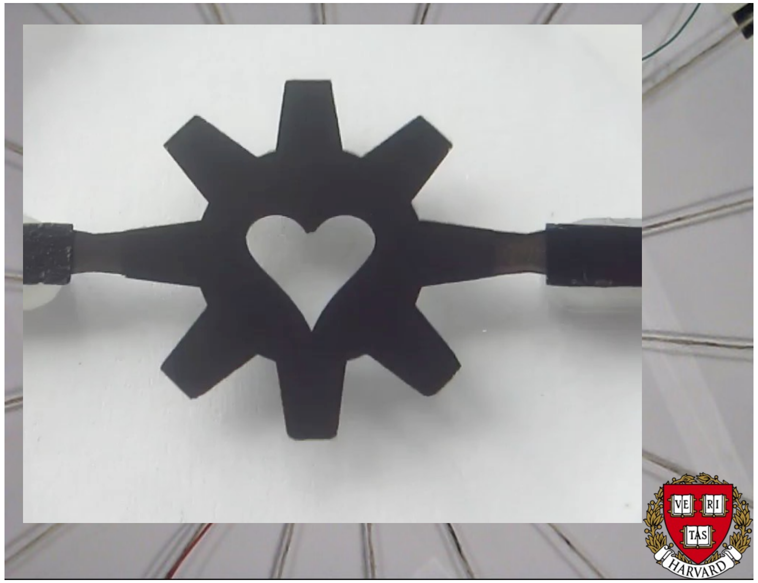
Simple structure

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 30% strain for long-term operation today
- Lightweight: Energy density 3 MPa/m^3
  - If we ignore the frame and power supply…
- Soft: Young's modulus ≈ 1 MPa
  - If we ignore the frame
- Capacitive: no power to hold a position
  - If we ignore losses in HV supply
- Can add intelligence through self-sensing

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

Some multilayer DEAs do show very impressive power density and high speed: At 400 Hz, this 140 mg DEA generates forces of 0.36 N and displacements of 1.15 mm

SV1: robot flapping simulation and experiment

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.

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.

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
- Frame if want high strain

Applications shown in the lab

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

Commercial applications

Real commercial devices (*canceled*)

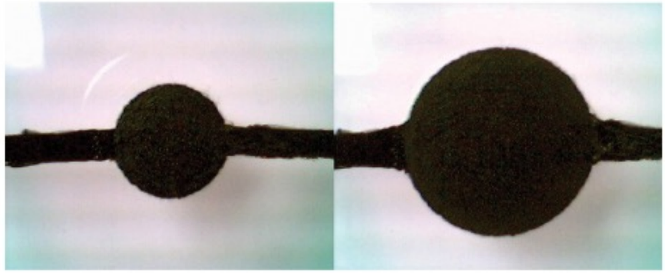
- Haptic devices for ipod touch
- Headphone shaker
- Laser speckle reducer

Nearly on market (*maybe?*)

- Multi-layer stacks for haptics

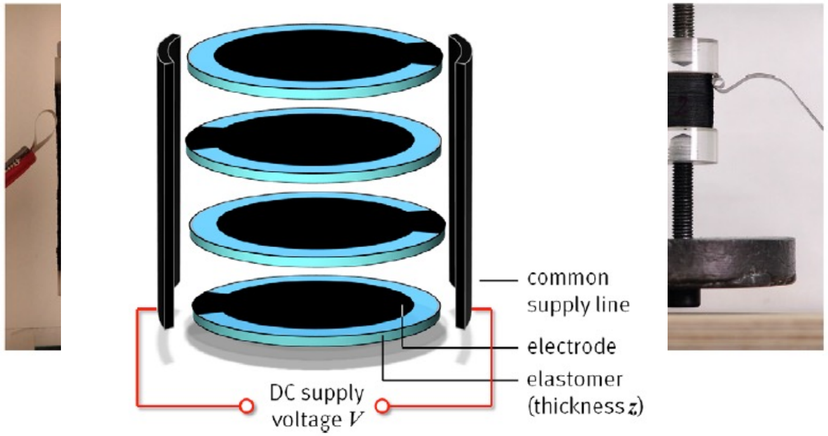
Two Main actuation modes of Dielectric Elastomer Actuators (same physics)

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



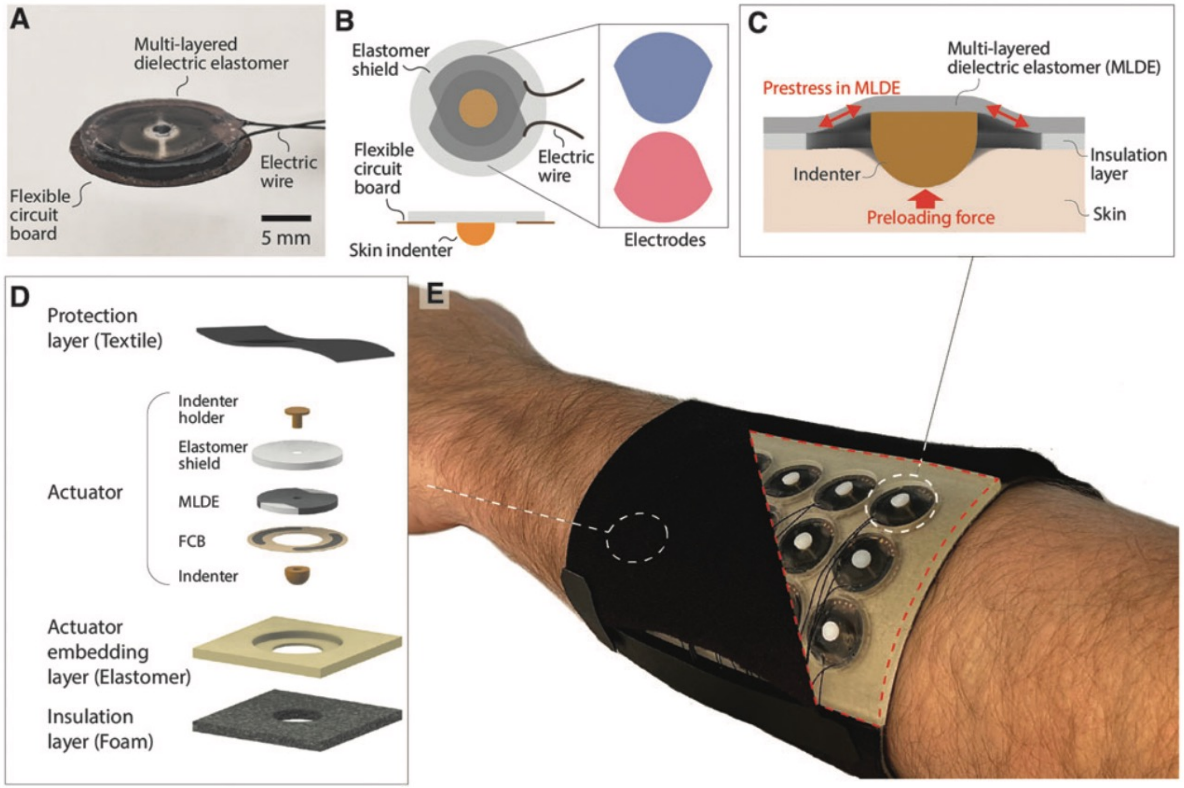
T. A. Gisby, et al, Proc. SPIE 7287, 728707 (2009).

- **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)

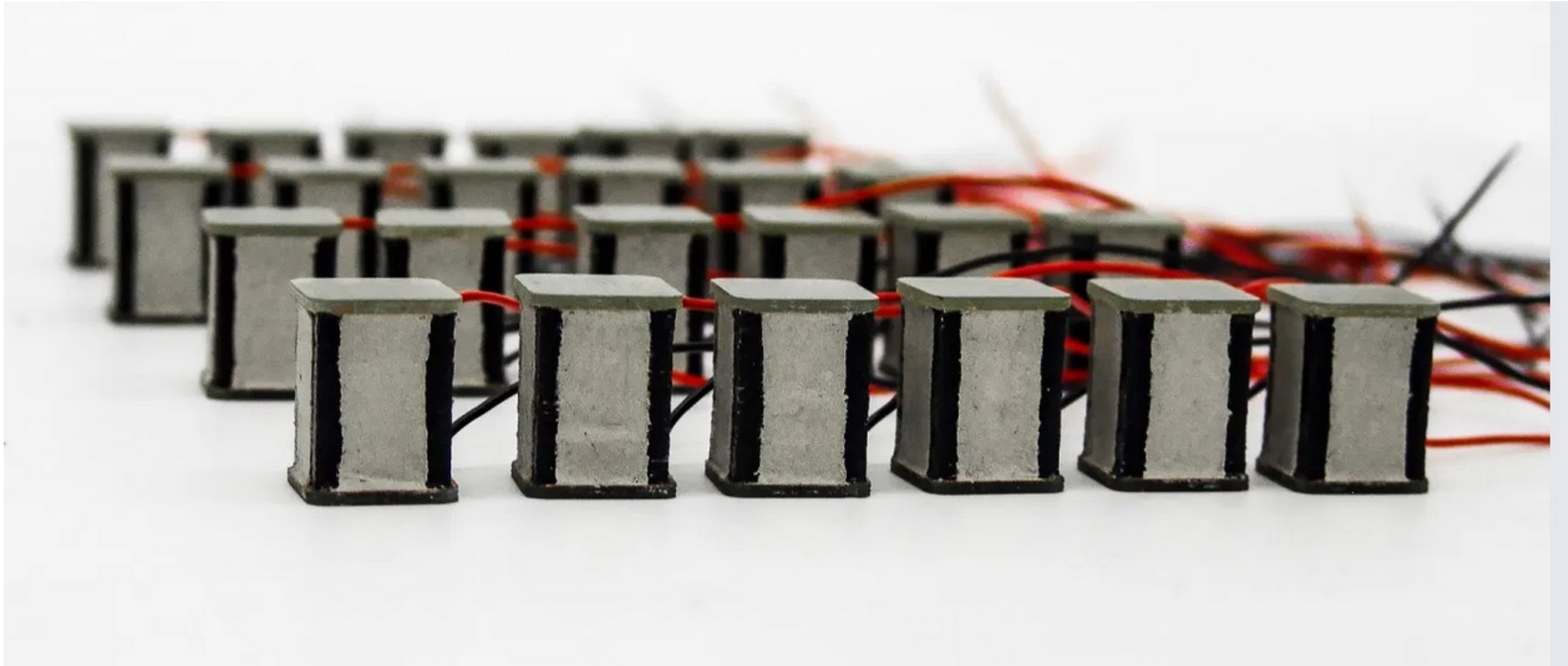


G. Kovacs et al, Sens. Actuators, 155A(2), 299 (2009).

One example of wearable DEAs for haptics

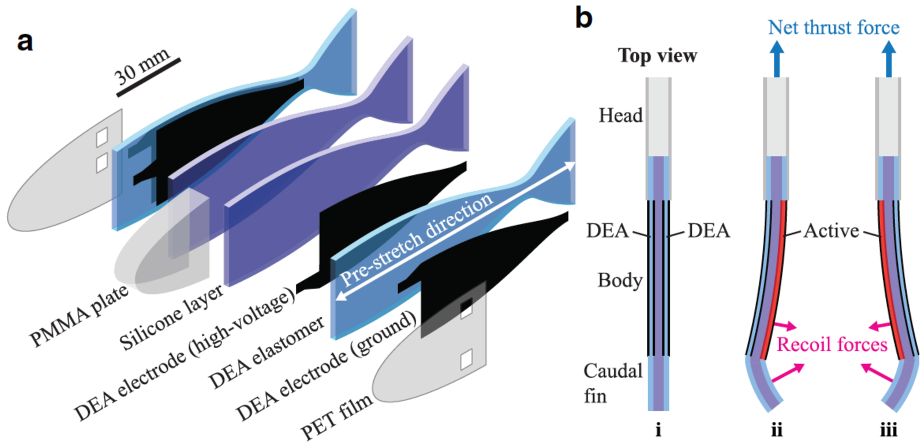


D.-Y. Lee *et al.*, "A Wearable Textile-Embedded Dielectric Elastomer Actuator Haptic Display," *Soft Robotics*, Jul. 2022, doi: [10.1089/soro.2021.0098](https://doi.org/10.1089/soro.2021.0098).



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

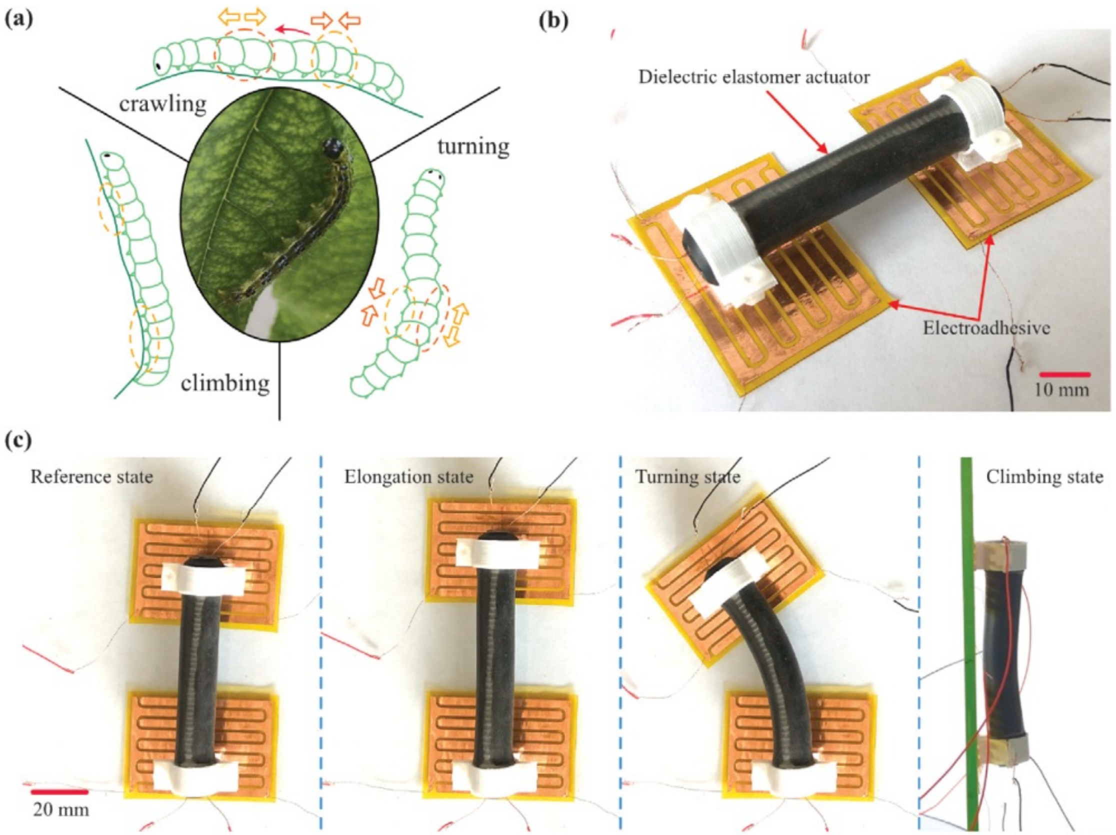
Swimming is easier than walking, especially when one has to carry a heavy power supply…



NOT untethered

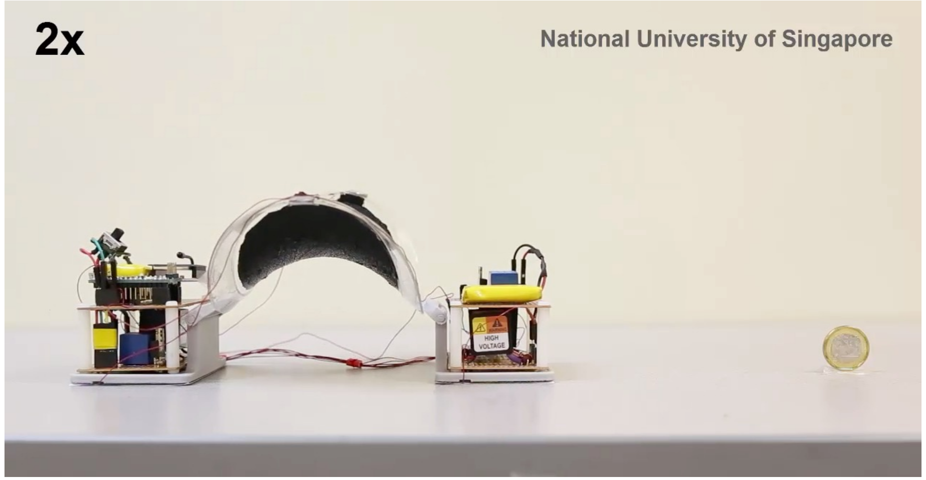
J. Shintake, V. Cacucciolo, H. Shea, D. Floreano,
Soft Biomimetic Fish Robot Made of Dielectric Elastomer Actuators.
Soft Robotics. **5**, 466–474 (2018).

NOT untethered

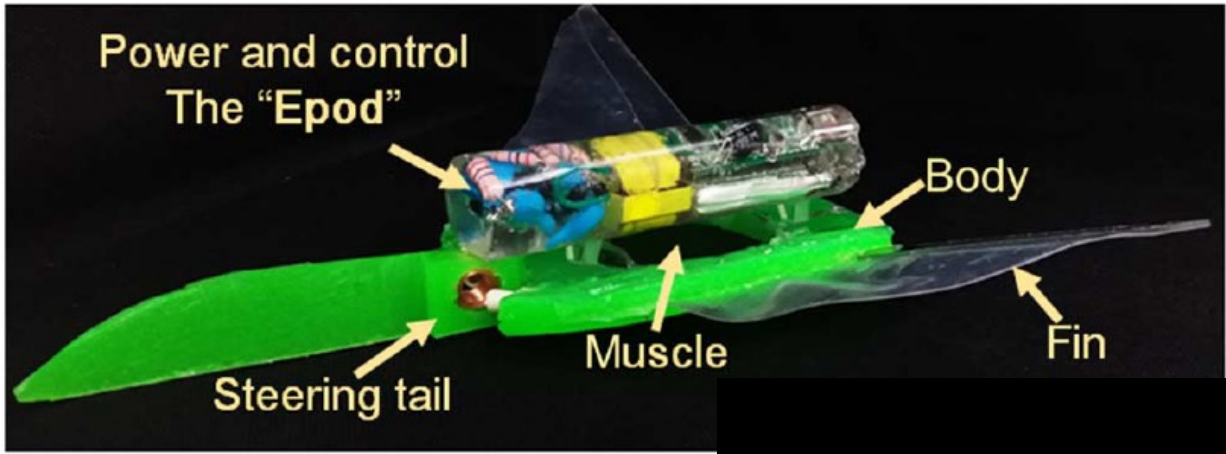


Y. Guo, J. Guo, L. Liu, Y. Liu, J. Leng, Bioinspired multimodal soft robot driven by a single dielectric elastomer actuator and two flexible electroadhesive feet. *Extreme Mechanics Letters*, 101720 (2022).

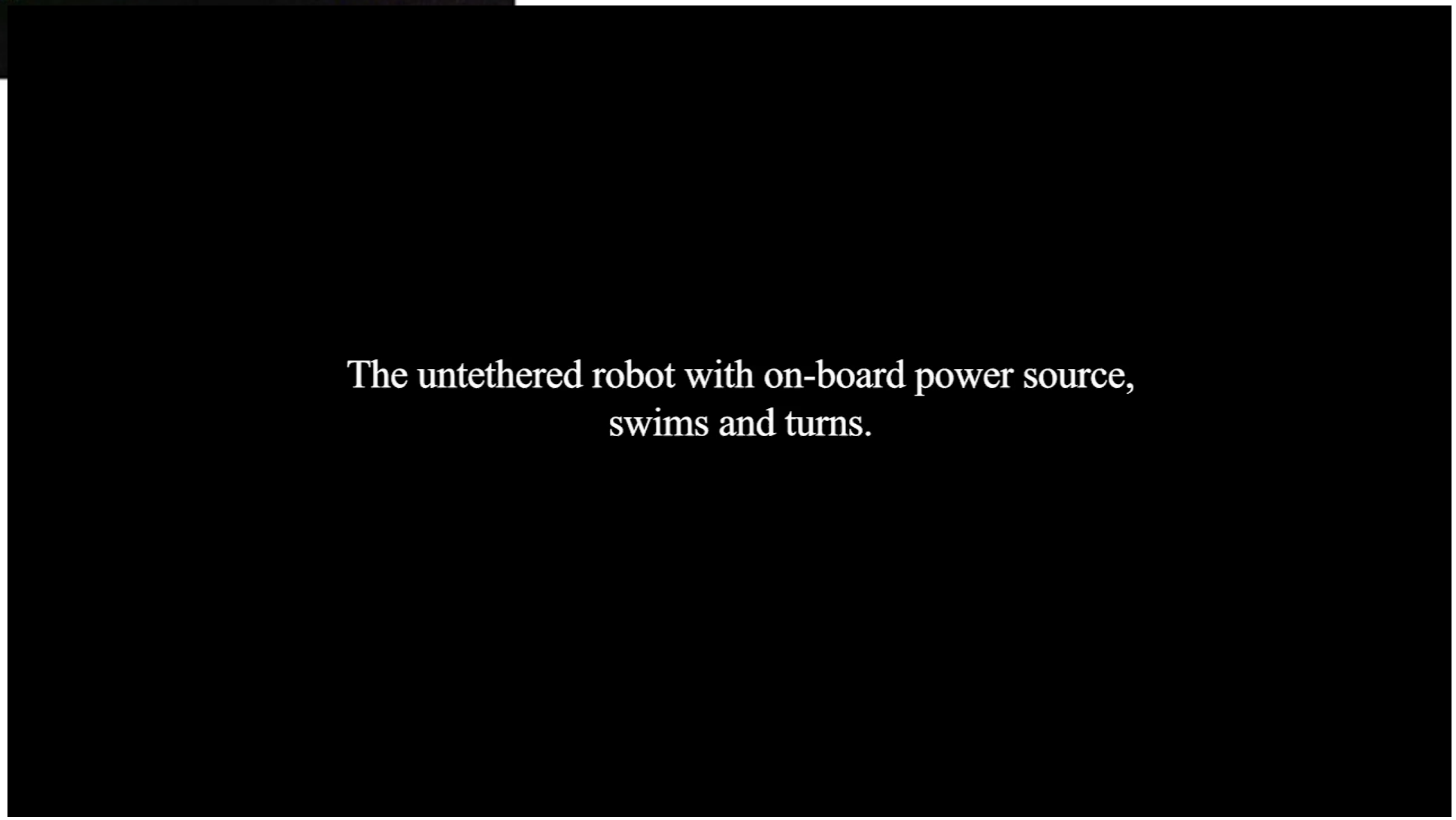
UNtethered



J. Cao, … J. Zhu, Untethered soft robot capable of stable locomotion using soft electrostatic actuators. *Extreme Mechanics Letters* **21**, 9–16 (2018).

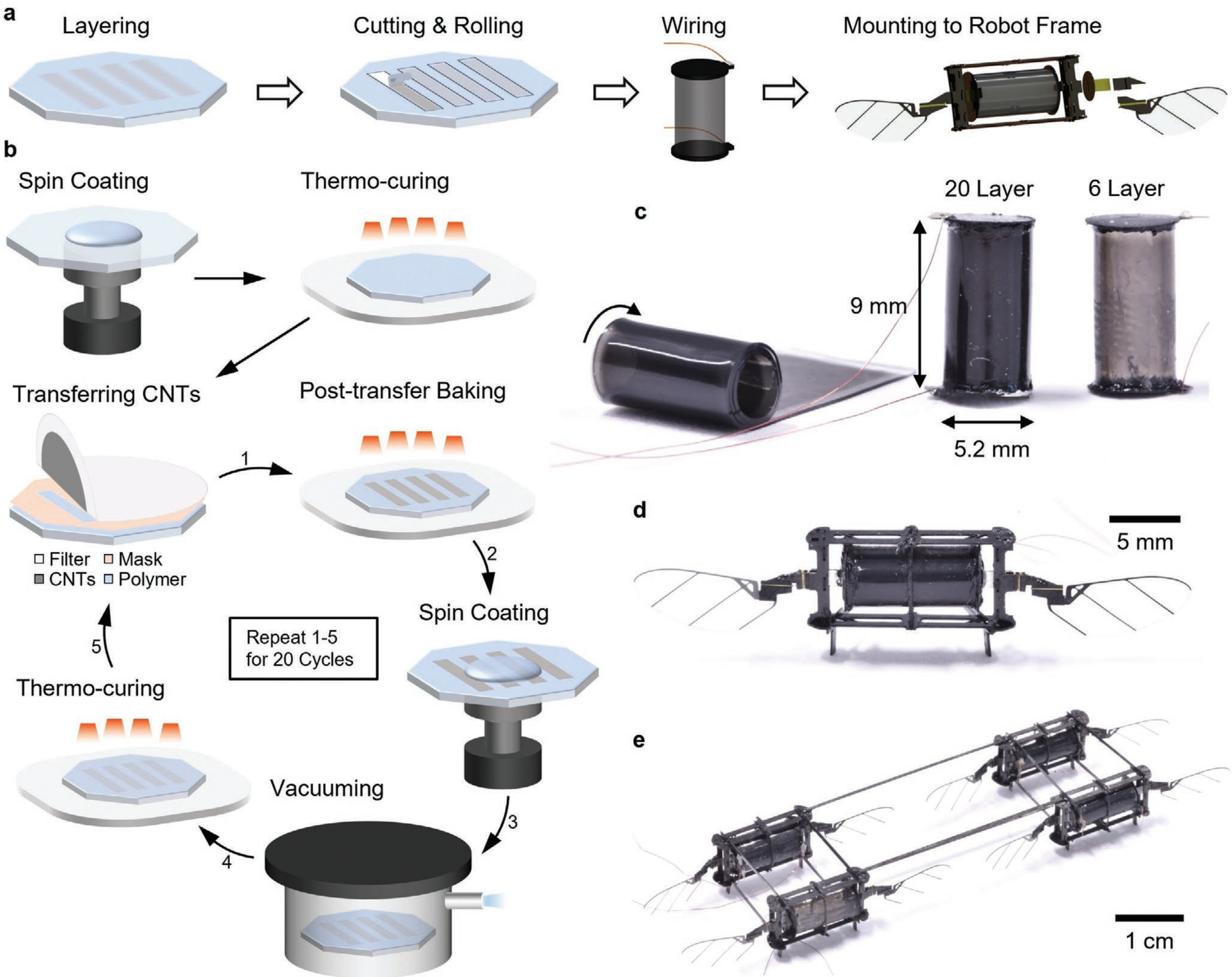


(then shown at 10 km depth)



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

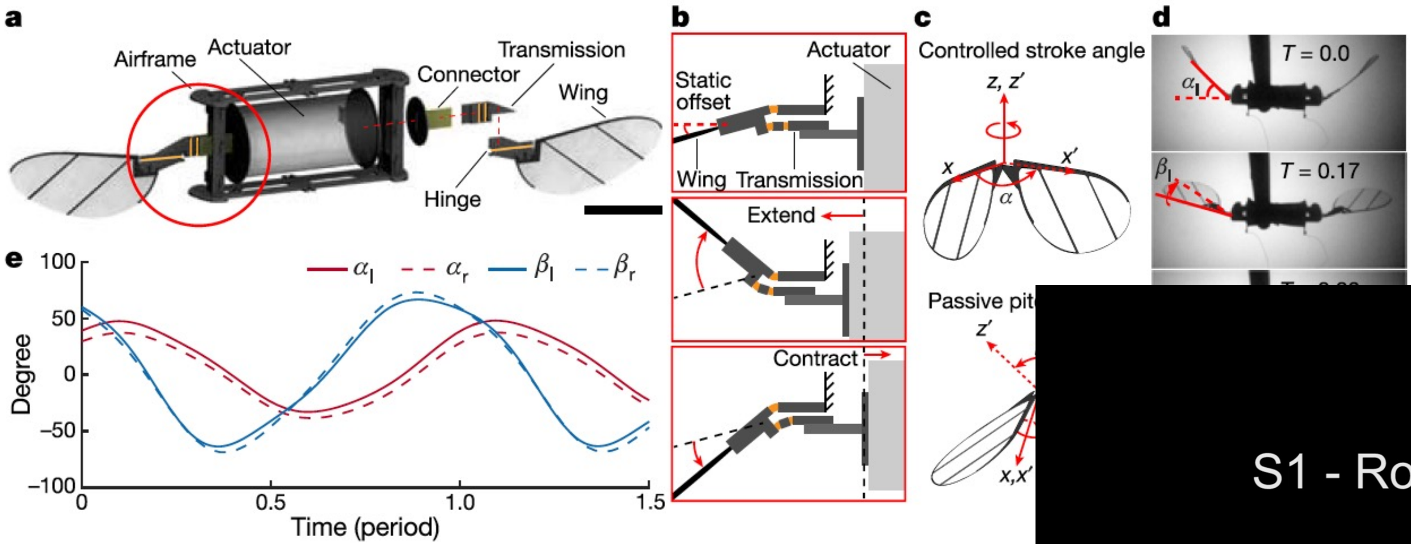
G. Li et al. *Nature*. **591**, 66–71 (2021).



Harvard / MIT rolled multi-layer DEA have the highest power density

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.

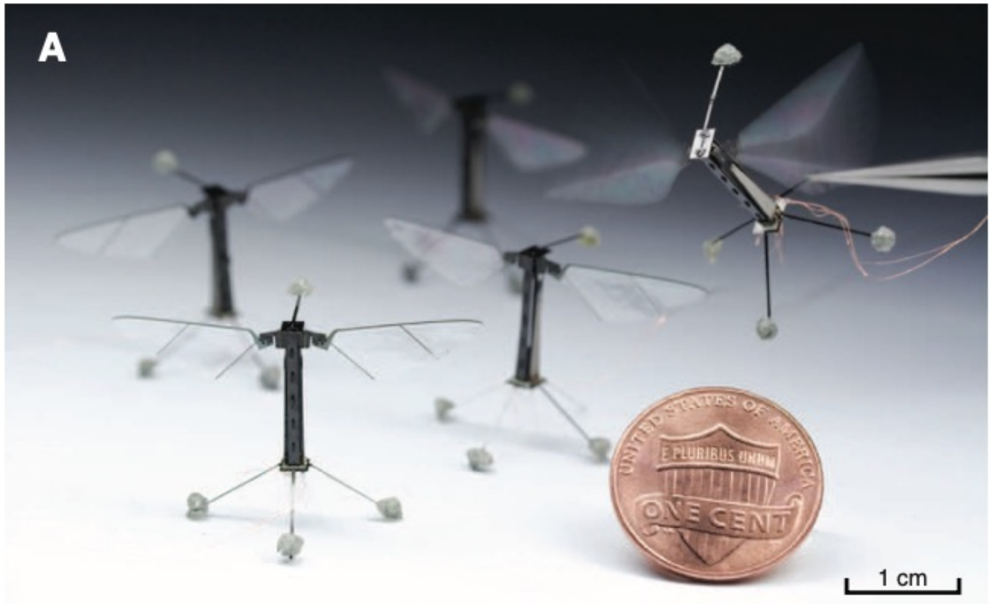
<u>Flying</u> is hardest task: need very high energy density and effective flapping motion.



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

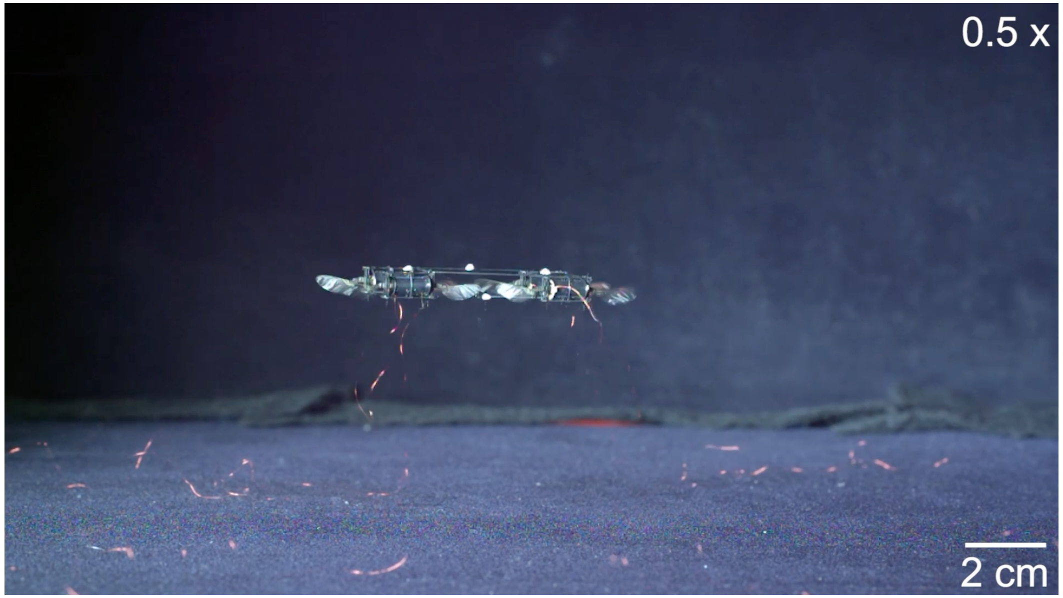
Y. Chen, H. Zhao, J. Mao, P. Chirarattananon, E. F. Helbling, N. P. Hyun, D. R. Clarke, R. J. Wood, Controlled flight of a microrobot powered by soft artificial muscles. *Nature* (2019), doi:<u>10.1038/s41586-019-1737-7</u>.

Why DEA rather than piezo?



K. Y. Ma, P. Chirarattananon, S. B. Fuller, R. J. Wood,
Controlled Flight of a Biologically Inspired, Insect-Scale Robot.
Science **340**, 603–607 (2013).

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



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).

Hybrid locomotion at the insect scale – combined flying and jumping for enhanced efficiency and versatility

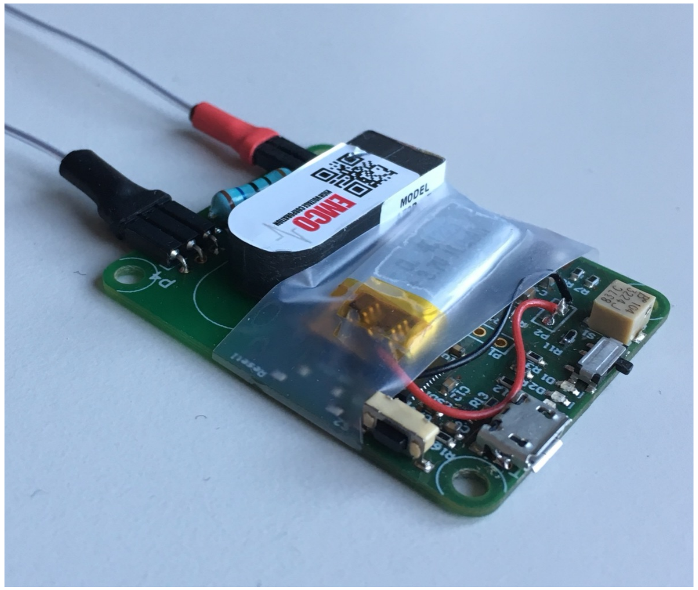
Yi-Hsuan Hsiao[1+], Songnan Bai[2+], Zhongtao Guan[1+], Suhan Kim[1], Zhijian Ren[1],
Pakpong Chirarattananon[2,3*], Yufeng Chen[1*]

[1]Department of Electrical Engineering and Computer Science, MIT, Cambridge, MA, USA.
[2]Department of Biomedical Engineering, City University of Hong Kong, Hong Kong, China.
[3]Centre for Nature-Inspired Engineering, City University of Hong Kong, Hong Kong, China.
[+]equal contribution
[*]corresponding author: pchirara@cityu.edu.hk, yufengc@mit.edu

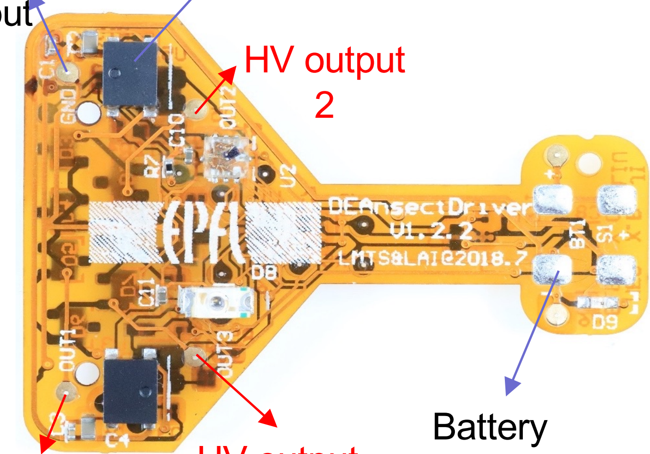
H. Hsiao, S. Bai, Z. Guan, S. Kim, Z. Ren, P. Chirarattananon, Y. Chen, Hybrid locomotion at the insect scale: Combined flying and jumping for enhanced efficiency and versatility. *Science Advances* **11**, eadu4474 (2025).

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

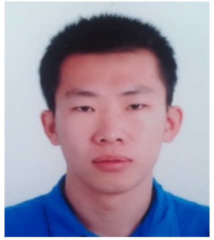


Miniature 2 channel 500 V 1 kHz power supply:
0.35 g

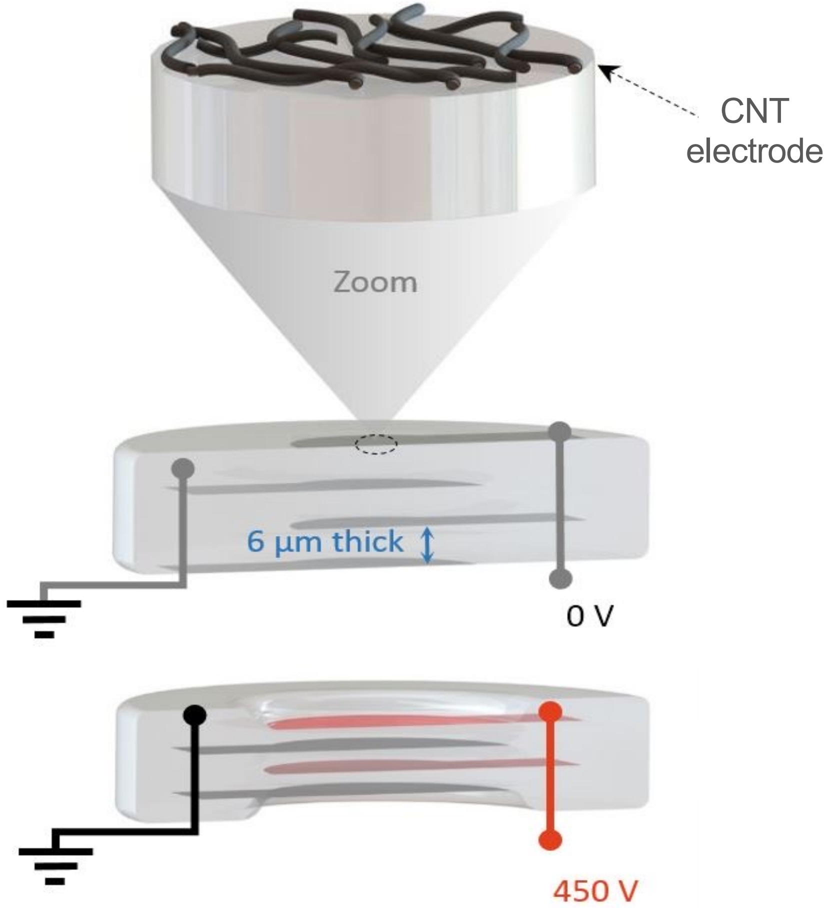
An obvious path to lower voltages: use thinner dielectric layers in the DEA

Sounds easy… but with very thin DEAs:

- Need to many stacks to get enough force
- need extremely soft and thin electrodes!
  - RC time constant must be high, but C increases as layers get thinner, so need low R
  - Very tricky if electrodes are only nm thick…



Xiaobin Ji



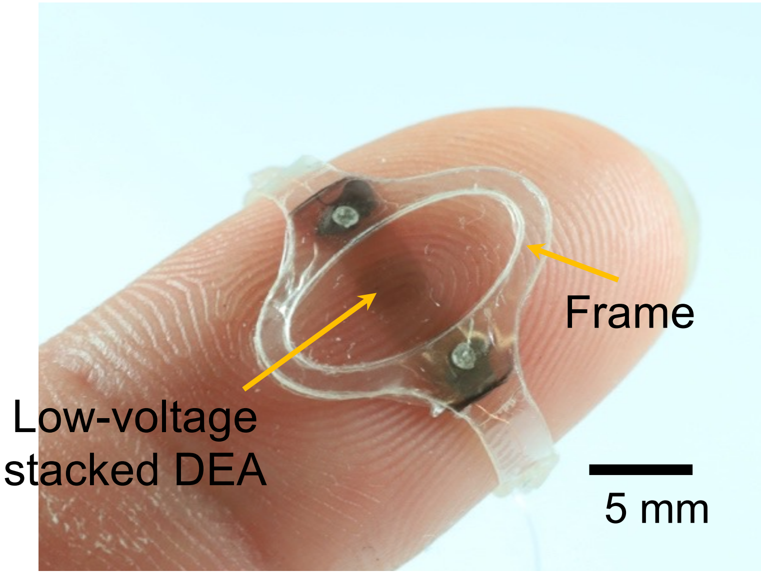
Low-voltage stacked DEAs using Langmuir-Blodgett assembled CNT monolayer electrodes

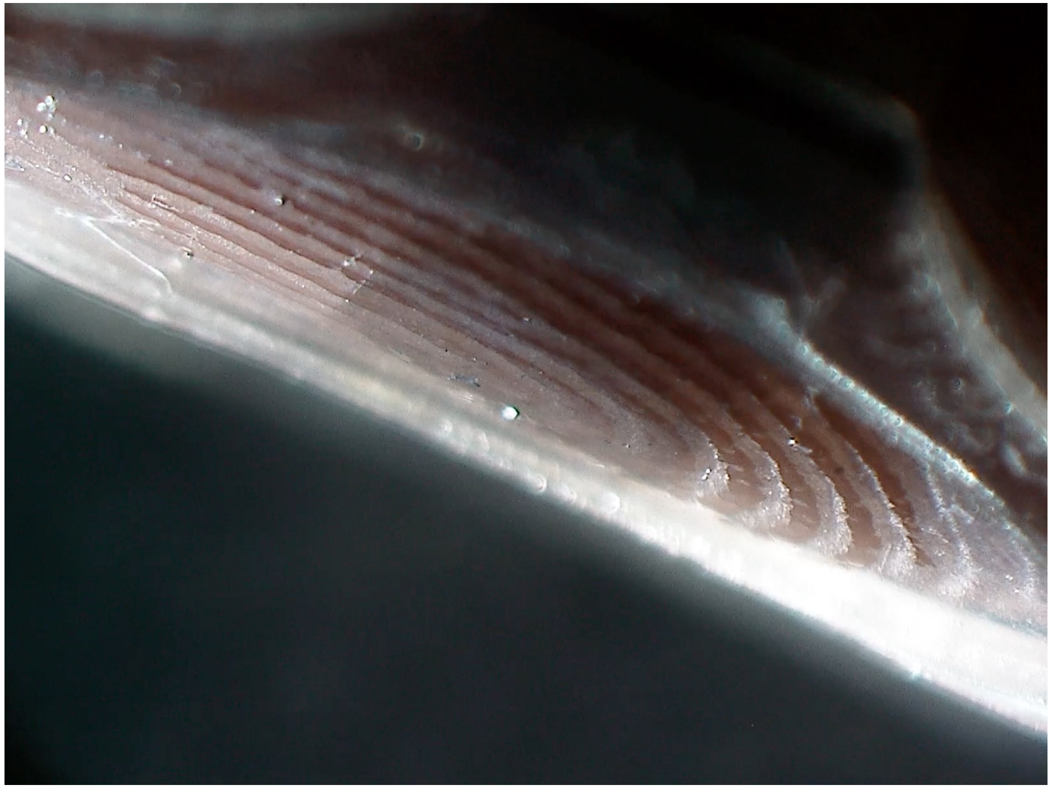
Full DEA strain at 450V, up to 500 Hz

Collaboration EPFL-LMTS & Université de Cergy Pontoise - LPPI

X. Ji et al, Science Robotics 2019

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



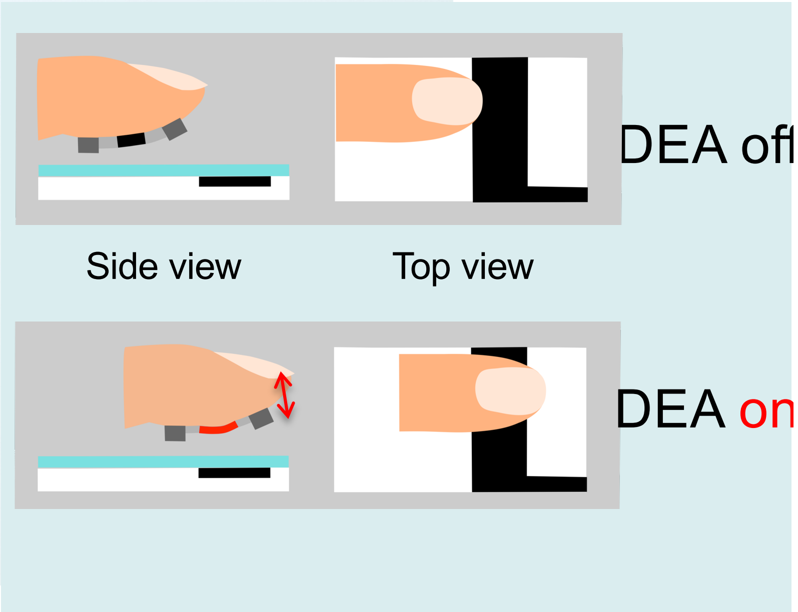


Key features:

- “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

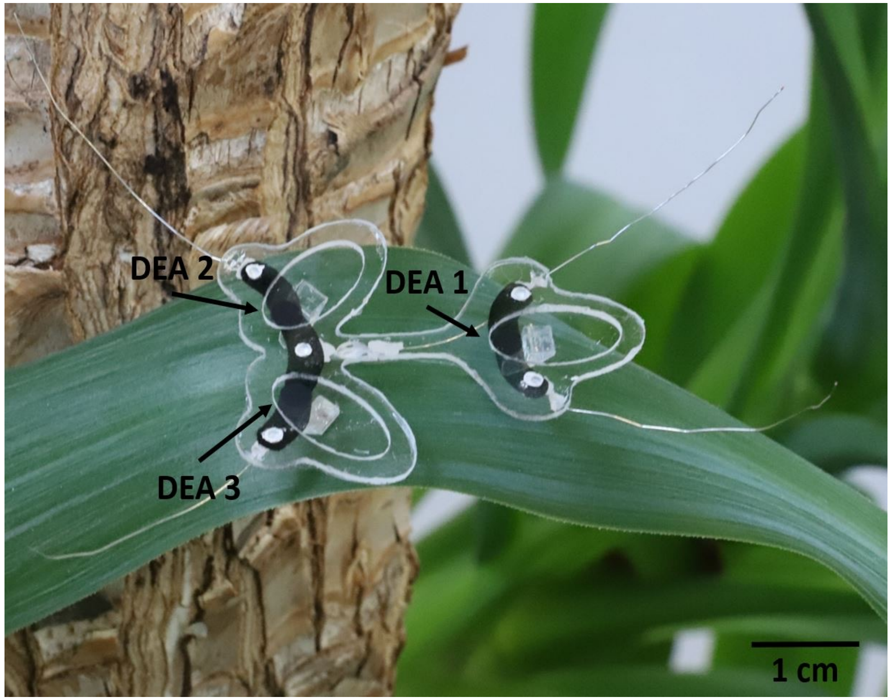
Control: with ”low-V” electronics: can have some processing power

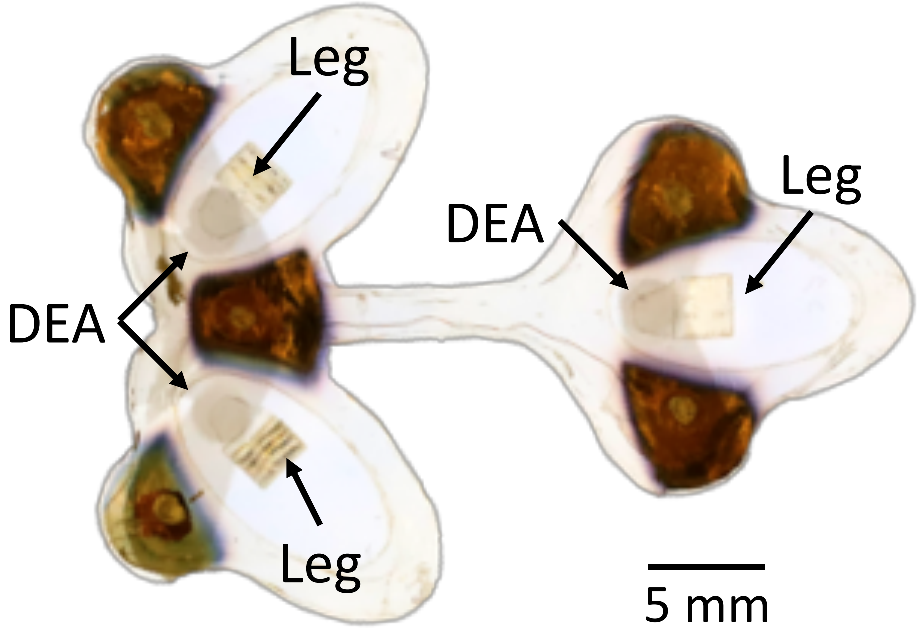
Electronics made by EPFL-LAI

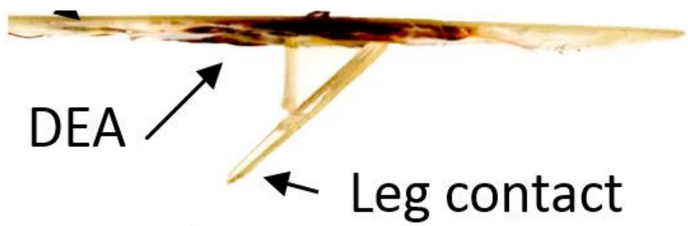


Use a finger to "see" letters!

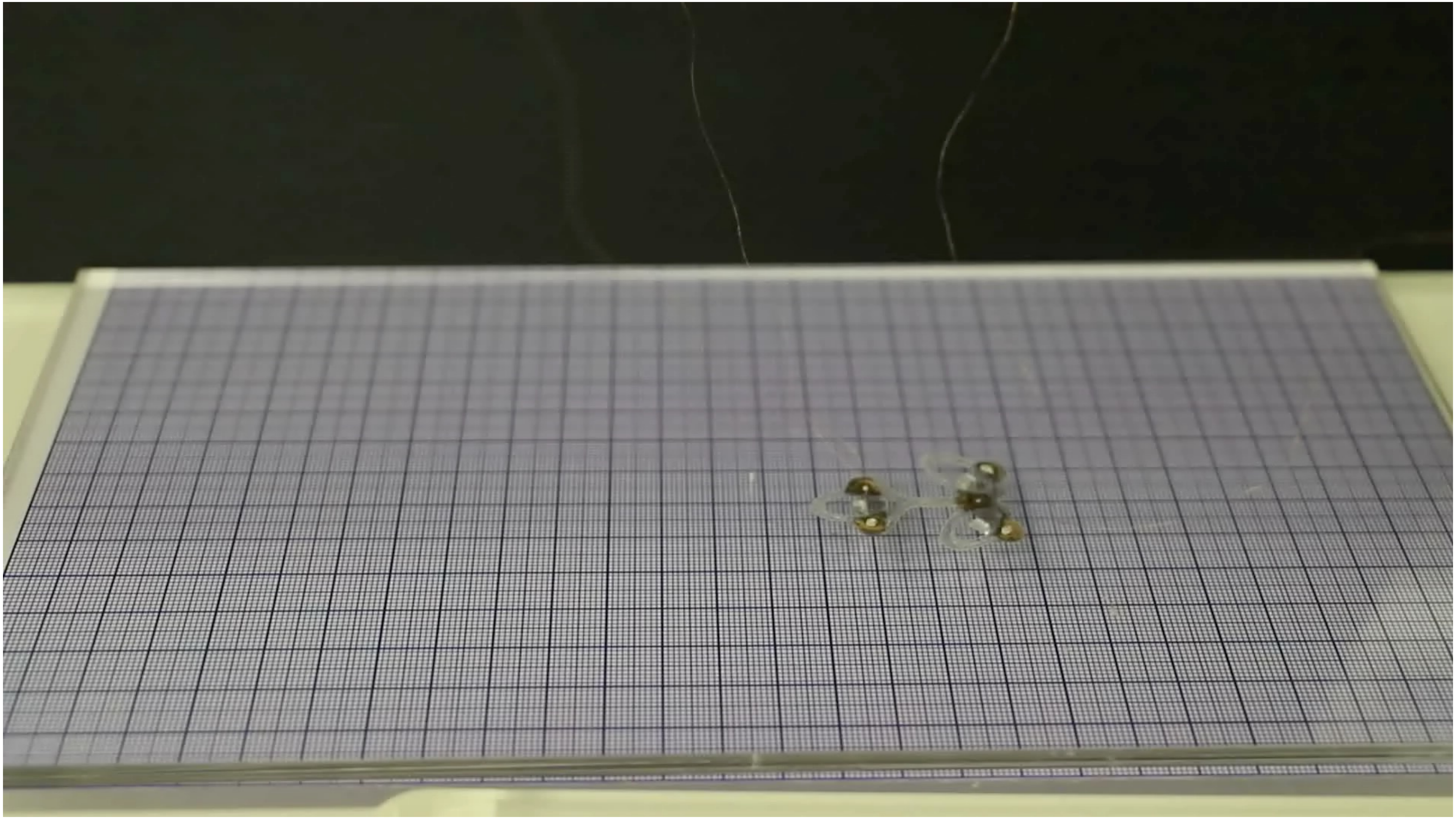
Soft robot using fast and low-voltage DEAs



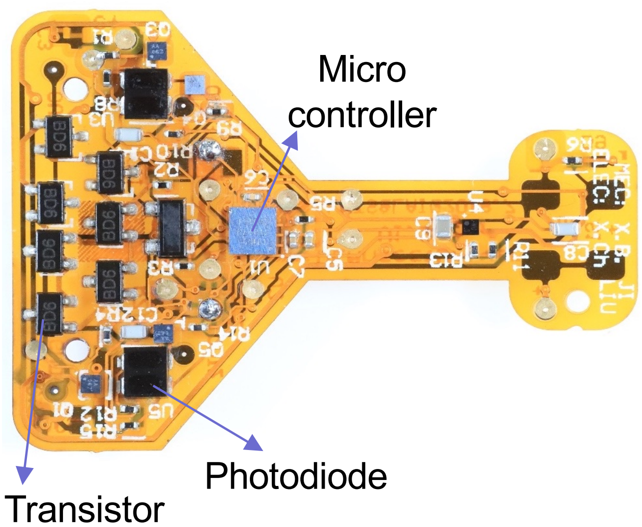


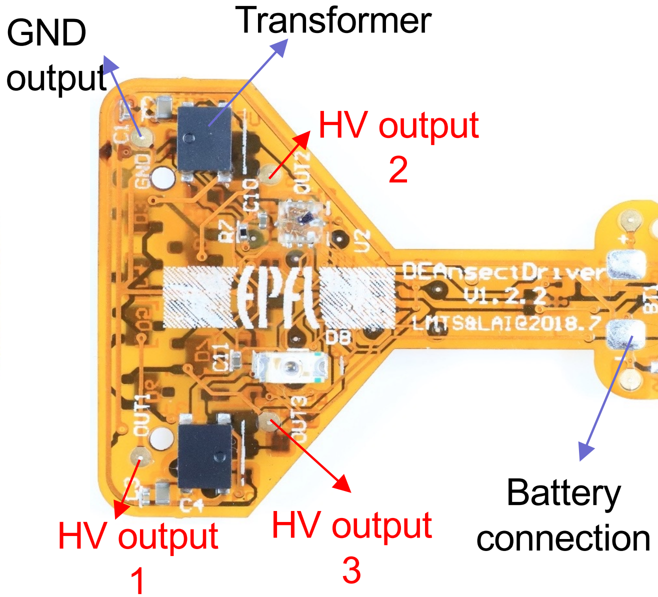


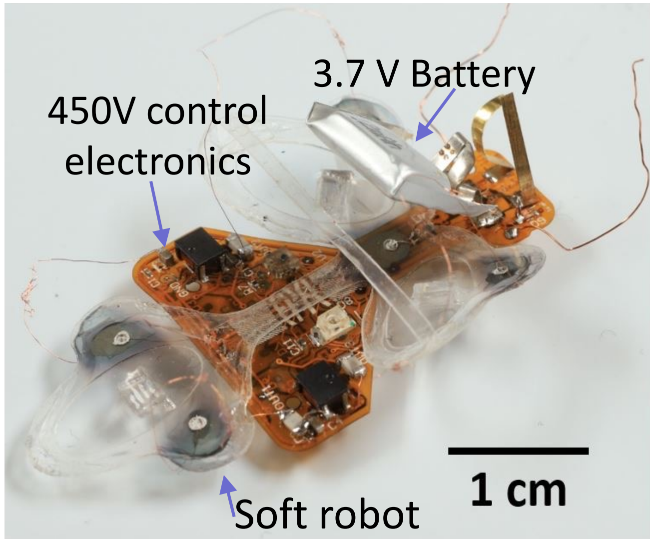
X. Ji ,.. Shea, *Adv. Func Mat* 2021



- Sub-500 V allows use of SMD components: no more big DC-DC converters!
- 770 milligram electronics including battery, sensors and microcontroller for 2 channels at 450 V and 1 kHz
- Allows **<u>untethered fast DEA robot</u>, with autonomous path following**







Electronics designed and made by EPFL-LAI (Prof. Perriard)

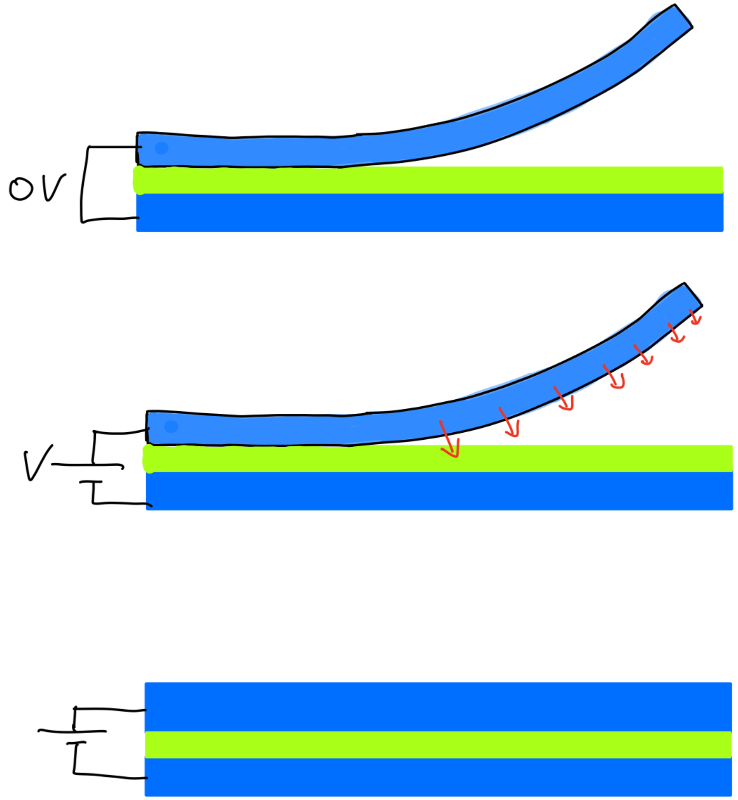
Xinchang Lui

First small scale Autonomous Untethered DEA robot!
(< 1 g, 4 cm-long)

3. ZIPPING ELECTROSTATICS

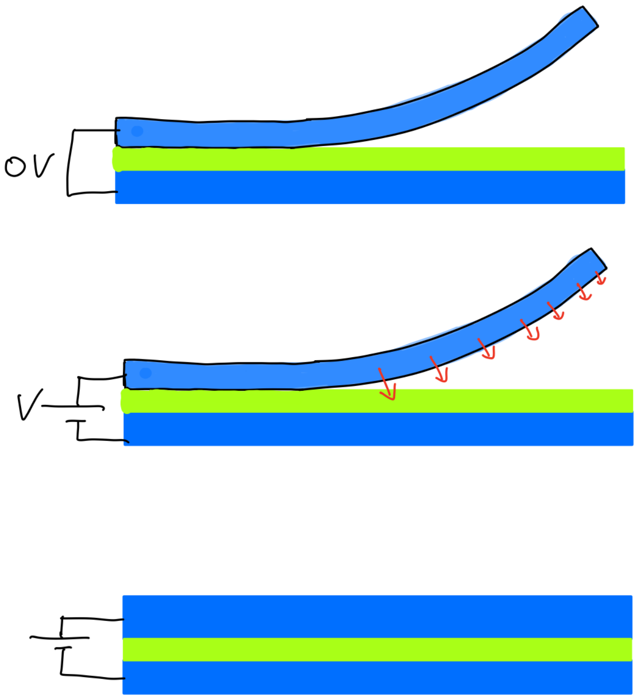
Zipping electrostatic actuators:

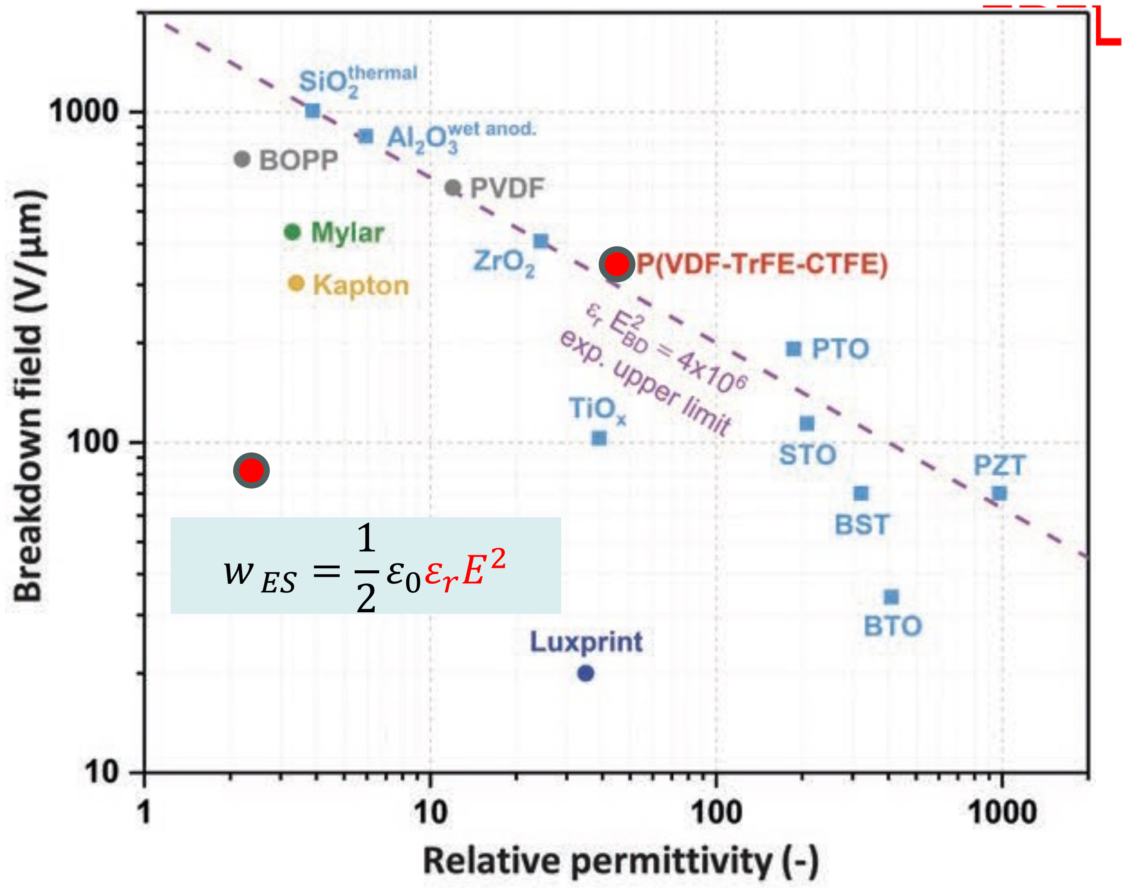
- large displacement and higher power density
- Use flexible (but not stretchable!) materials with higher E_{BD} and higher permittivity.
- Metal electrodes: easy fab, low resistance



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

Electrostatic Zipping





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

- High power density: use materials with high permittivity and high breakdown field
- No need for stretchable electrodes! Easier fabrication than DEA

Many groups develop compliant Electrostatic Zipping devices ! (aka ElectroHydraulics)

- Peano-HASEL (C. Keplinger group)

  N. Kellaris et al., *Science Robotics*, 2018
  P. Rothemund 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)

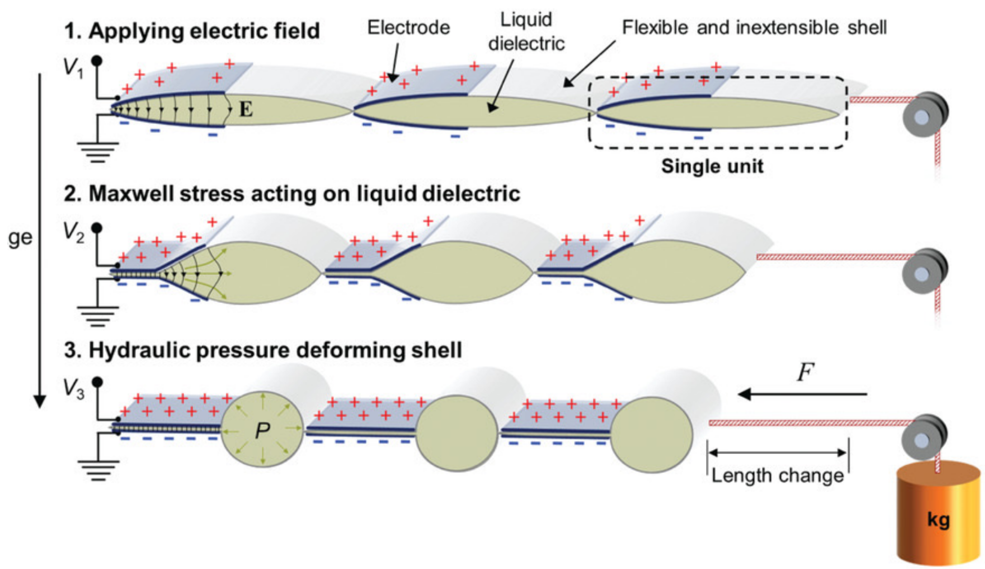
  F. Hartmann et al, *Advanced Science* 2020

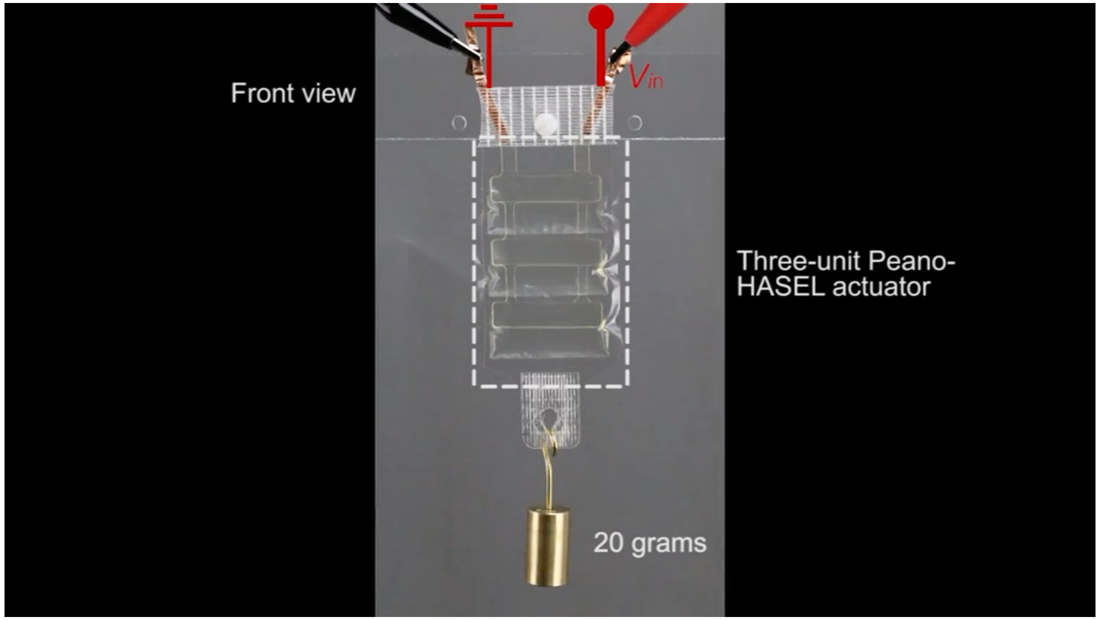
- Bellow Muscle actuators (M. Fontana group)

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

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

Peano-HASELs (Keplinger group) are the best-known example of zipping soft actuators



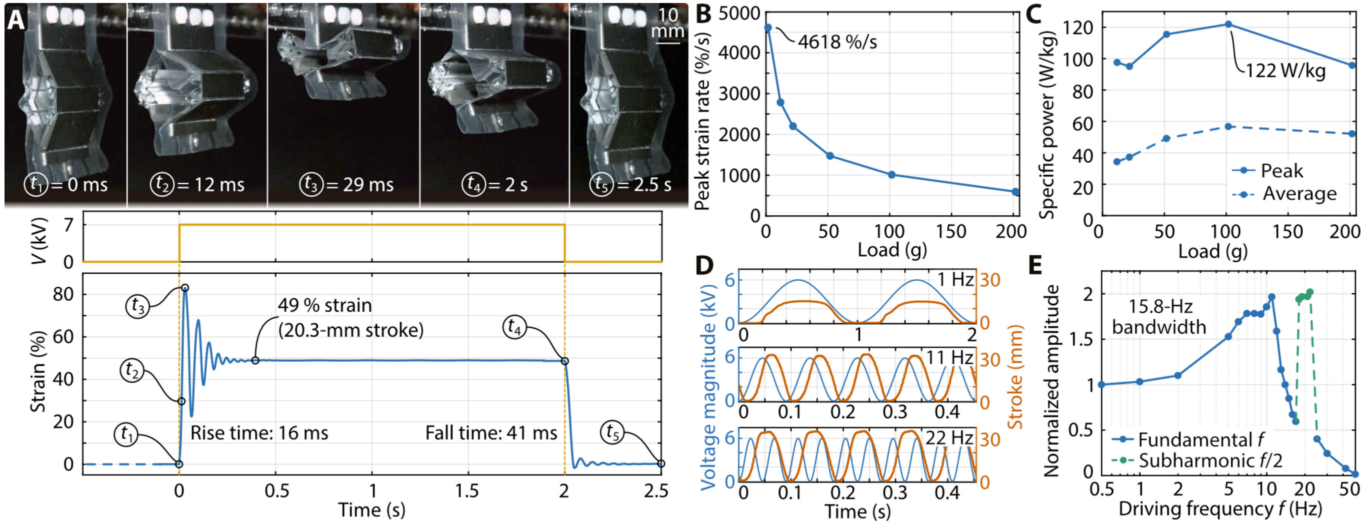


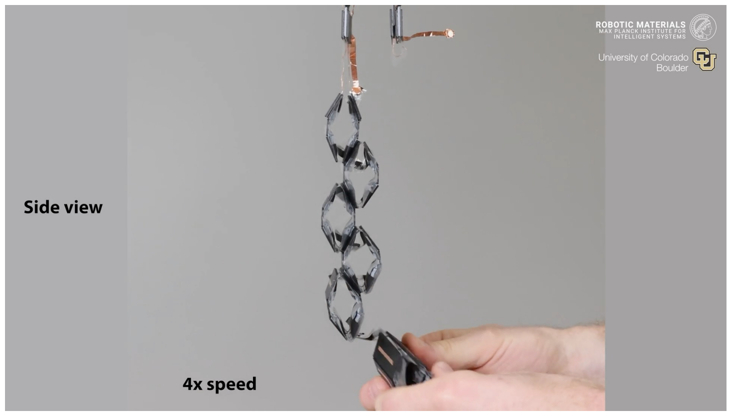
- Can be accurately modeled
- Does not use high permittivity insulator

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

P. Rothemund, N. Kellaris, S. K. Mitchell, E. Acome, C. Keplinger, HASEL Artificial Muscles for a New Generation of Lifelike Robots — Recent Progress and Future Opportunities. *Advanced Materials* **33**, 2003375 (2020).

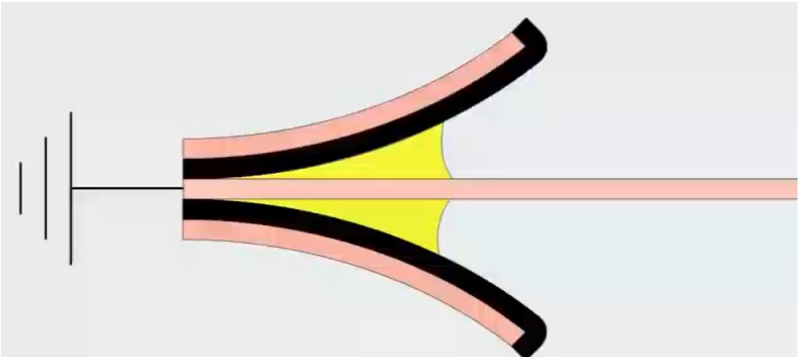
HASELS





Z. Yoder, E. H. Rumley, I. Schmidt, P. Rothemund, C. Keplinger, Hexagonal electrohydraulic modules for rapidly reconfigurable high-speed robots. *Science Robotics* **9**, eadl3546 (2024).

Electro-ribbon actuators (Rossiter group), Bristol



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

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

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 brl Bristol Robotics Laboratory

Taghavi … Rossiter, Science Robotics 2018

Electro-pneumatic Pumps for Soft Robotics

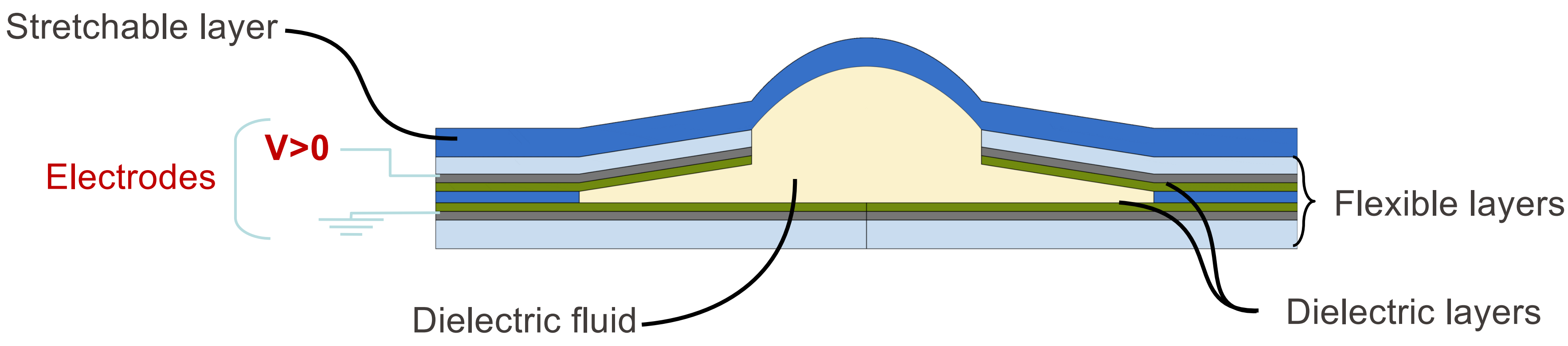
Richard Suphapol Diteesawat, Tim Helps, Majid Taghavi, Jonathan Rossiter

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.

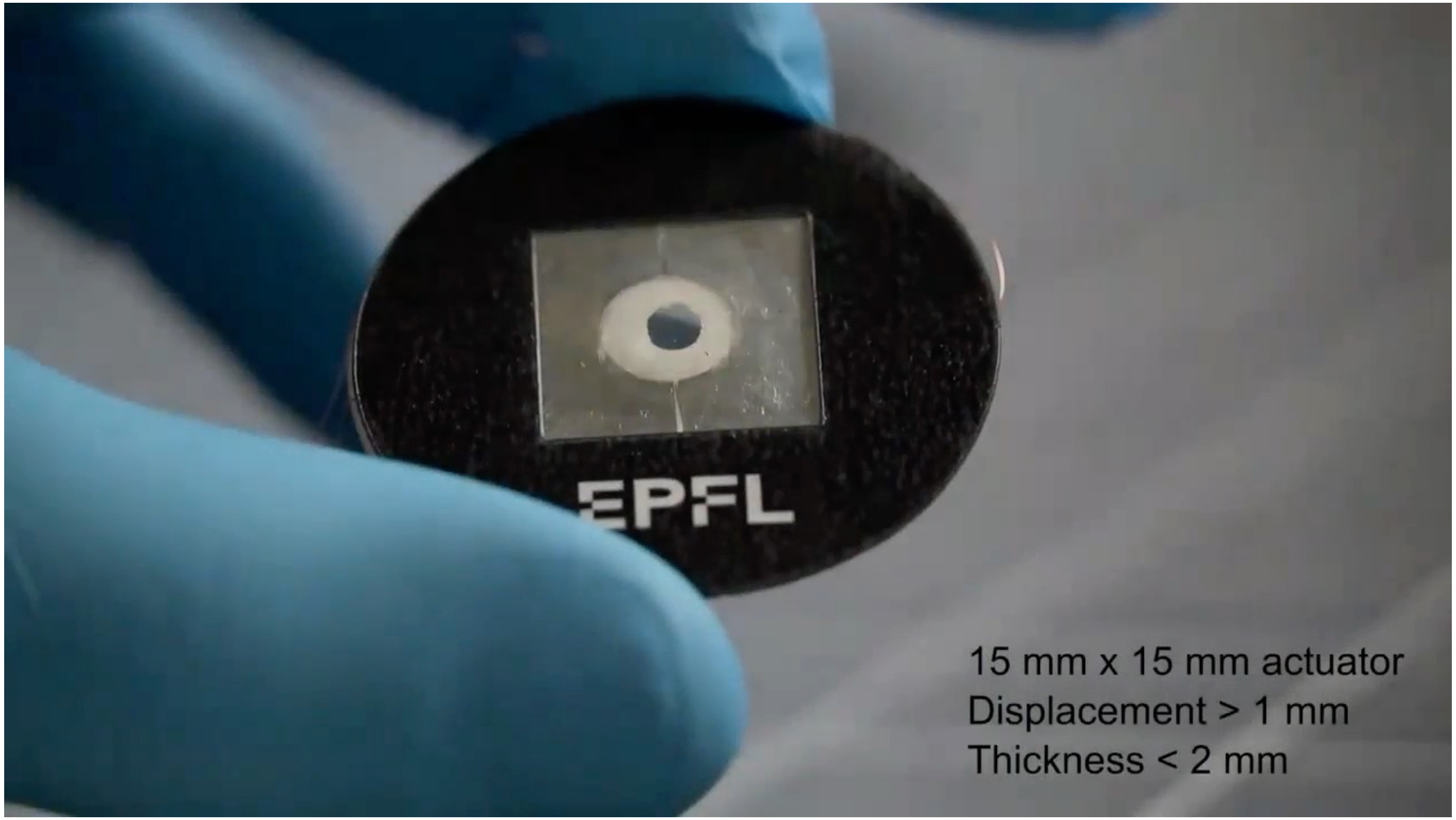
University of BRISTOL brl Bristol Robotics Laboratory

HAXELs:
Hydraulically Amplified electrostatic taXELs



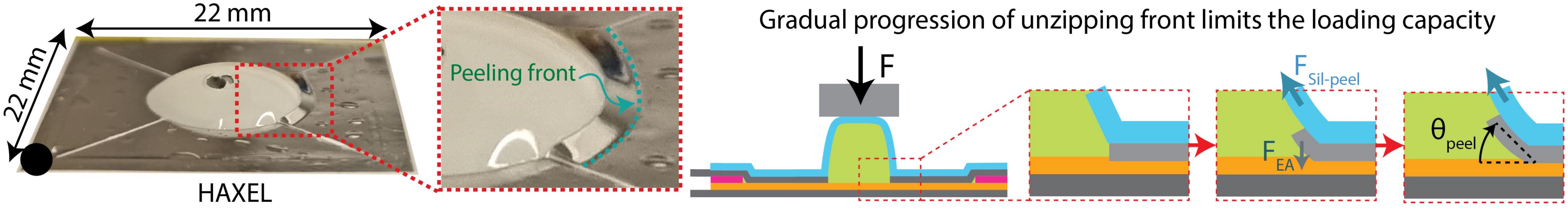
- Built-in hydraulic amplification
- central stretchable silicone region:
  - allows for higher strain
  - Good mechanical impedance match to the skin
- high-ε (ε_r=40) dielectric

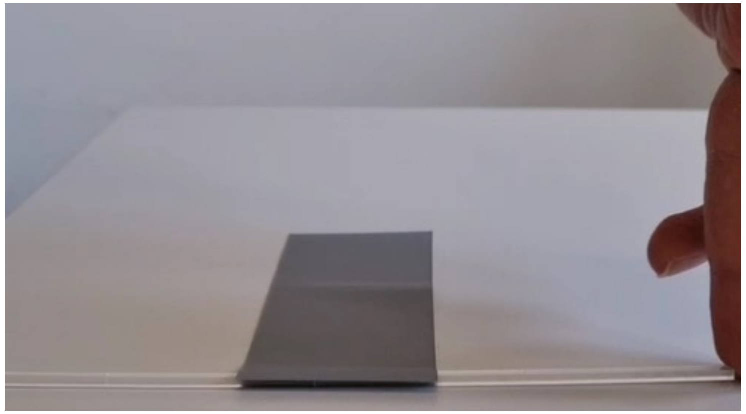
E. Leroy, R. Hinchet, H. Shea,
Multimode Hydraulically Amplified Electrostatic Actuators for Wearable Haptics.
Advanced Materials. **32**, 2002564 (2020).

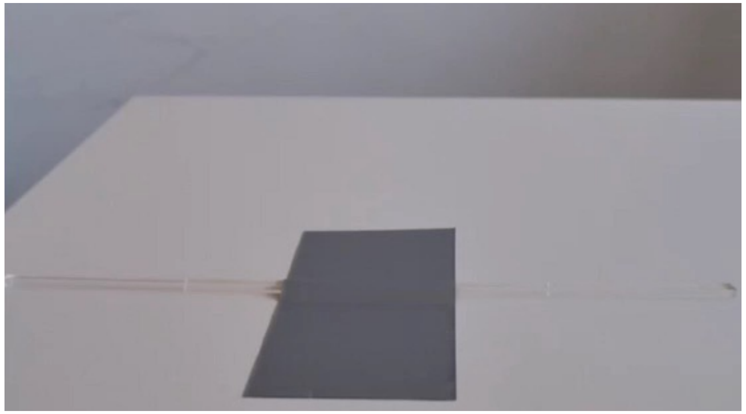


By separating electrostatic actuation from region of motion, can use higher energy density materials to displace the coupling, and soft materials for large deformations

What limits the force a HAXEL can hold? Peeling (like for EA….)

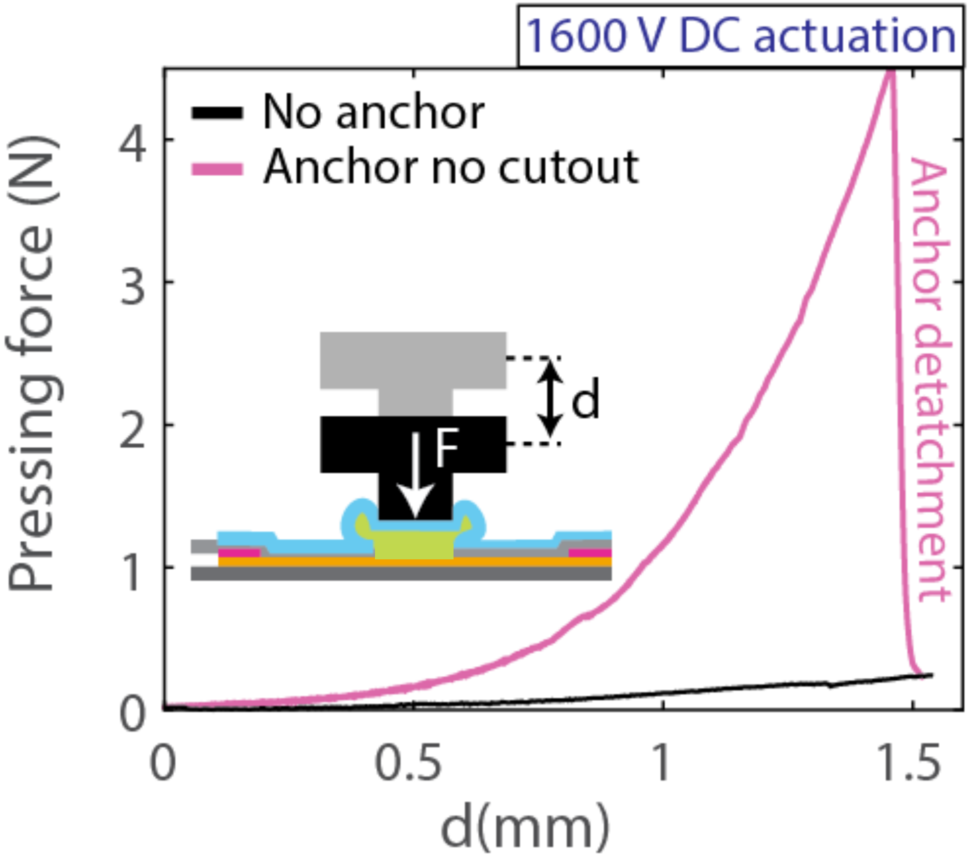






Firouzeh, Mizutani, et al, Adv. Mat. 2024

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

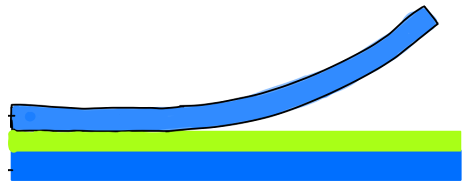
Firouzeh, Mizutani, et al, Adv. Mat. 2024

Transparent HAXELs !

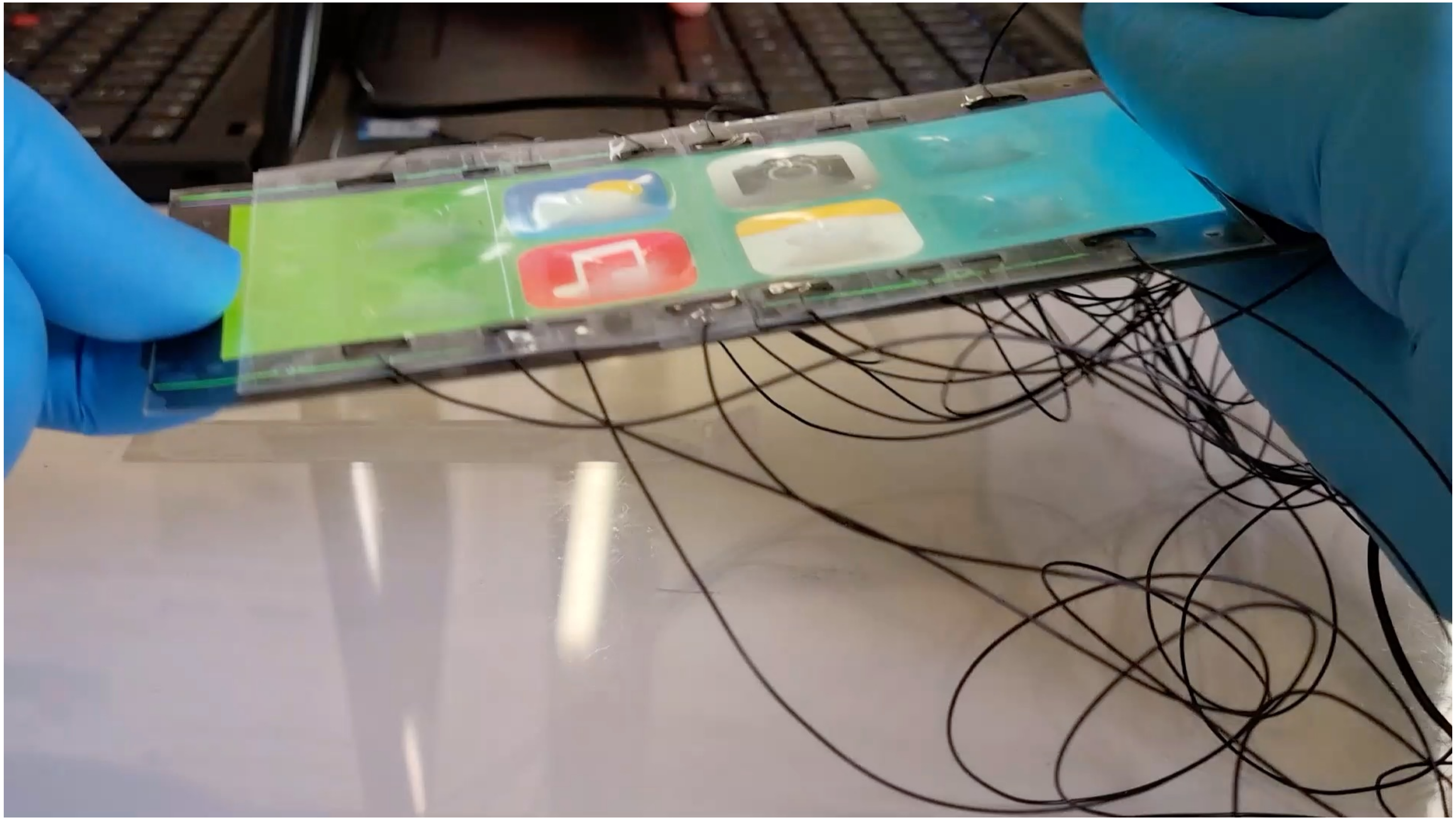
Zipping actuator needs only flex, not stretch!

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)



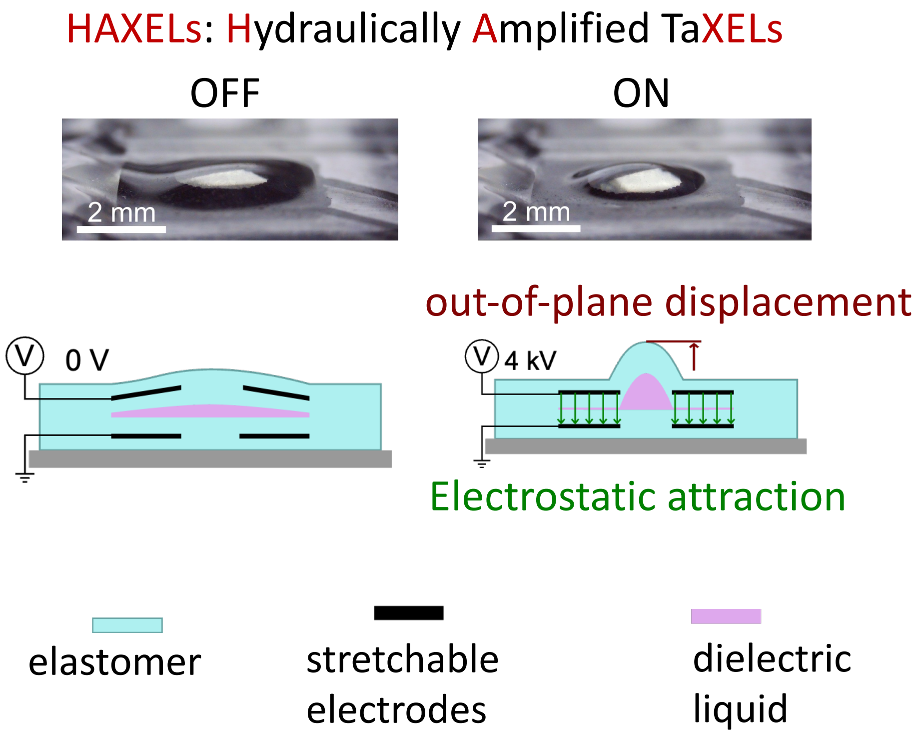
Transparent HAXELS: buttons pop up on touchscreens!



Ayana Mizutani

Firouzeh, Mizutani, et al, Adv. Mat. 2024

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

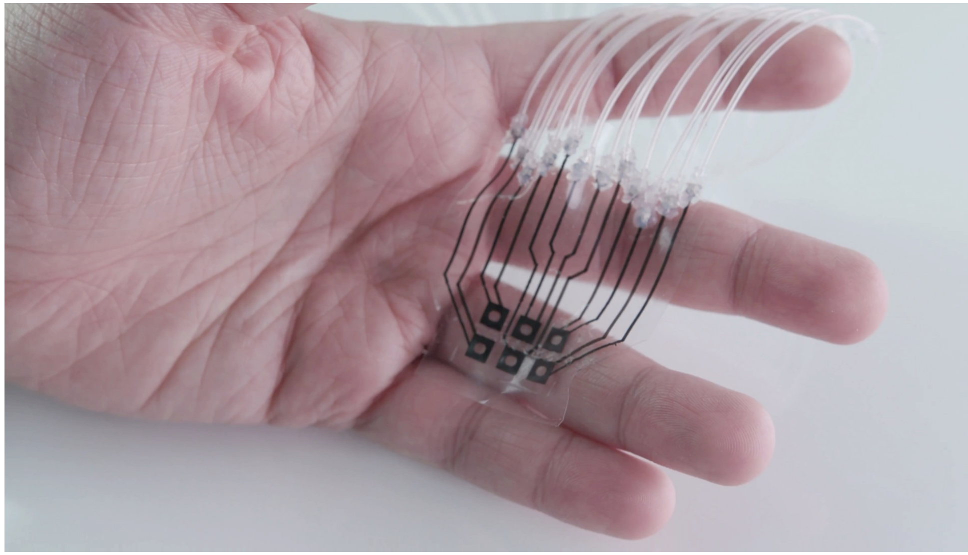


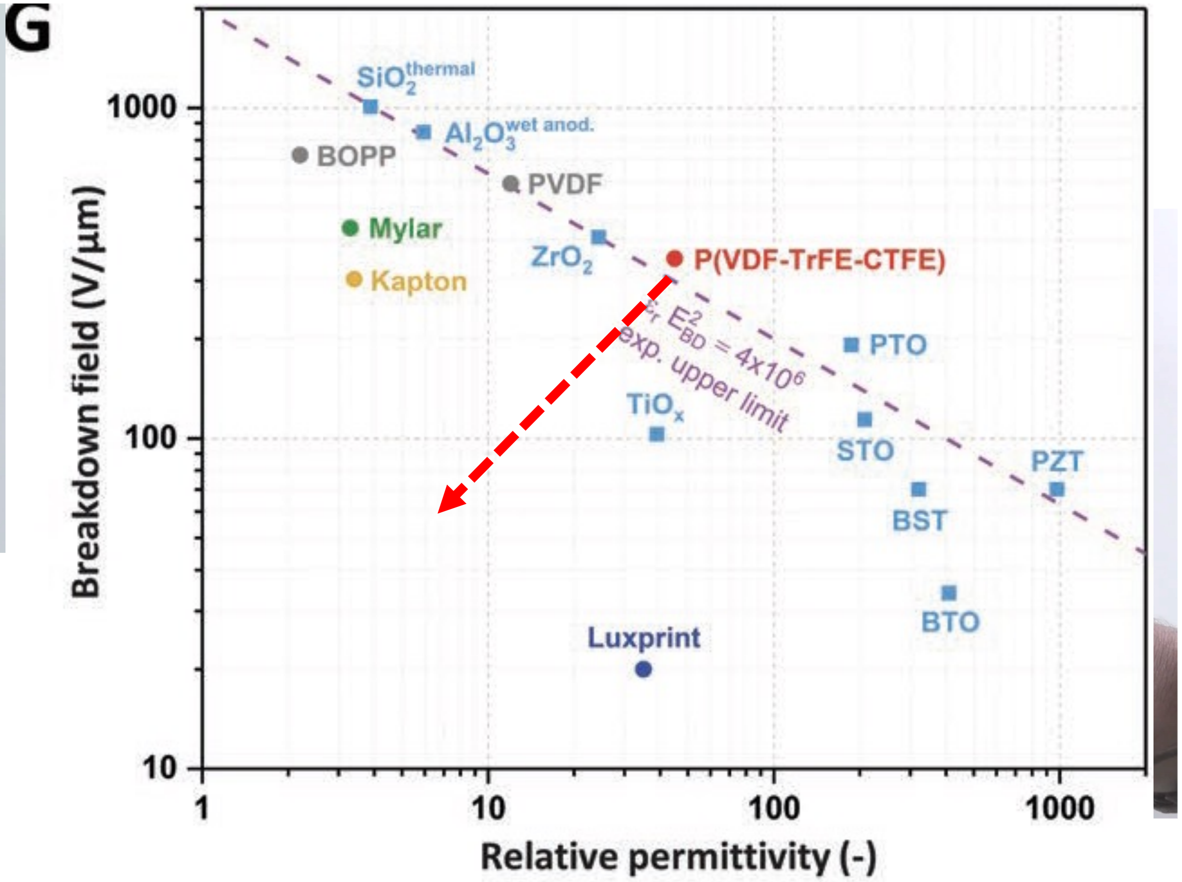
Giulio Grasso

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

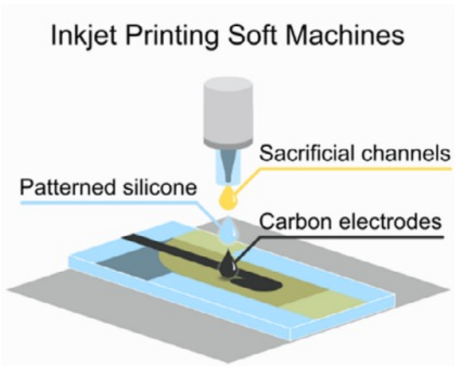
G. Grasso *et al*., Adv. Func. Mat, 2023

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



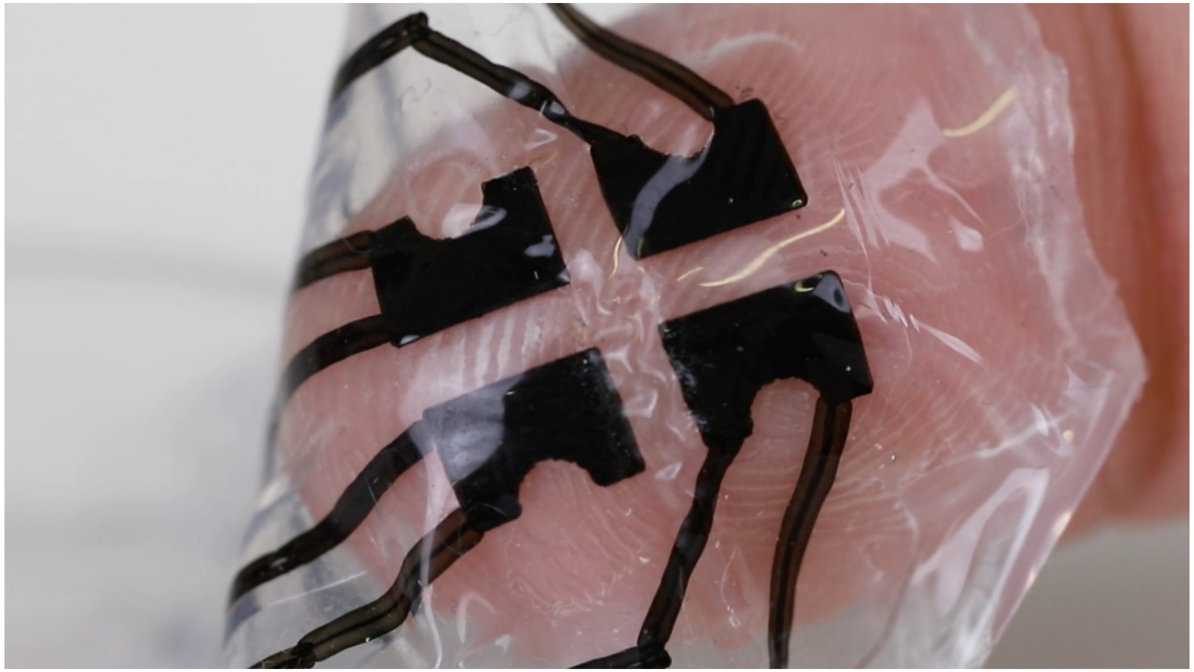


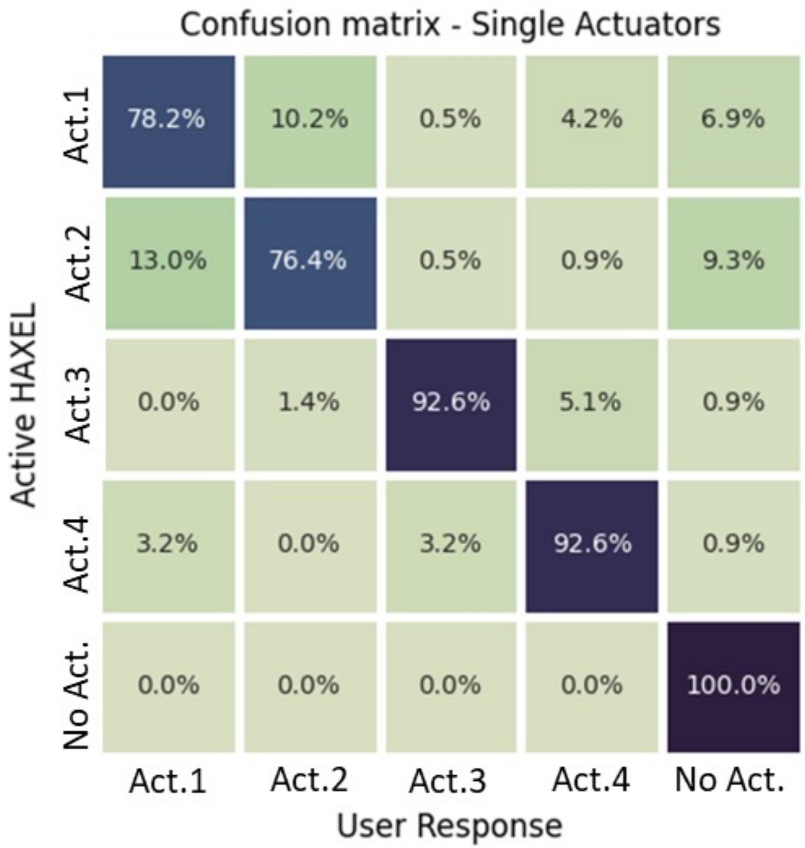
Giulio Grasso



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

Users easily correctly identify the actuated quadrant

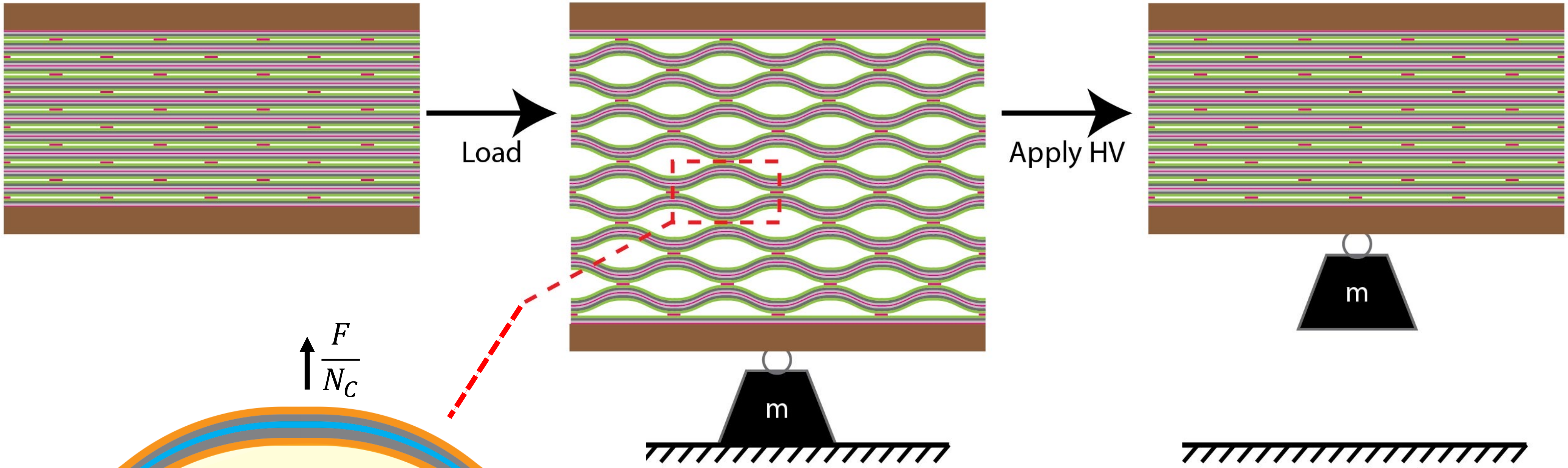


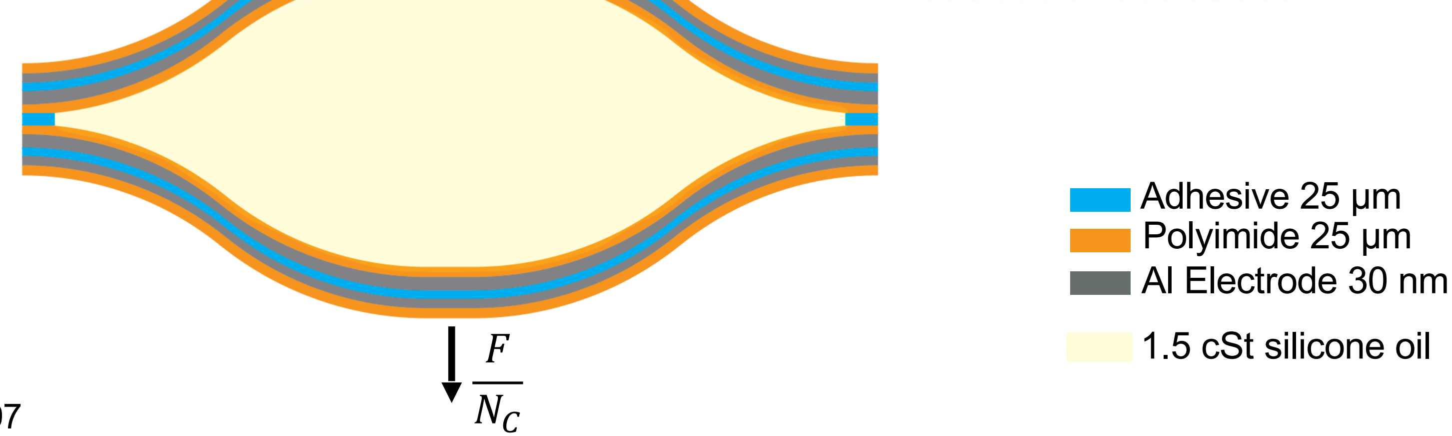


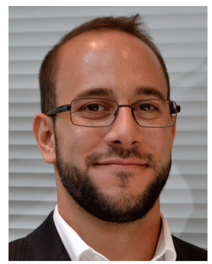
30 mN, 200 μm stroke

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

Our work today on zipping: getting higher forces and faster speeds = more power to enable exosuits



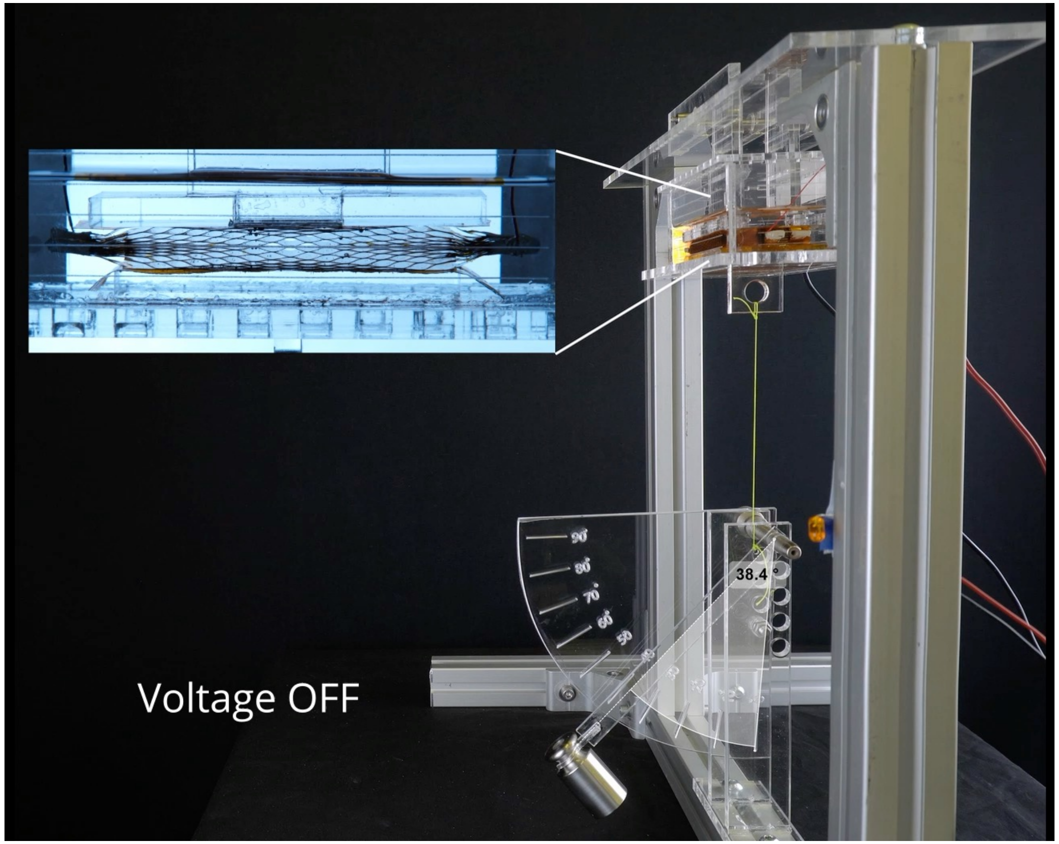




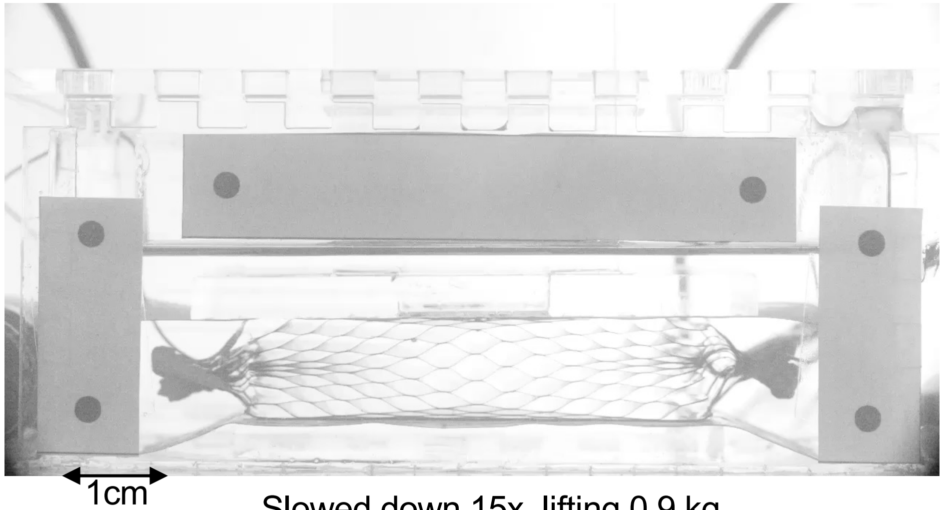
Dr. Amir Firouzeh

Dr. Fabio Caruso

Our Honeycomb Electro-Hydraulic Actuators are inspired by Electro-Ribbon Actuators and HASELs



Real time, 100g with 10:1 lever arm



Slowed down 15x, lifting 0.9 kg

- This size can lift 4 kg
- High peak power ~1 W
- Working on fiber-format

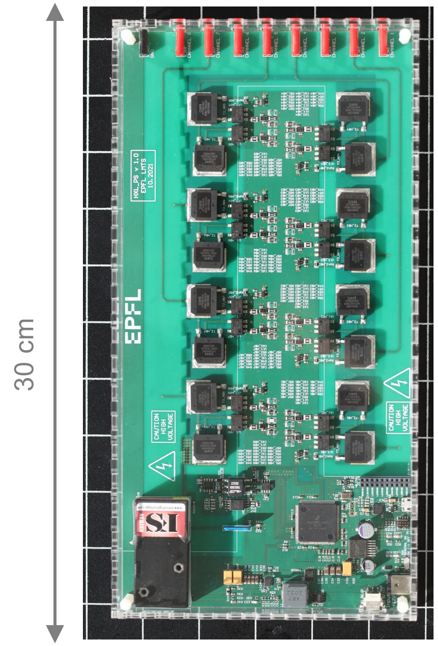
Caruso, Firouzeh, et al, manuscript under preparation

EPFL

HV electronics are small when they are low power

https://www.advancedenergy.com/

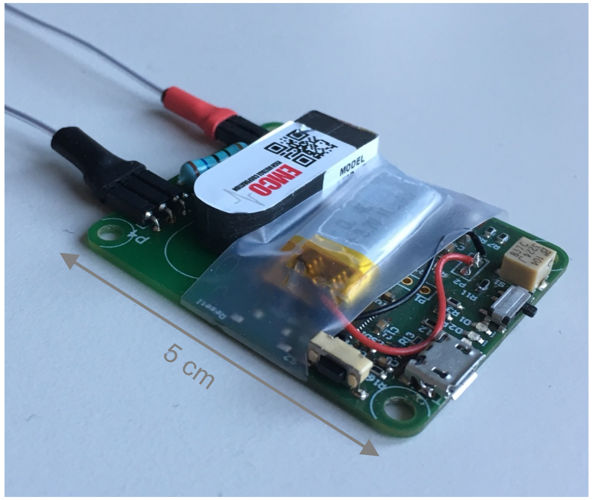
600 W 40 kV,
1 kHz,
100 kg



10 W 4 kV,
8 half bridges, 1 kHz
700 g

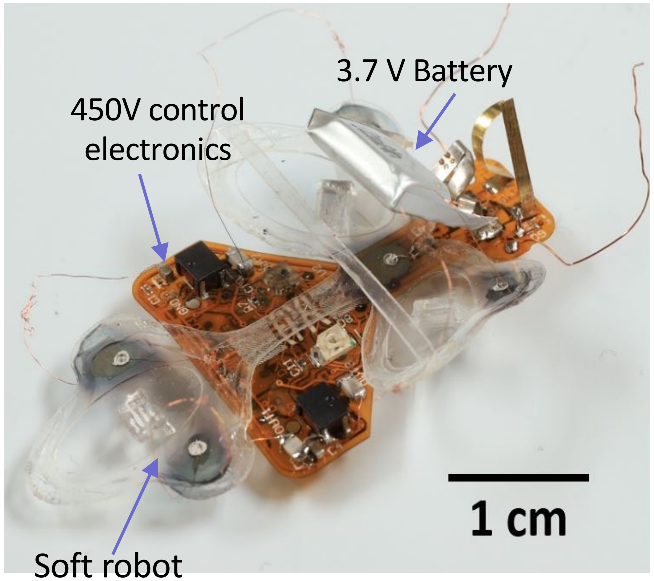
https://gitlab.epfl.ch/schouten/OCHVPS

(open-source hardware)



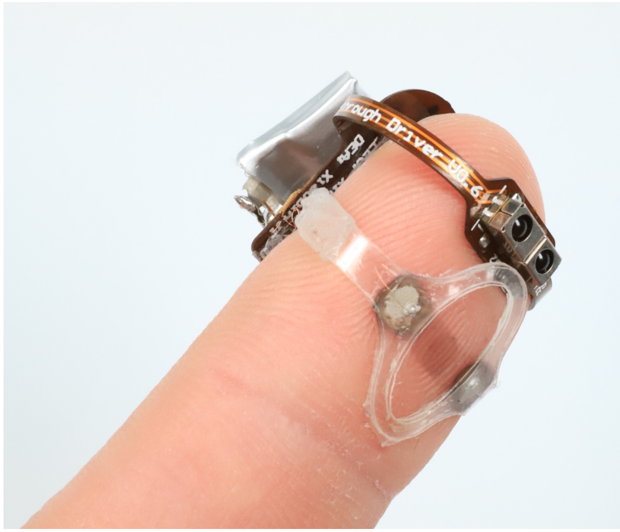
0.25 W 5 kV,
1 Hz,
16 g

500 V electronics can be very compact.



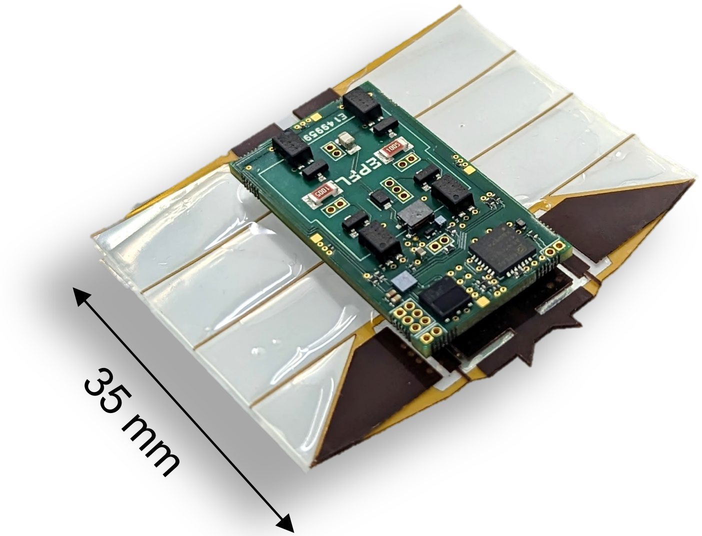
∽100 mW, at 450 V
770 mg and 1 kHz

Xiaobin Ji *et al*, Science Robotics 2019
Electronics by EPFL-LAI



∽ 50 mW, 500V,
350 mg, 1 kHz

Xiaobin Ji *et al*, Adv. Func. Mat. 2021
Electronics by EPFL-LAI



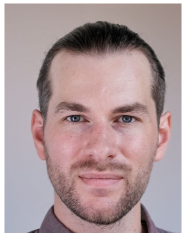
∽ 500 mW, 600V
5 g, 200 Hz, bipolar

F. Hartmann *et al*, under review
Electronics by EPFL-LMTS

Local signal processing enables smart systems

Untethered ultra-thin swimming robots

Energy autonomous operation in outdoor environments

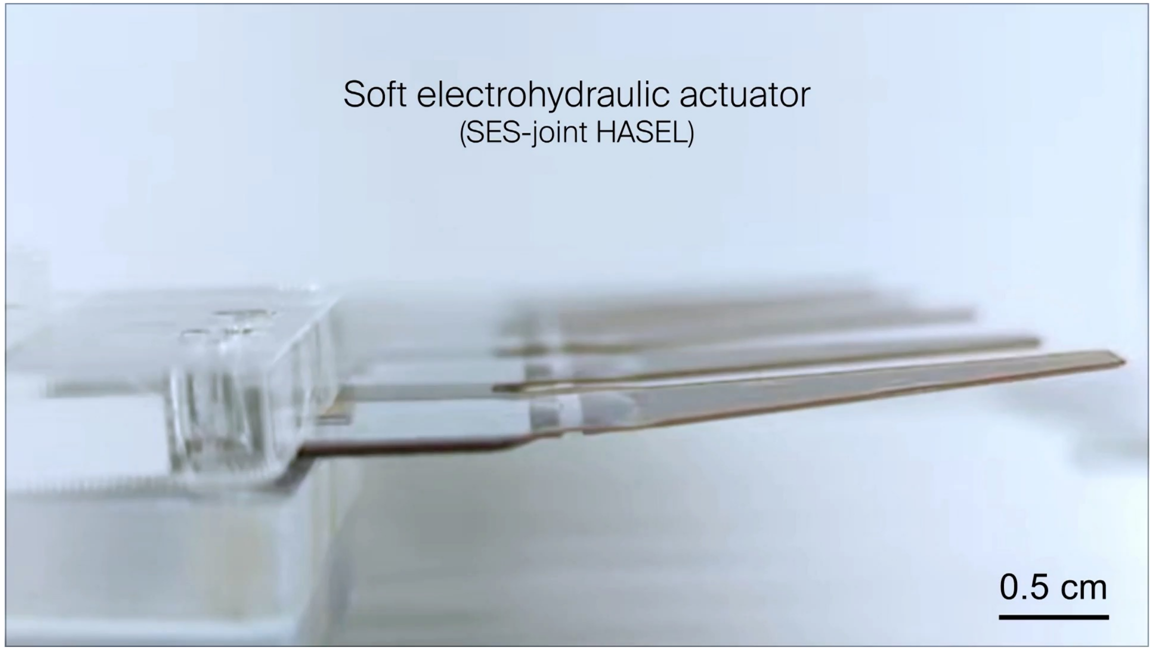


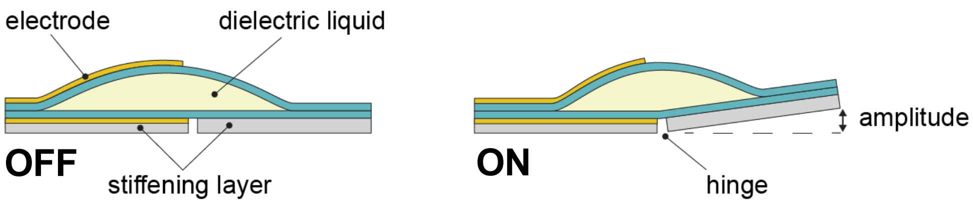
F. Hartmann *et al*,
Science Robotics 2025

"This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No101016411".

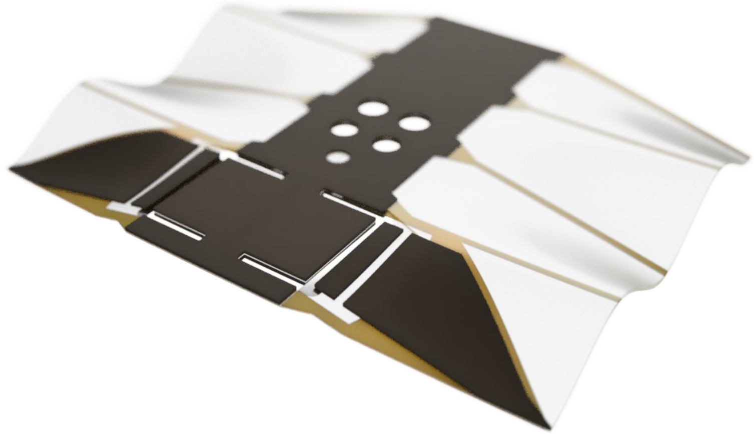
Horizon H2020 project SOMIRO

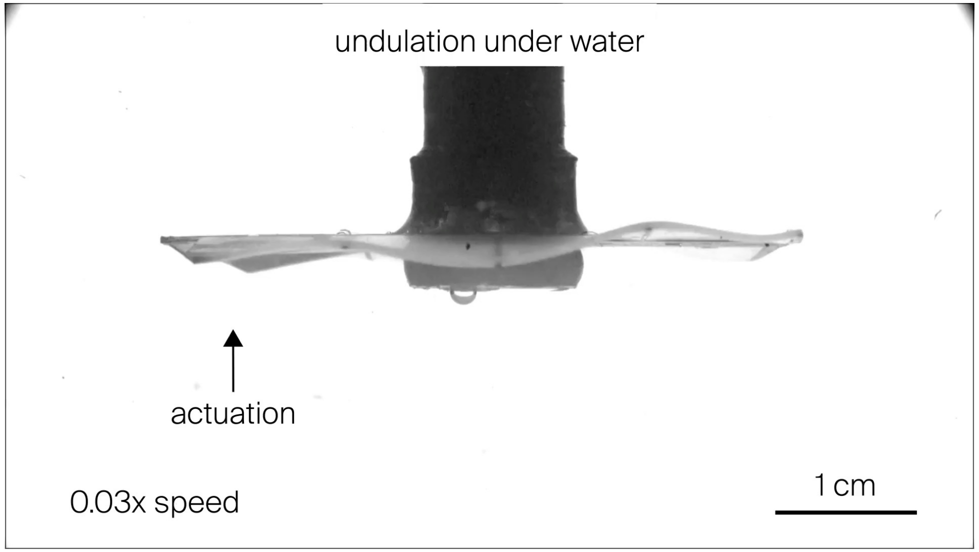
Undulating fin propulsion driven by zipping actutors





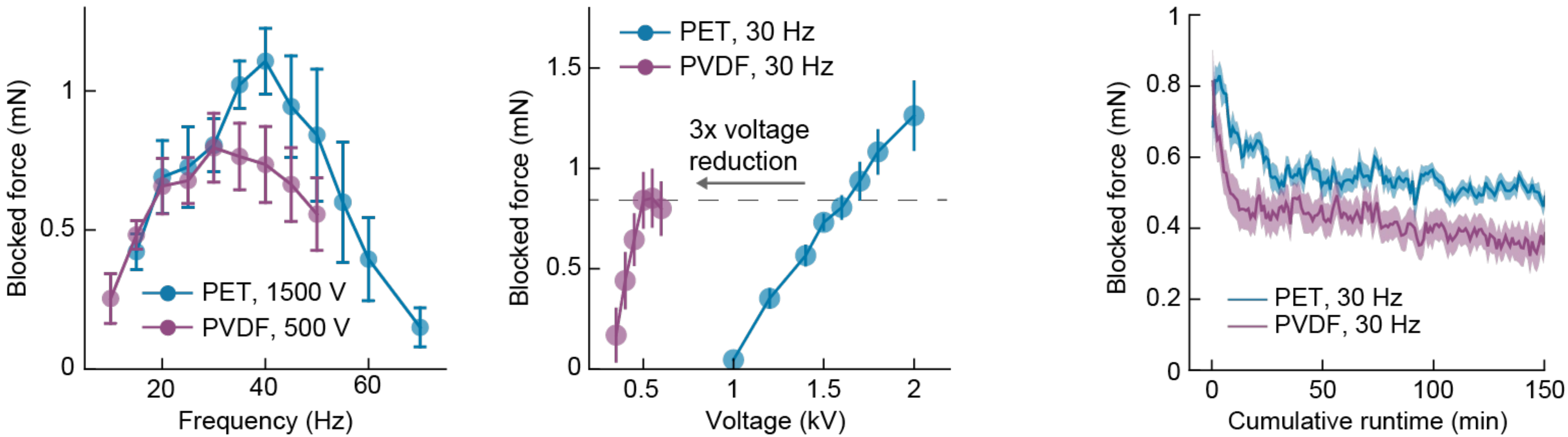
SES-joint HASEL with thin PVDF dielectric

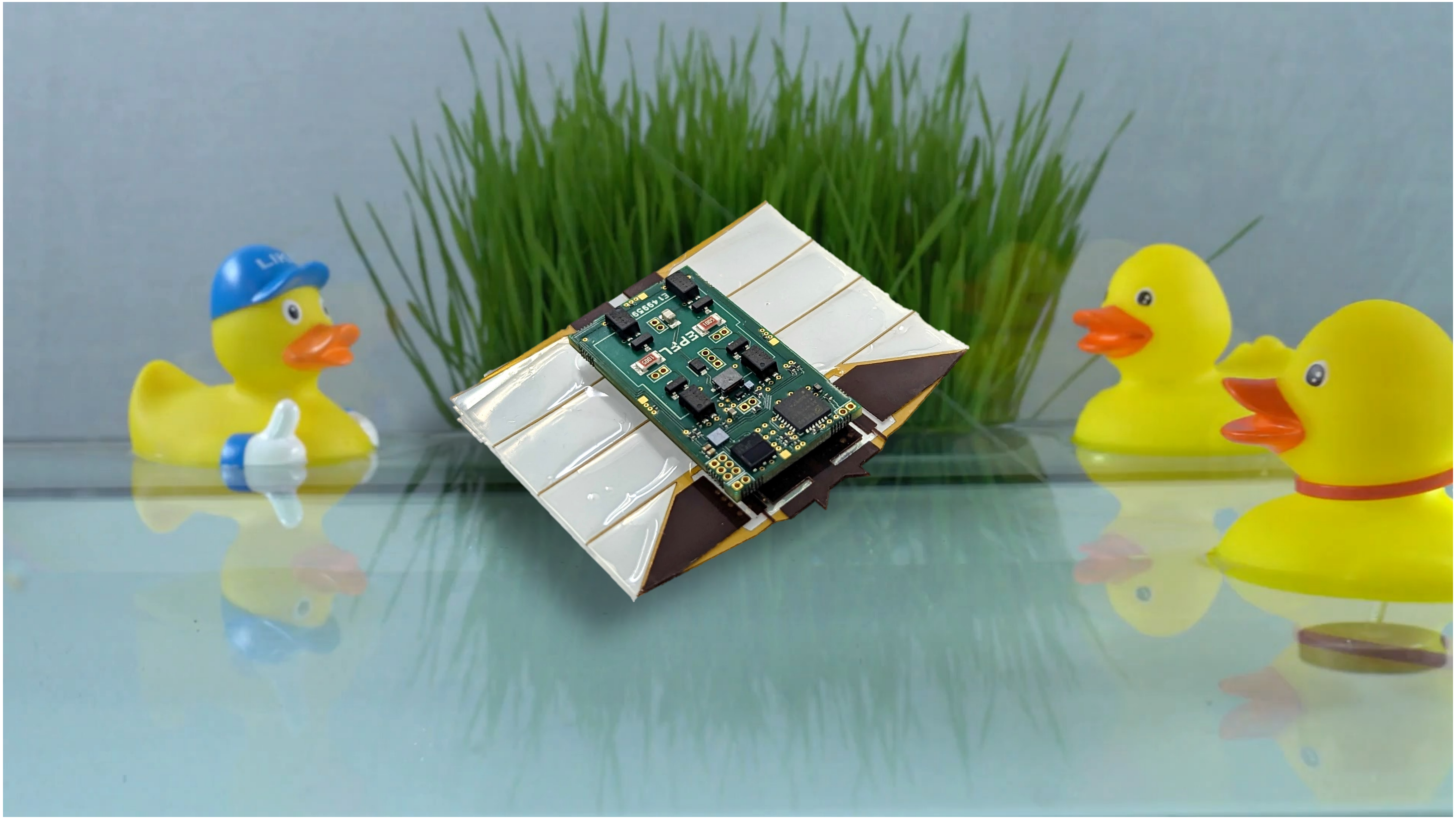


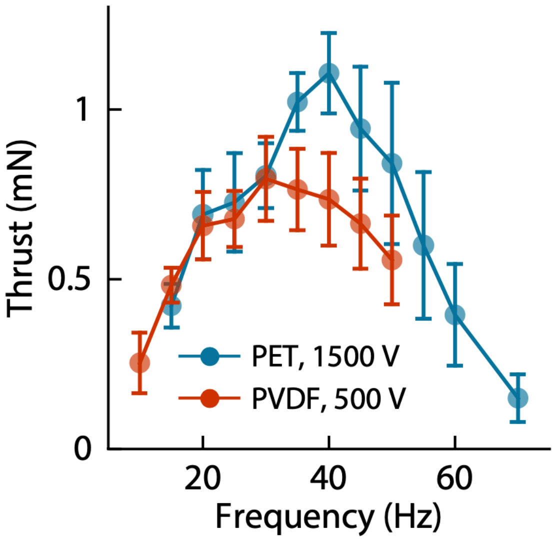


F. Hartmann et al,
Science Robotics 2025

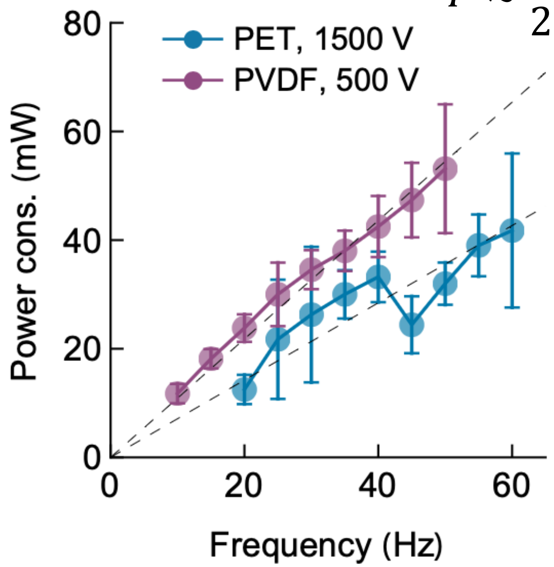
- 3x Voltage reduction by using PVDF-TrFE-CTFE rather than PET (thanks to 9x higher permittivity)
- We operate at resonance

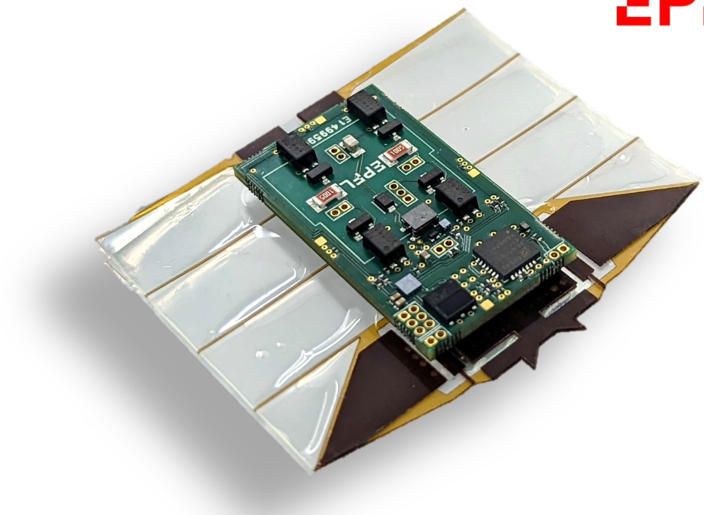



EPFL



$$P \approx \frac{1}{2} C V^2 f$$

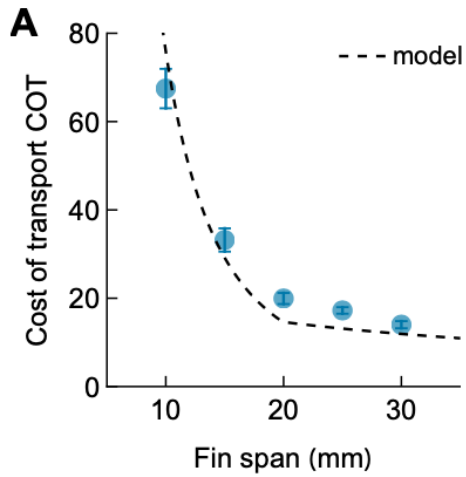




600V 200 Hz, bipolar supply
Consumes 600 mW !

Where did the power go?
Mostly to the fly-back converter…

Robot efficiency is different from **actuator** efficiency:
where should design effort go?



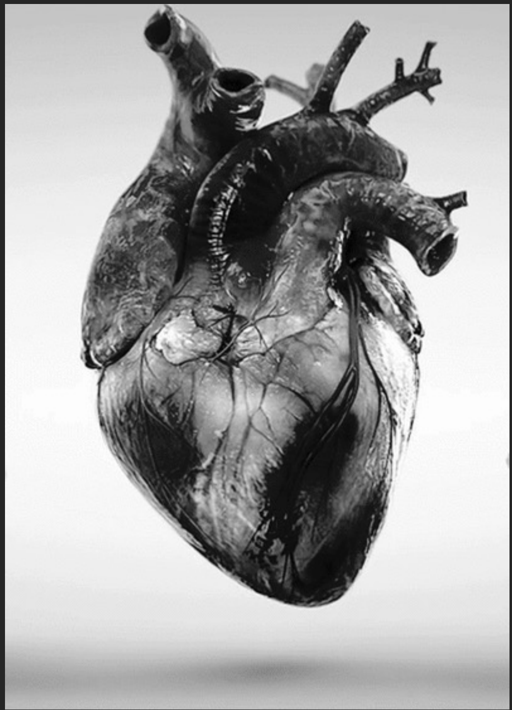
F. Hartmann *et al*,
Science Robotics 2025

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

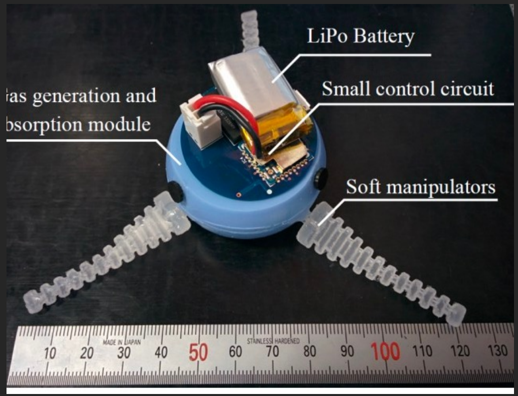
Soft Robotics Inc.

Chemical reaction to generate pressure

M. Wehner et al, Nature, 2016.

Miniature mechanical pump

M. Tolley et al, Soft Robotics, 2014.



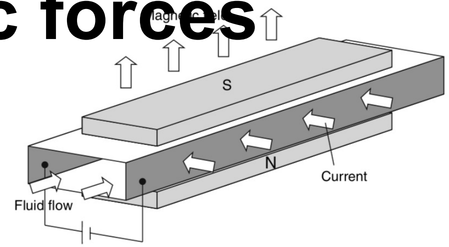
T. Kitamori et al, IROS 2016.

Moving liquids with electric forces

Broad field:

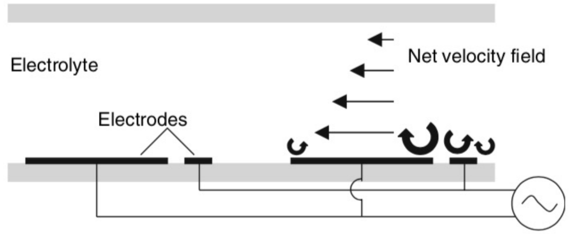
- Dielectrophoresis
- Electrostriction
- ElectroOsmosis
- Magnetohydrodynamics
- (even Combustion…)

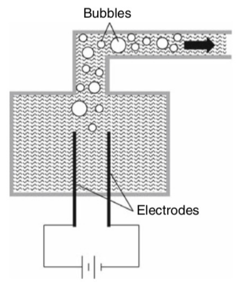
But generally not soft…



MagnetoHydroDynamic

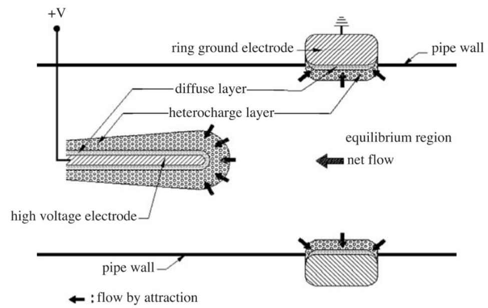
ElectroOsmotic





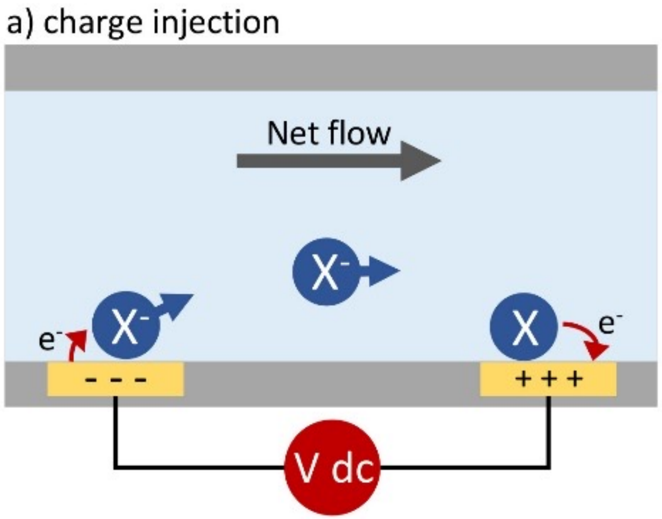
Phase change

ElectroHydroDynamic (EHD)

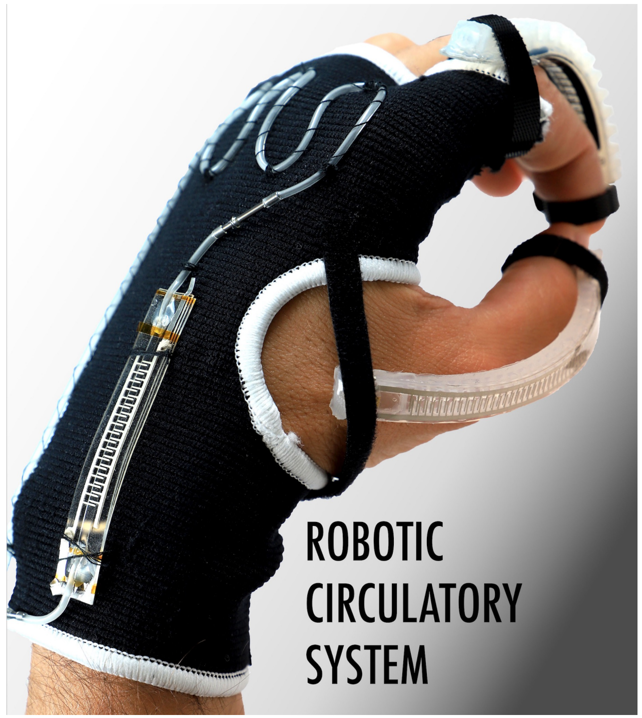


- Iverson, B. D. & Garimella, S. V. Recent advances in microscale pumping technologies: a review and evaluation. *Microfluidics and Nanofluidics,* 2008.
- J. Seyed-Yagoobi, “Electrohydrodynamic pumping of dielectric liquids,” J. Electrostat., 2005.

We can use ElectroHydrodynamics (EHD) to continuously pump an insulating fluid



- We use “Charge injection” EHD
- Challenging to make EHD flexible
- Challenging to obtain the high pressures needed for robotics



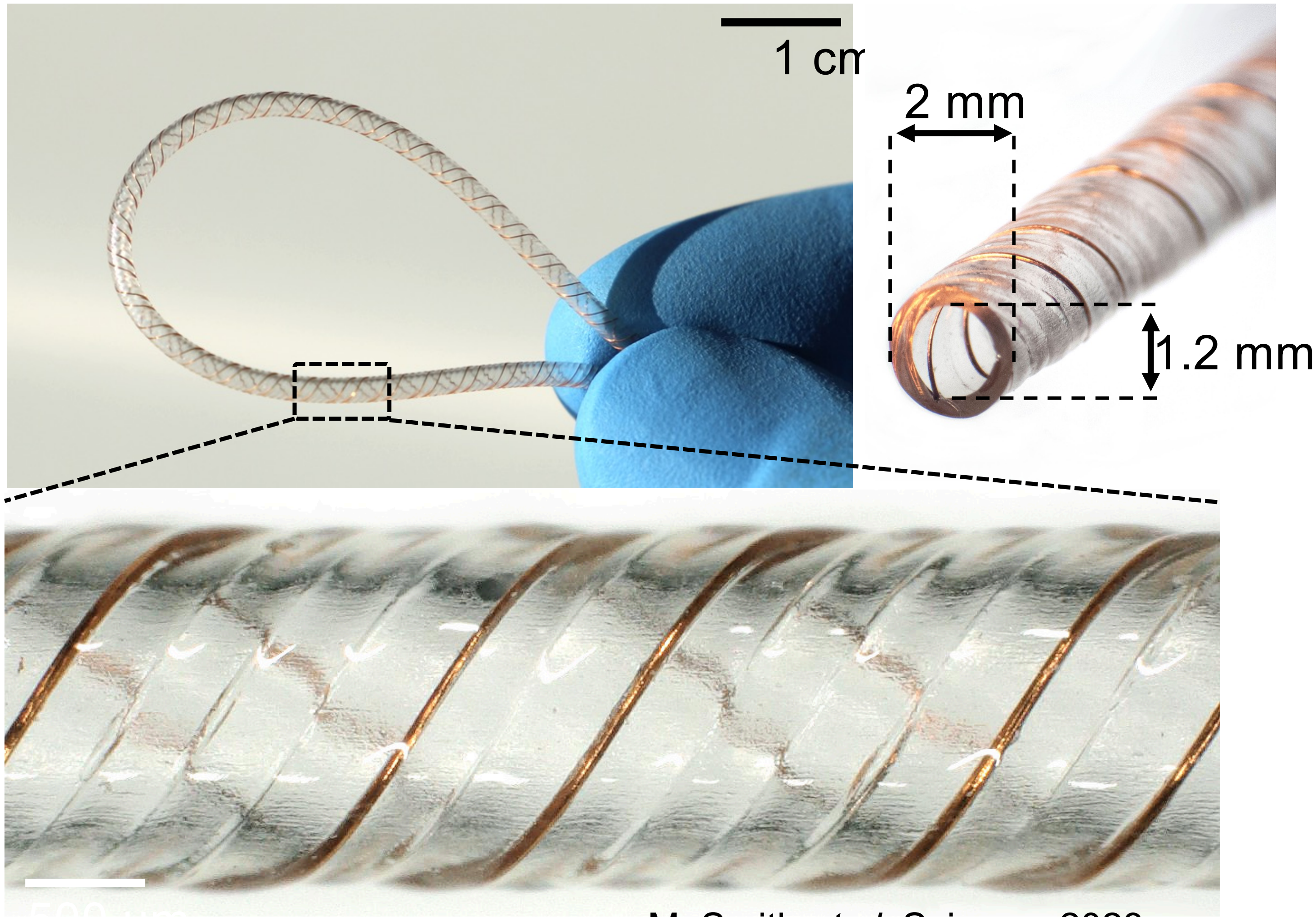
- Reversible flow direction
- Operates at several kV
- Generates about 0.1 Bar

- Flat, not so easy to use in textile
- Limited performance

V. Cacucciolo, J. Shintake, Y. Kuwajima, S. Maeda, D. Floreano, H. Shea, Stretchable pumps for soft machines. *Nature* **572**, 516–519 (2019).

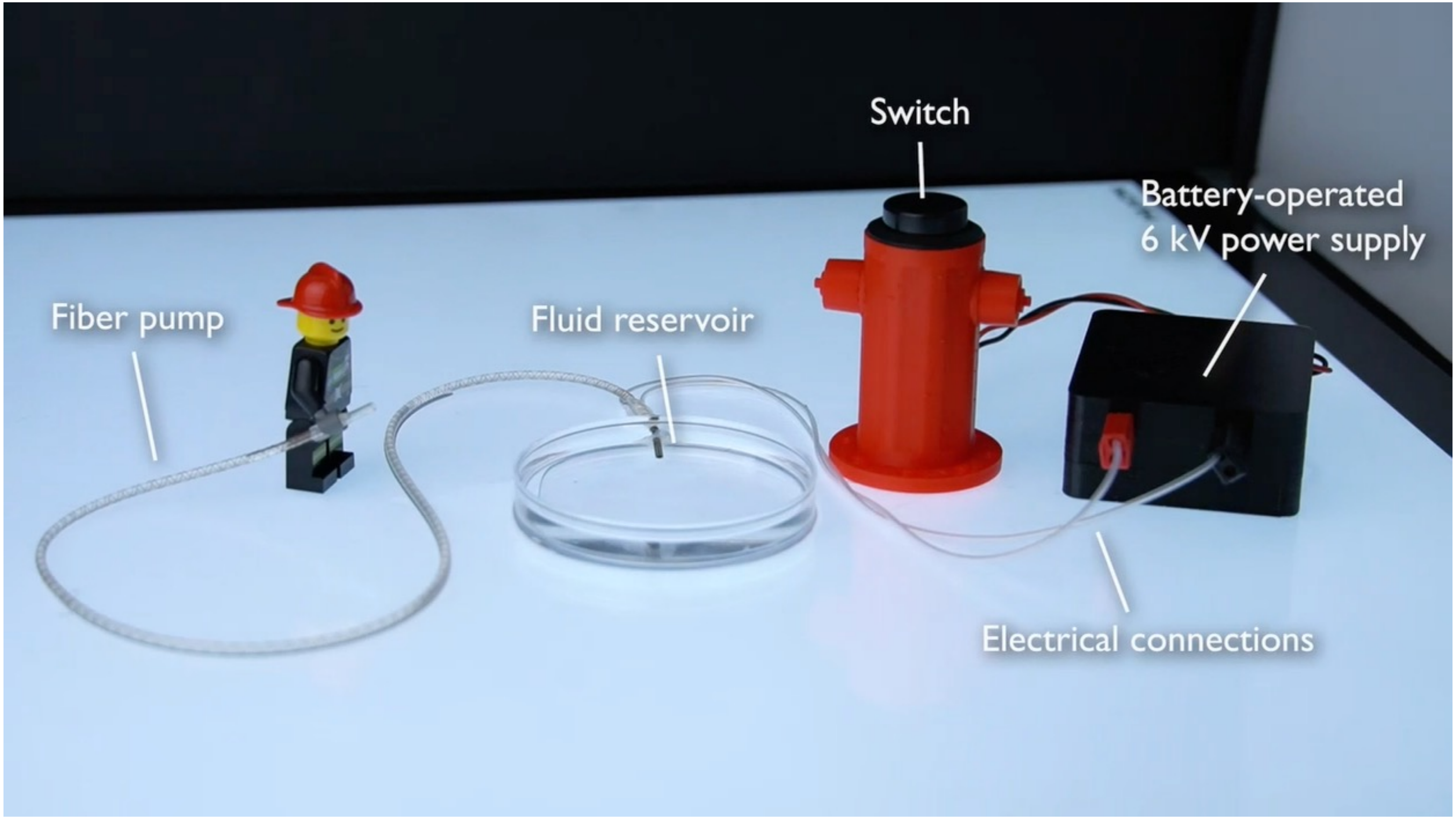
Fiber pumps for wearable fluidic systems

- 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**



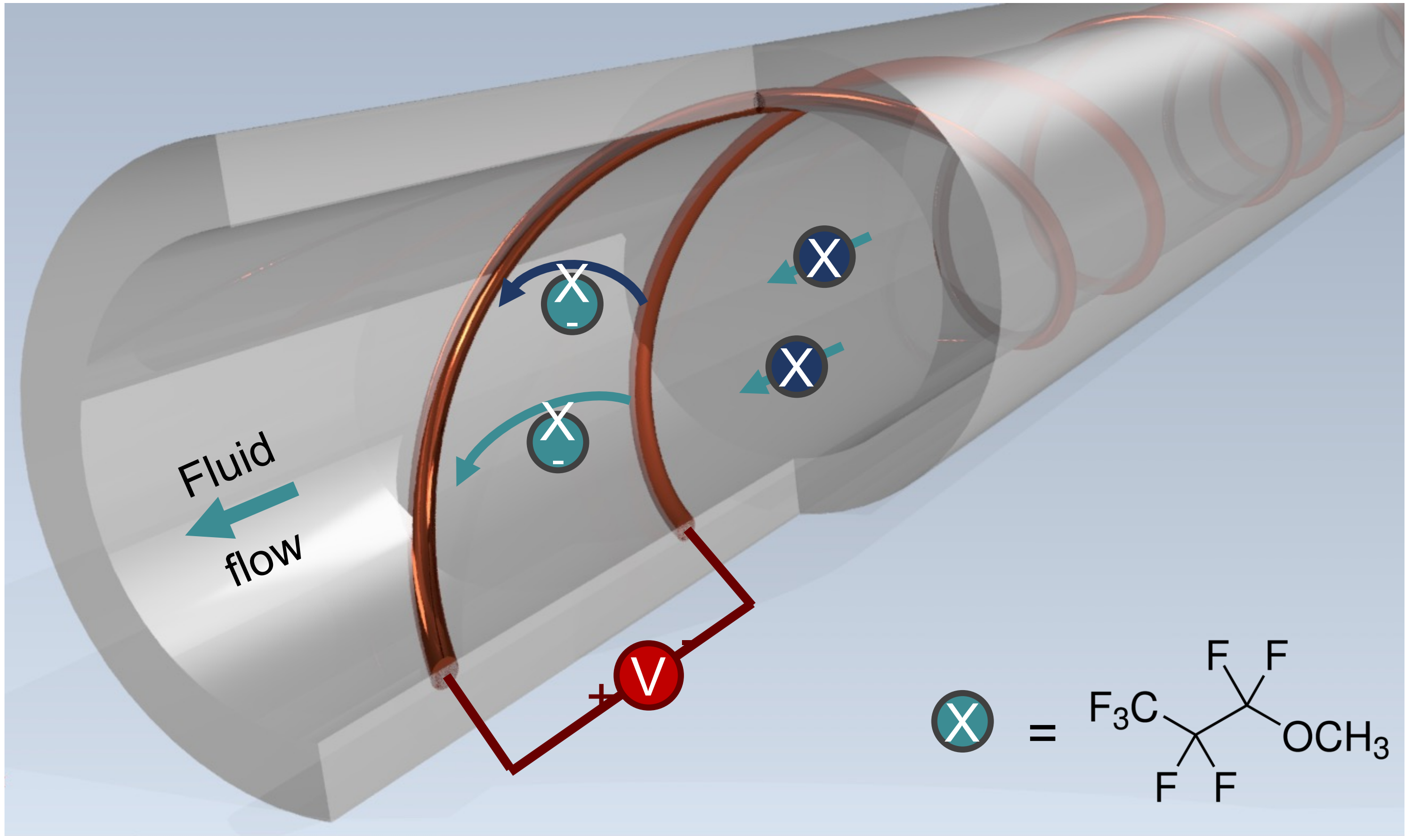
M. Smith *et al*, Science, 2023

Fiber pumps: the tube is the pump!



Charge injection electrohydrodynamics (EHD)

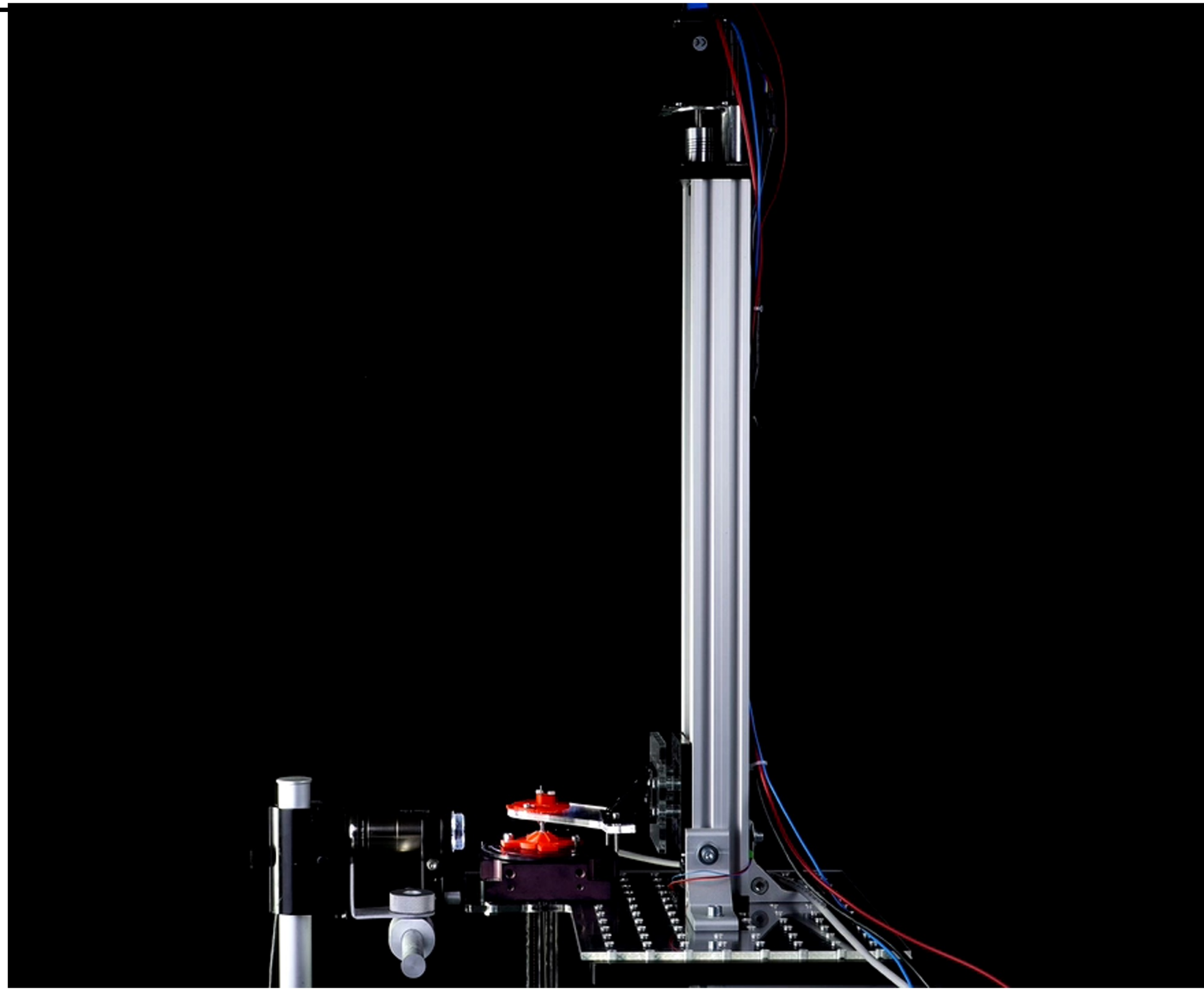
- Dielectric fluid becomes ionised at the negative electrode
  - Novec 7100 fluid
  - (or other insulating liquids)
- Ions are accelerated by electric field
- Asymmetrically spaced electrodes generate a net flow in chosen direction
- High voltage (kV)
- Low current (µA)
- Low power consumption (sub-W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



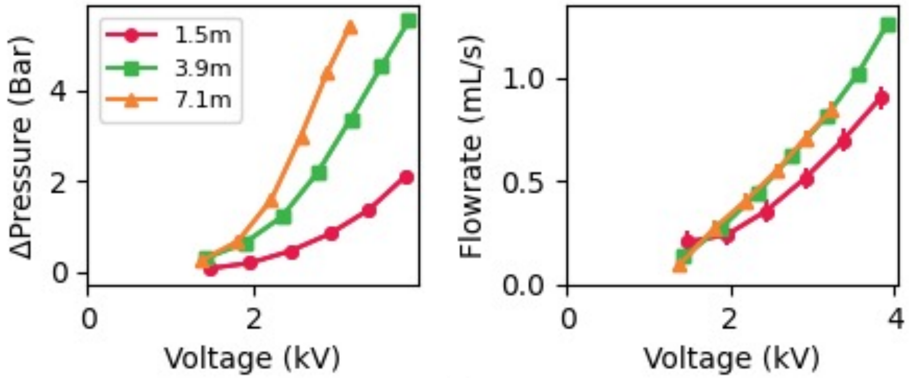
M. Smith *et al*, Science, 2023

Scalable filament winding fabrication method

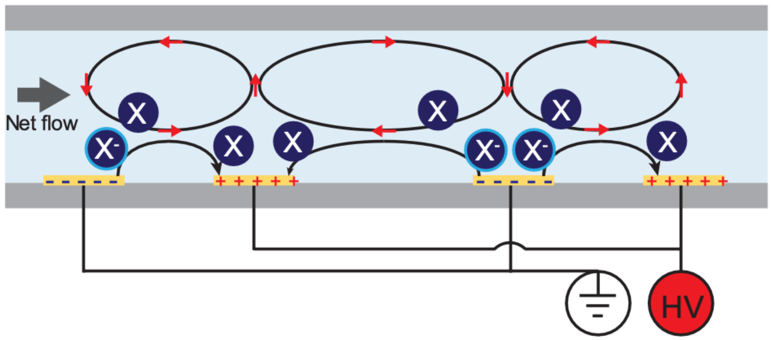
- Pumps are wound from filaments of
  - Polyurethane
  - Copper wire
- Twisted together around a central mandrel
- PU fused with heat after winding



Pressure is proportional to fiber length.
Longer fibers ➔ higher fluidic power

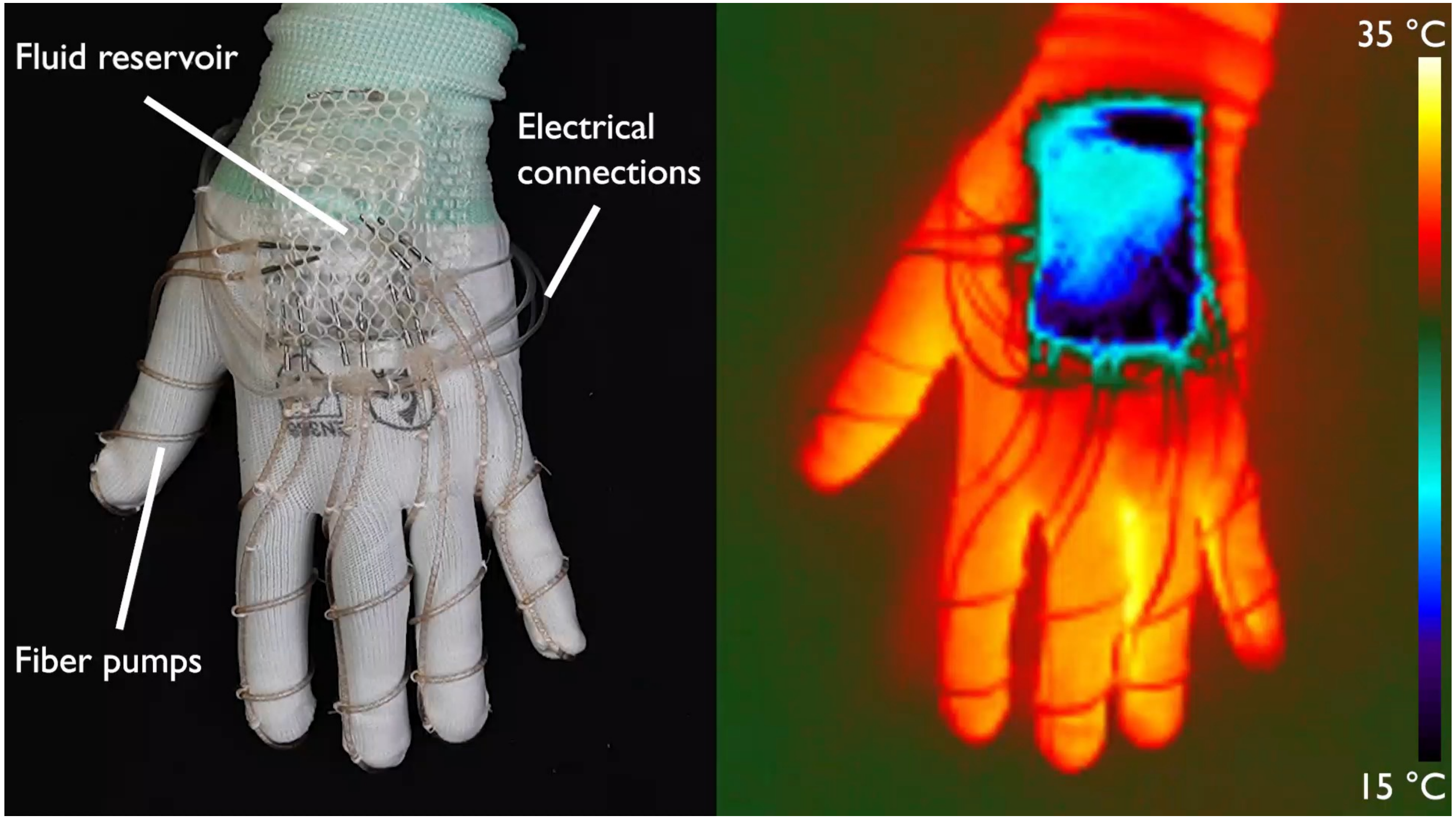


- Pressures of over 2 bar / m. and pumps over 6 m long.
- Maximum flowrate 1 ml/s for all pump lengths
- Fluidic power 20 mW/m
- Low efficiency is main limitation today



Thermal haptic glove for immersive virtual reality

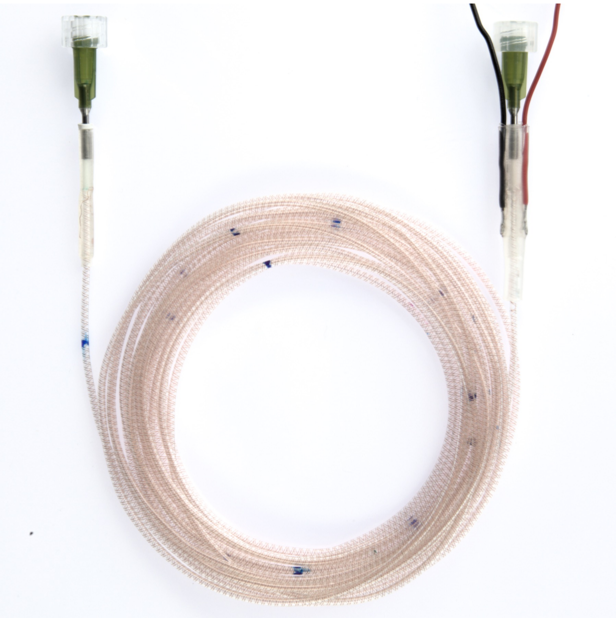
- Flexibility and stretchability of devices does not inhibit dexterity
- Distributed pumps allows each finger to be controlled independently
- Difficult to achieve using conventional pumps and equipment



M. Smith *et al*, Science 2023

A 6m pump generates 5 atm of pressure and 1mL/s flow:

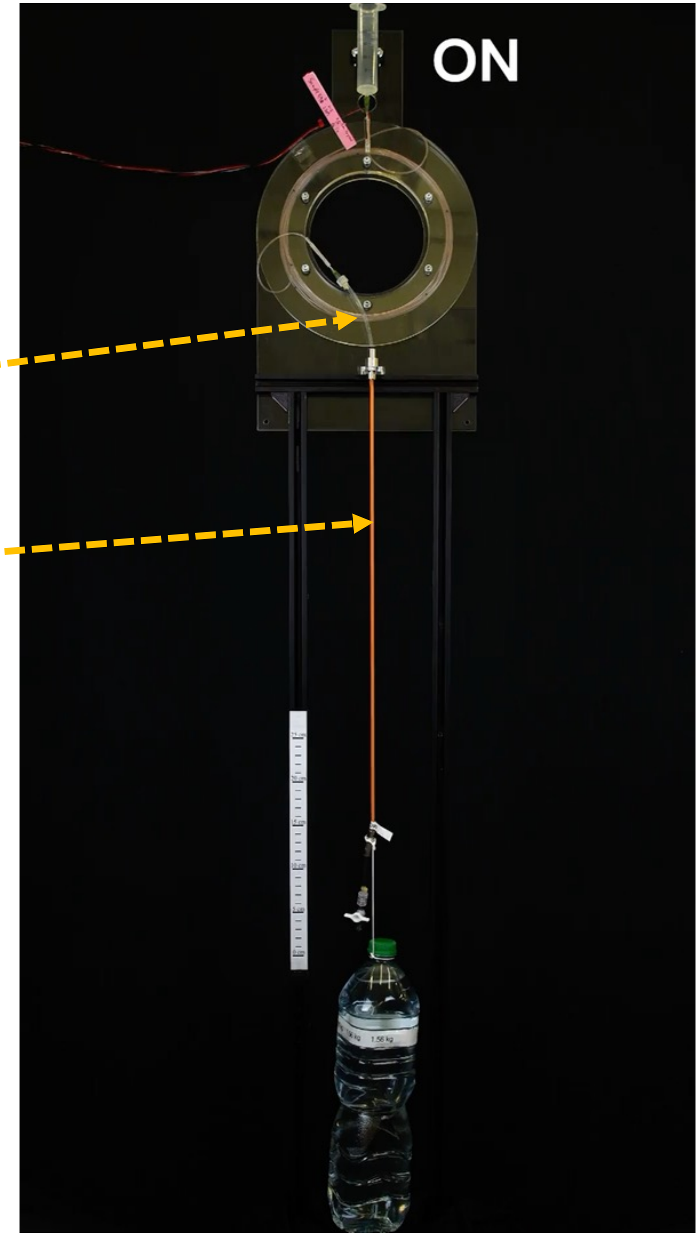
we can drive hydraulic artificial muscles!



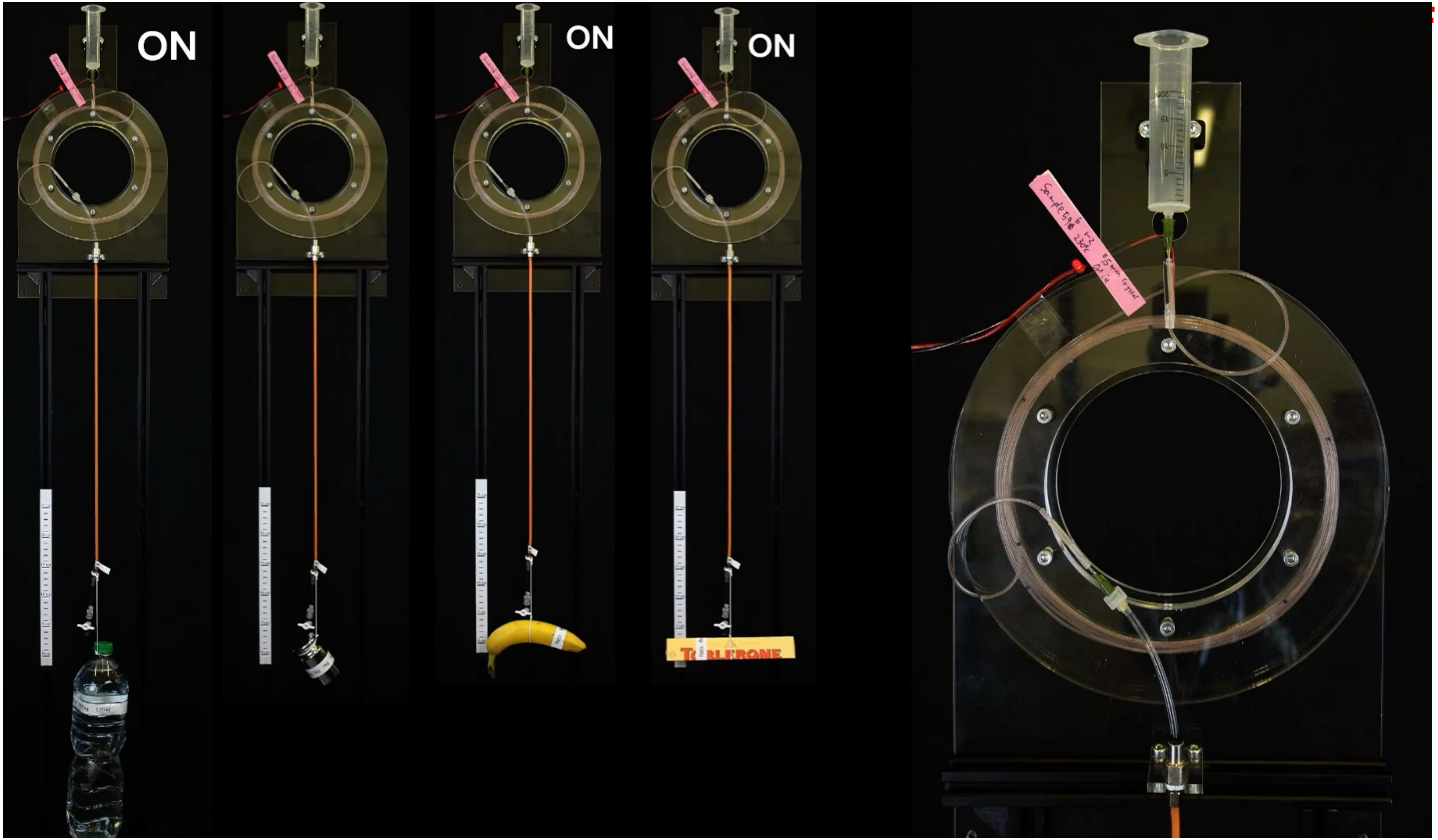
6 m long coiled
fiber pump

McKibben actuator
(shortens when inflated)

Movie: real time
Lifting 1.5 kg



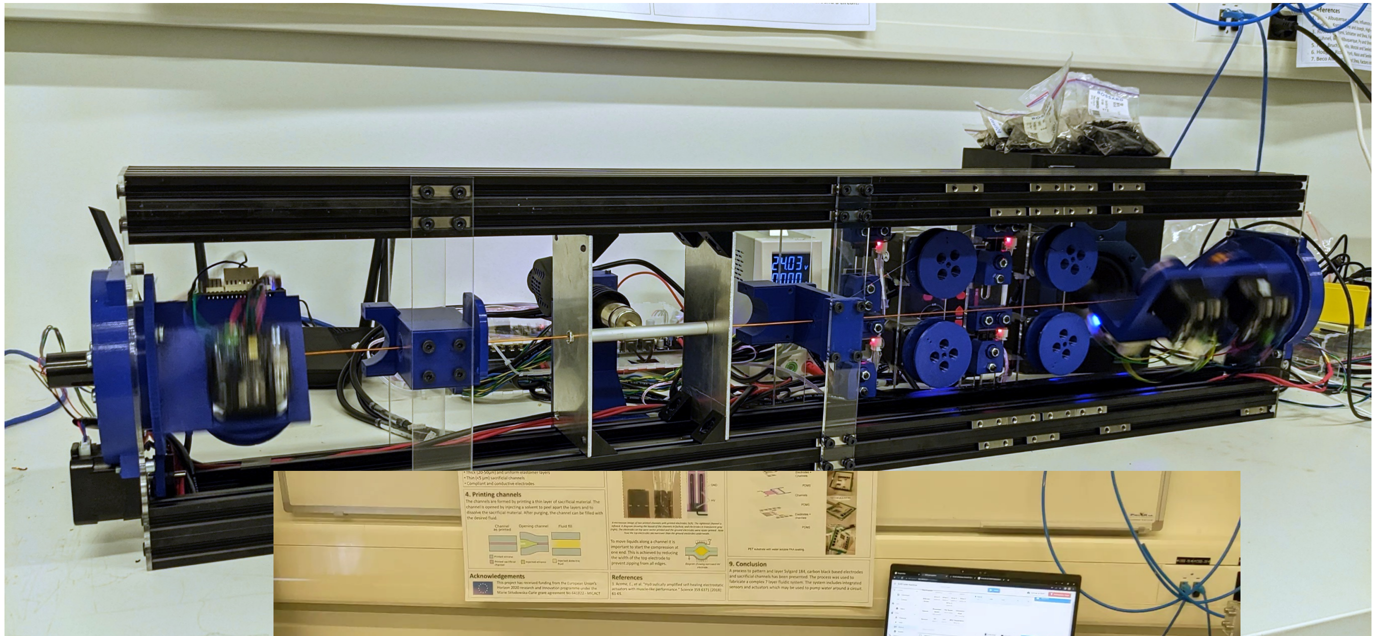
EPFL

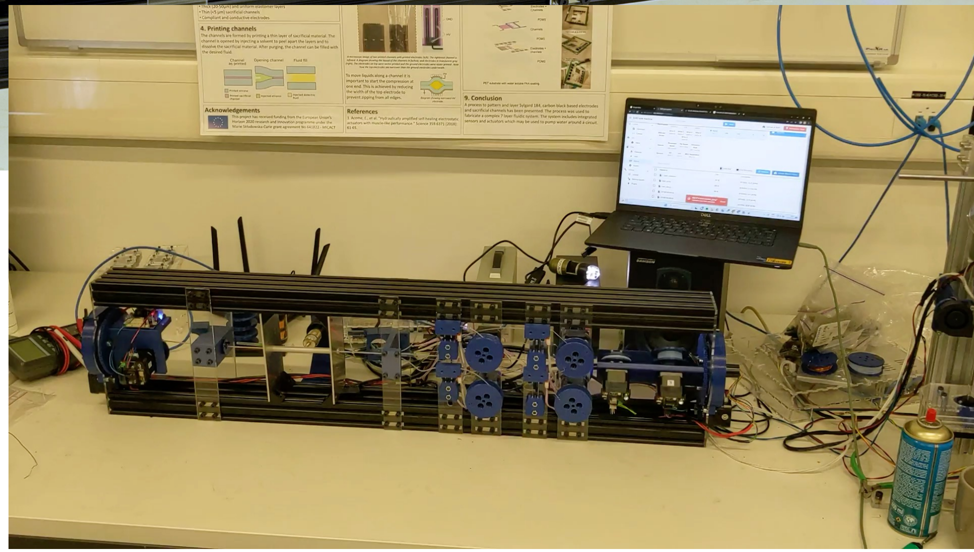


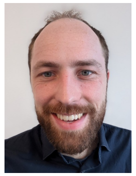
1

Multi-Meter long EHD fabrication

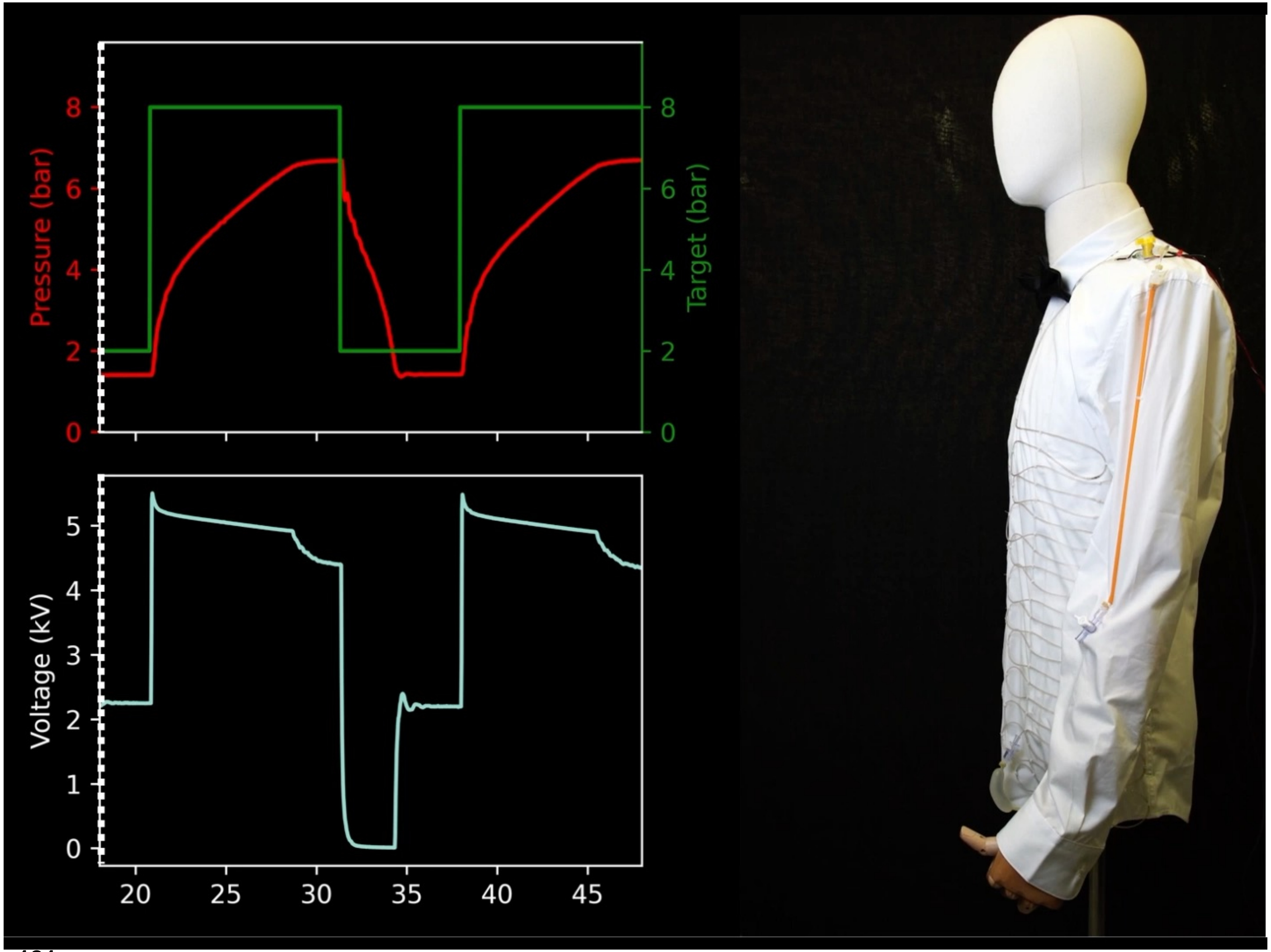
- Similar process similar to the previous slide except:
  - Winds filaments on a rotating and moving Teflon tube instead of on a fixed steel rod
  - Flow-through Heating using a hot air gun instead of an oven

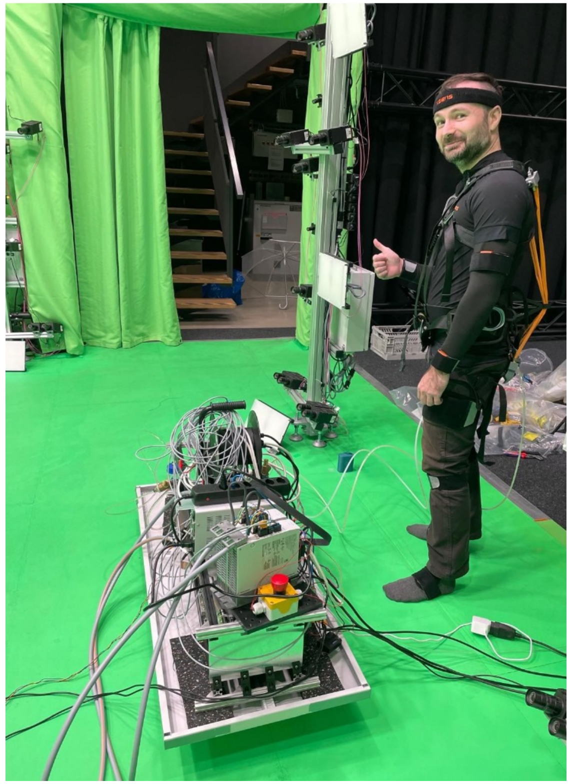




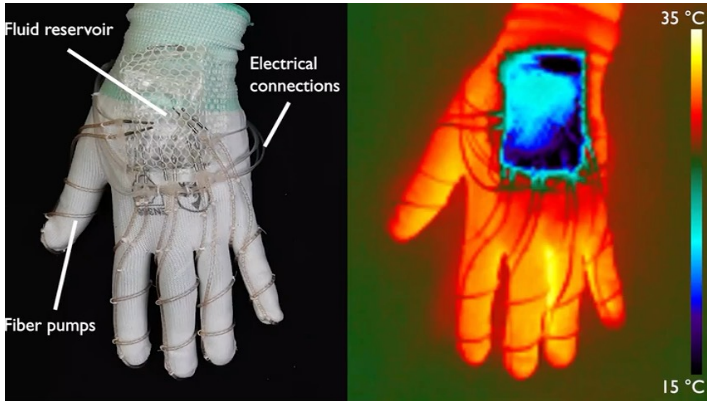


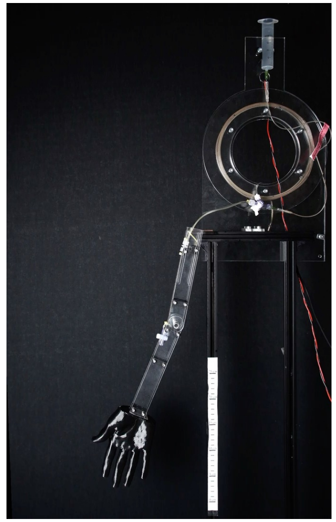
Dr. M. Schouten


Pressure (bar)
Target (bar)
Voltage (kV)
0
2
4
6
8
0
1
2
3
4
5
20
25
30
35
40
45



High performance fiberPumps will enable many applications in untethered wearable soft robotics



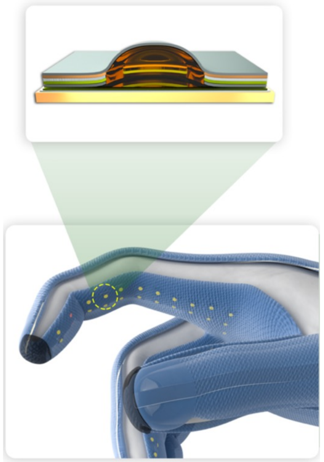


- Thermal transport on body: fast and quiet
- Generate pressure in distributed manner on body for soft exoskeletons
- Longer fiber, higher pressure !

- 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
- …

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/