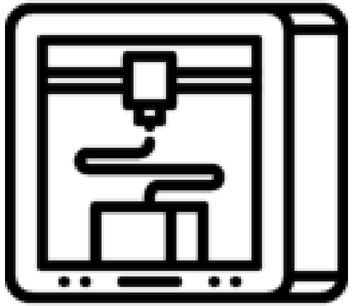
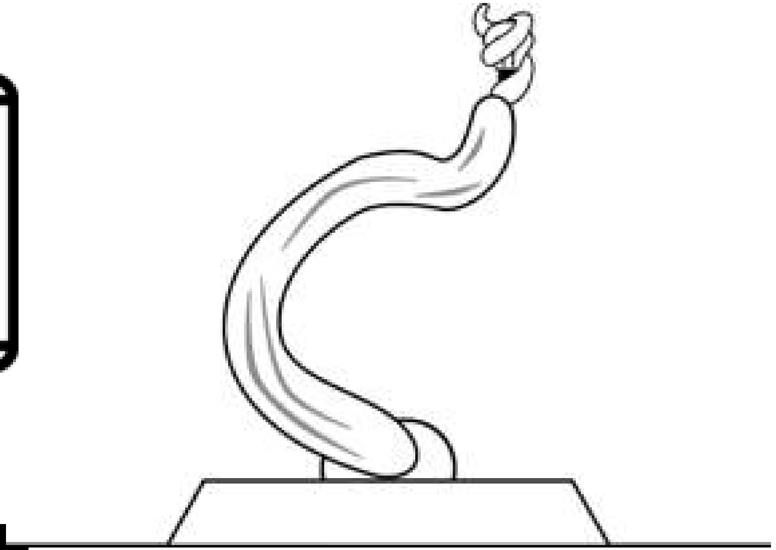



Fabricademy:
3D printed soft robots

Falk J. Tauber

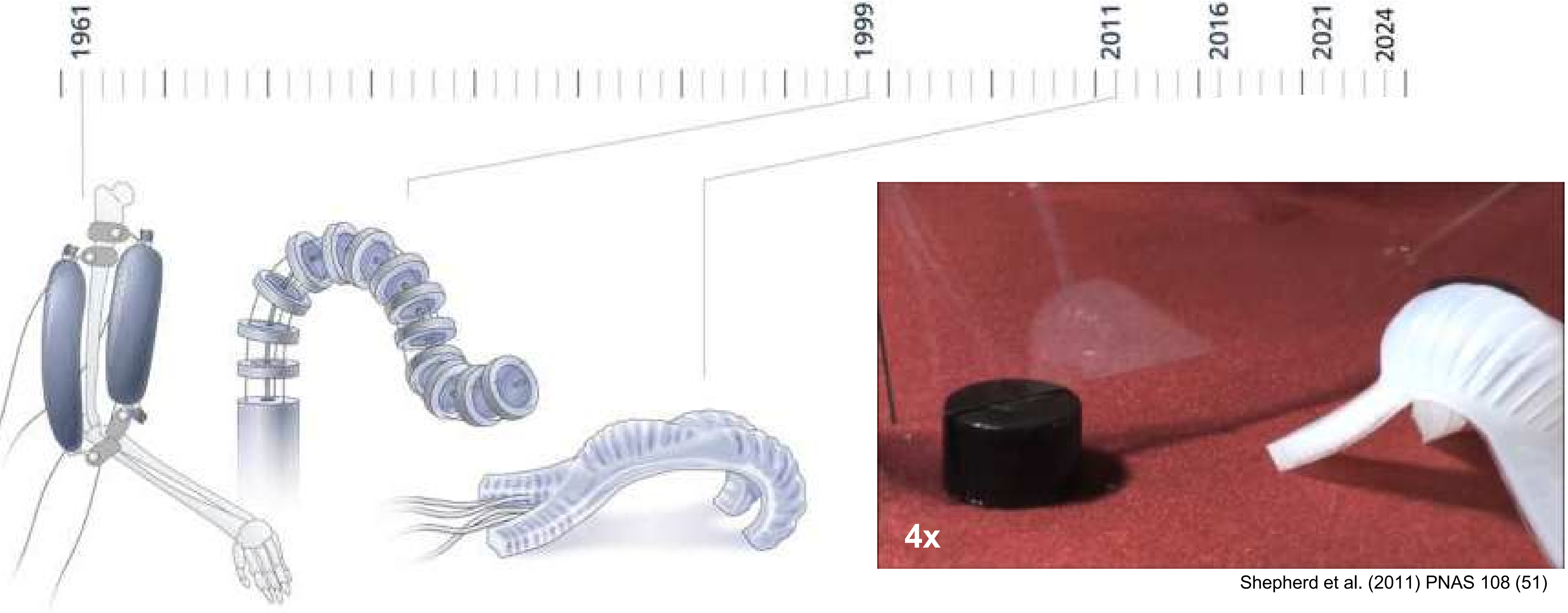
falk.tauber@biologie.uni-freiburg.de

livMatS

BGF Botanic Garden Freiburg

universität freiburg

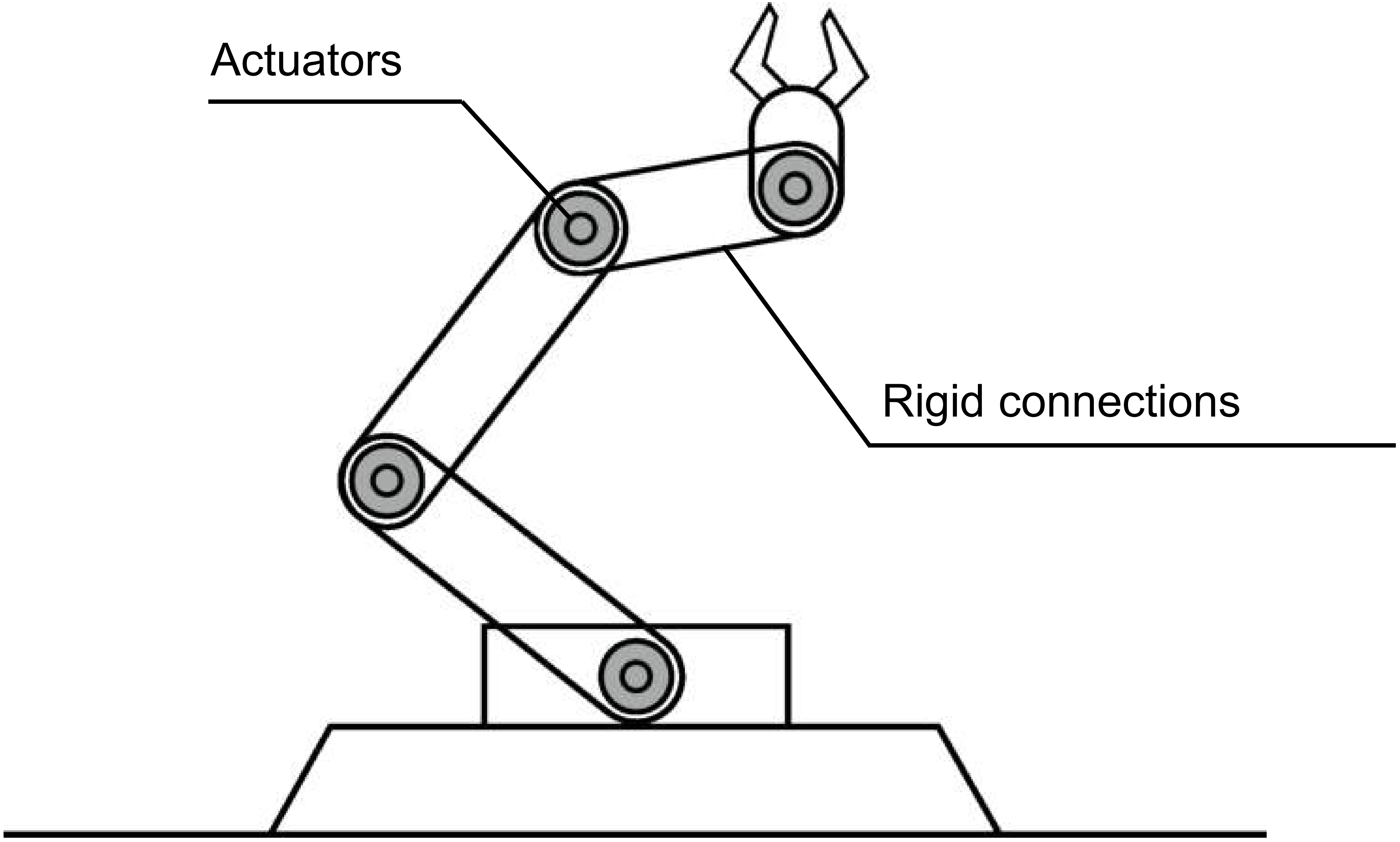
History of soft robots

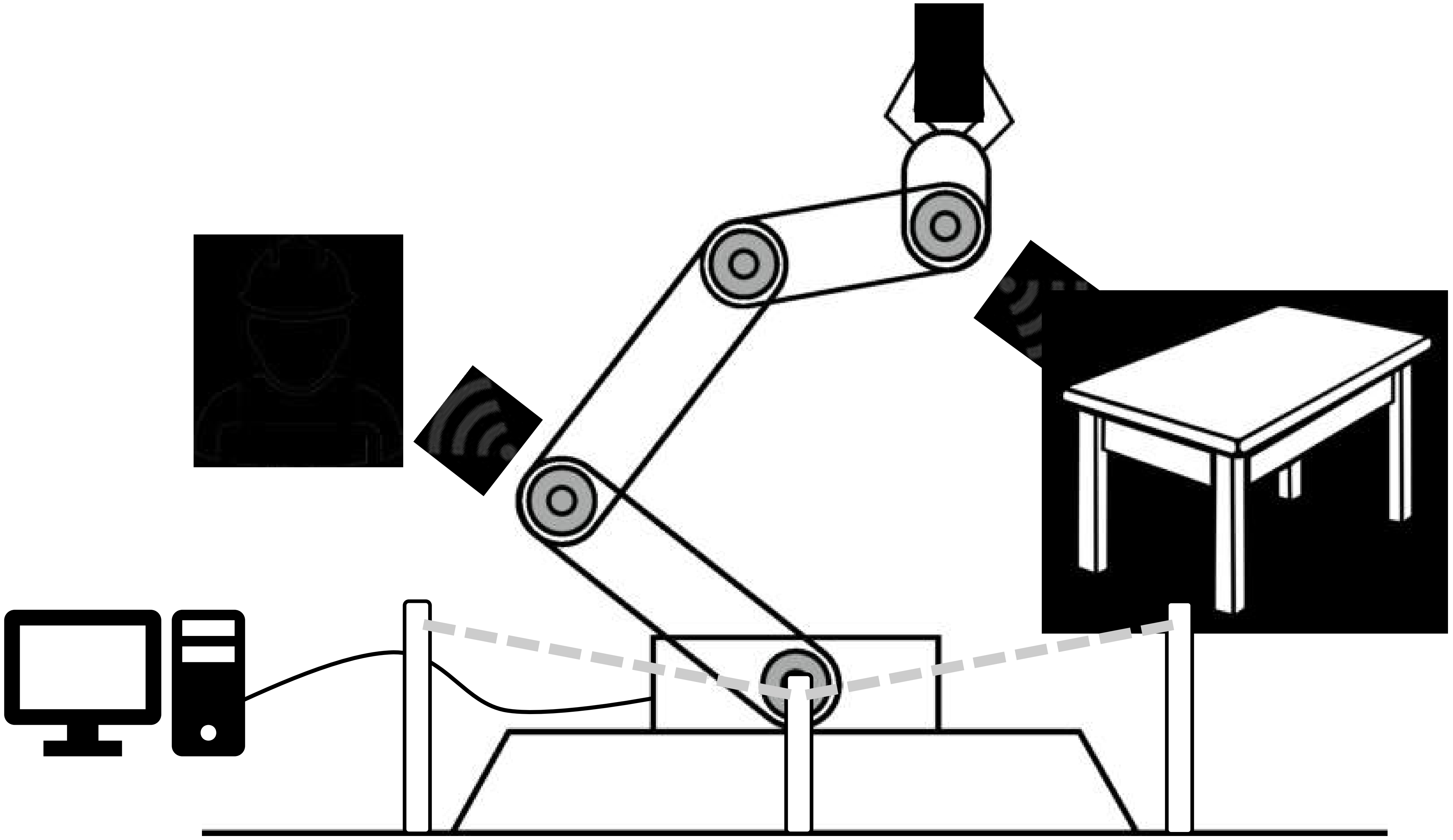


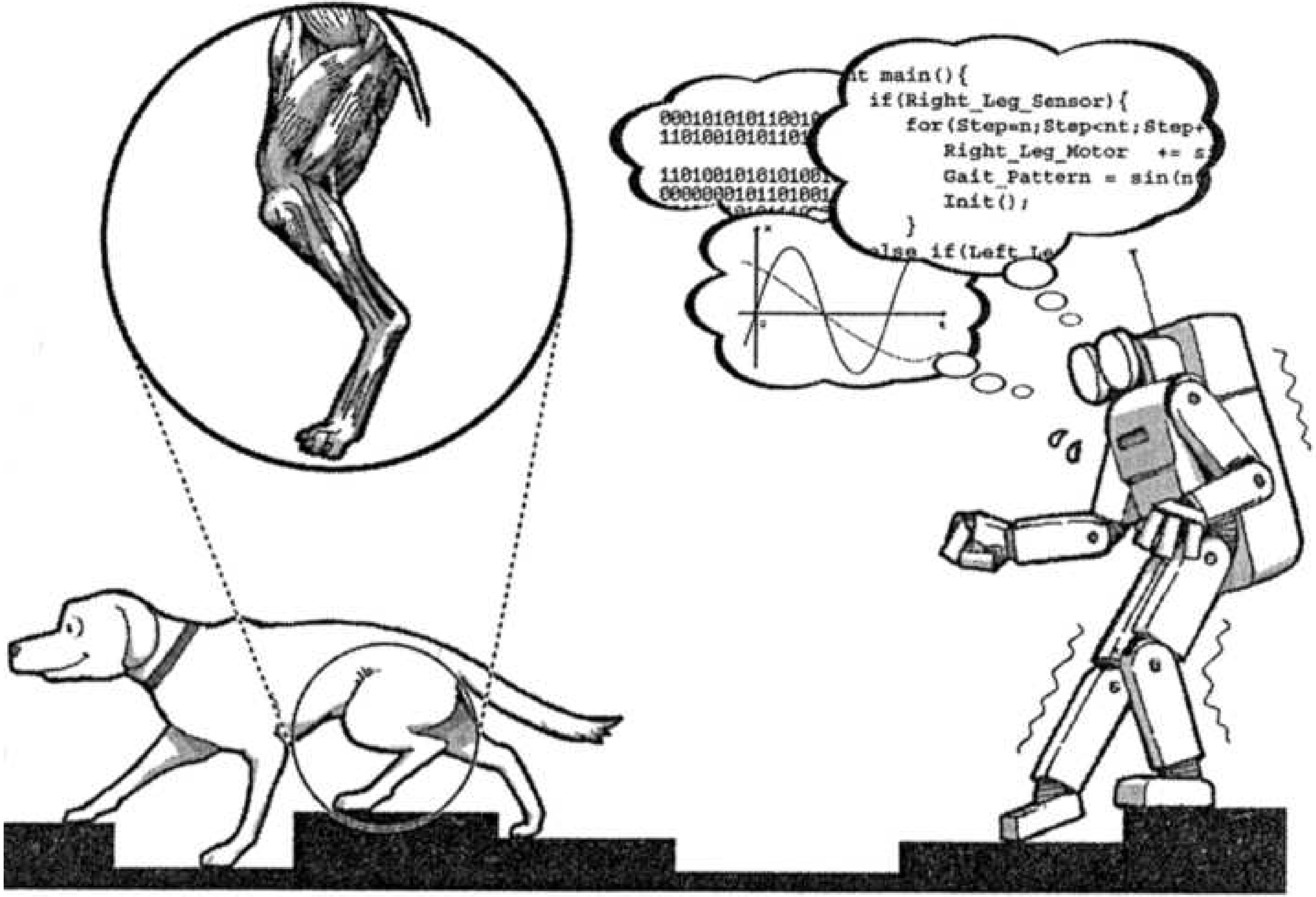
Shepherd et al. (2011) PNAS 108 (51)

Tauber et al. (2023) IOP Bioinspiration & Biomimetics 18 (3)

What is the difference to hard robots?

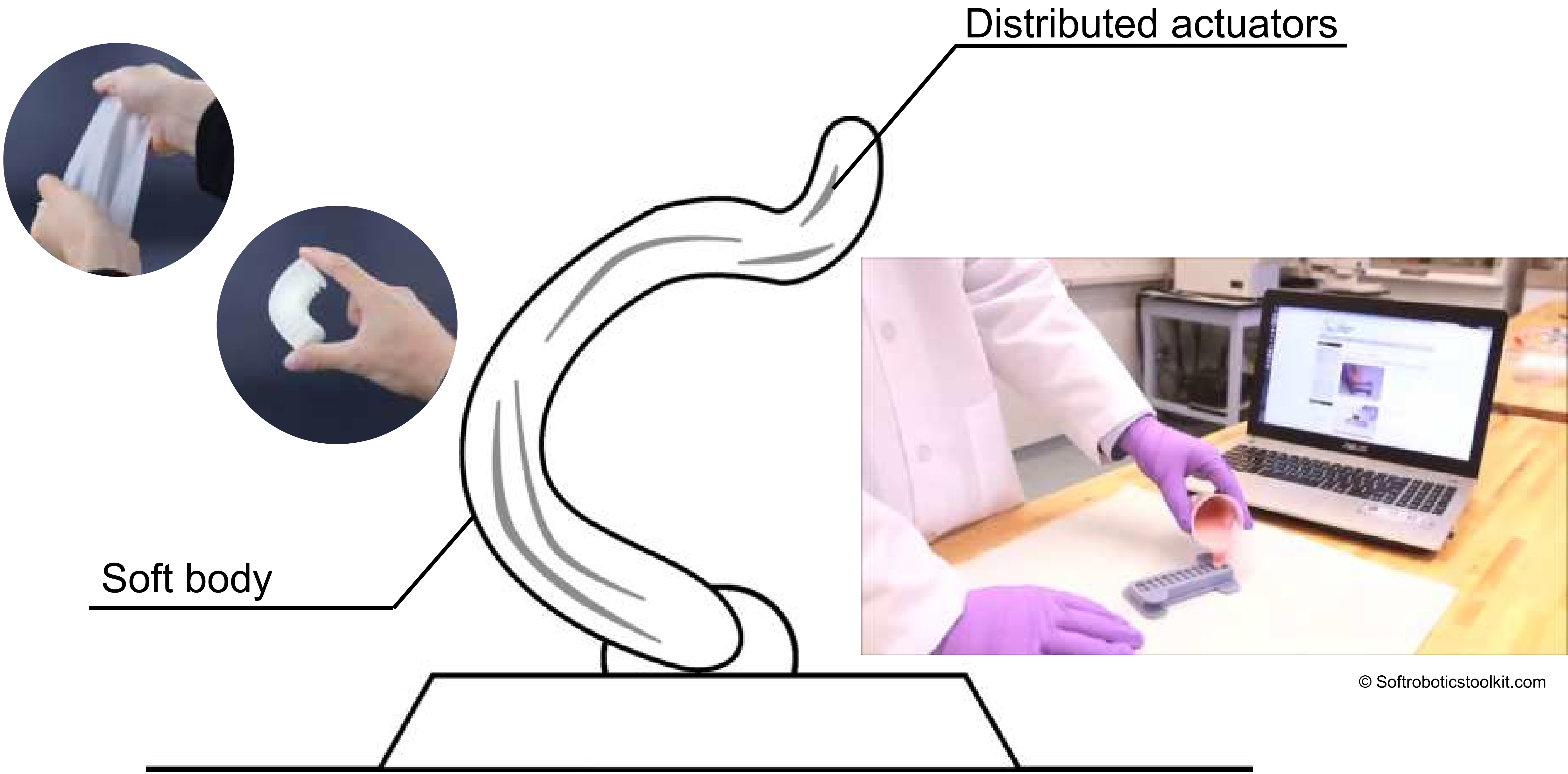

Actuators
Rigid connections



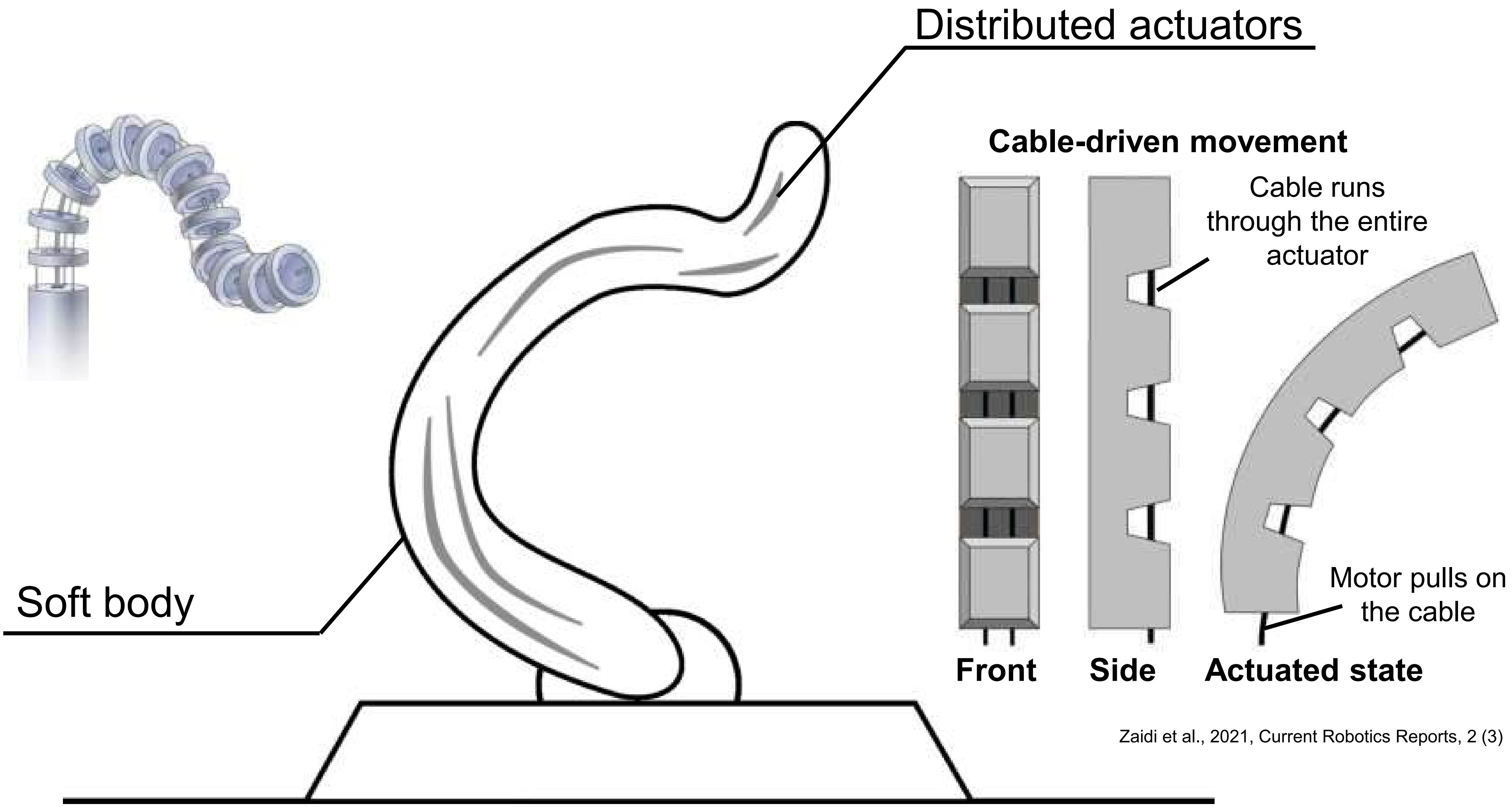


Pfeifer & Bongard (2006) How the Body Shapes the Way We Think. MIT Press.

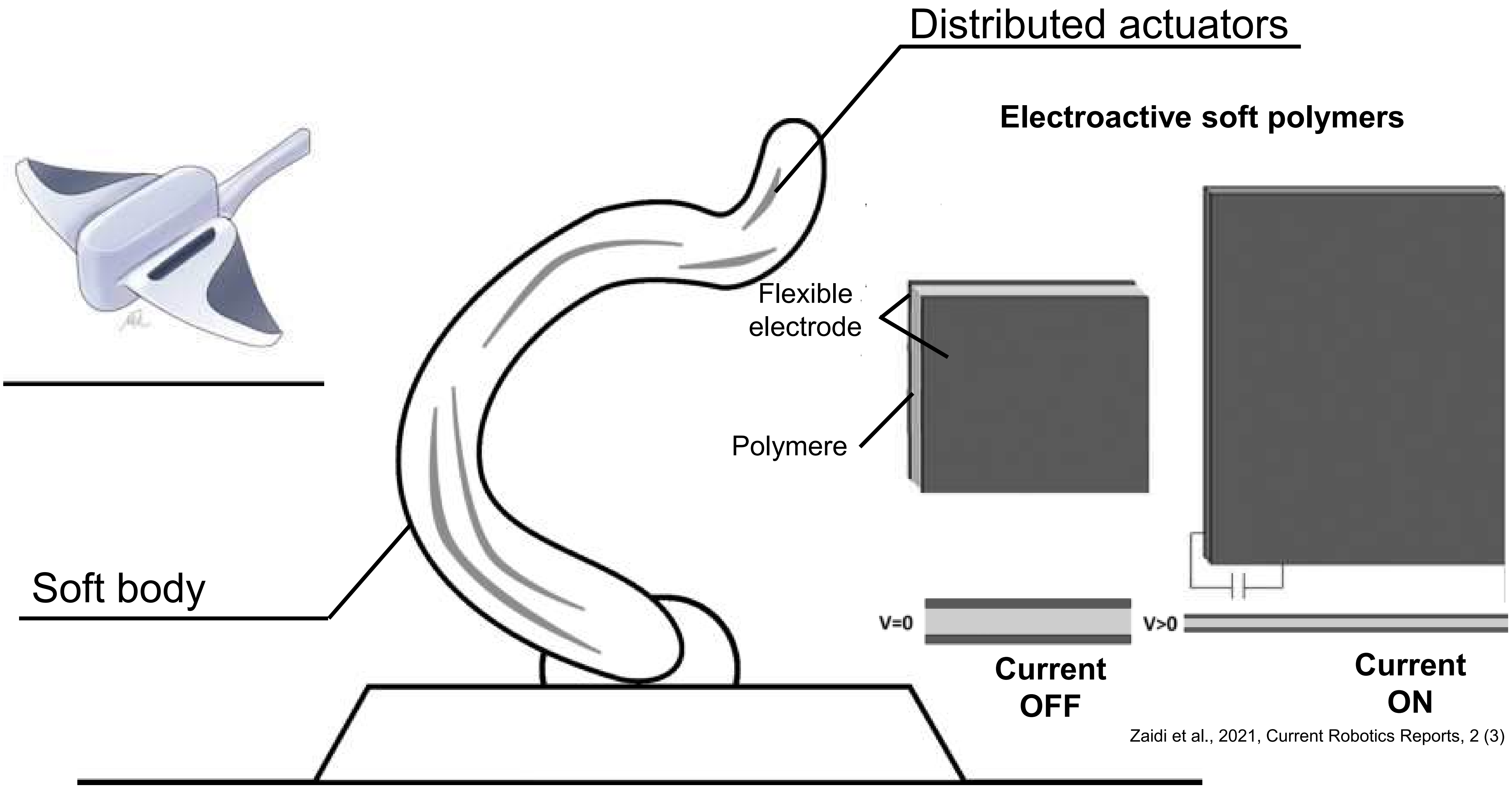

NATURE



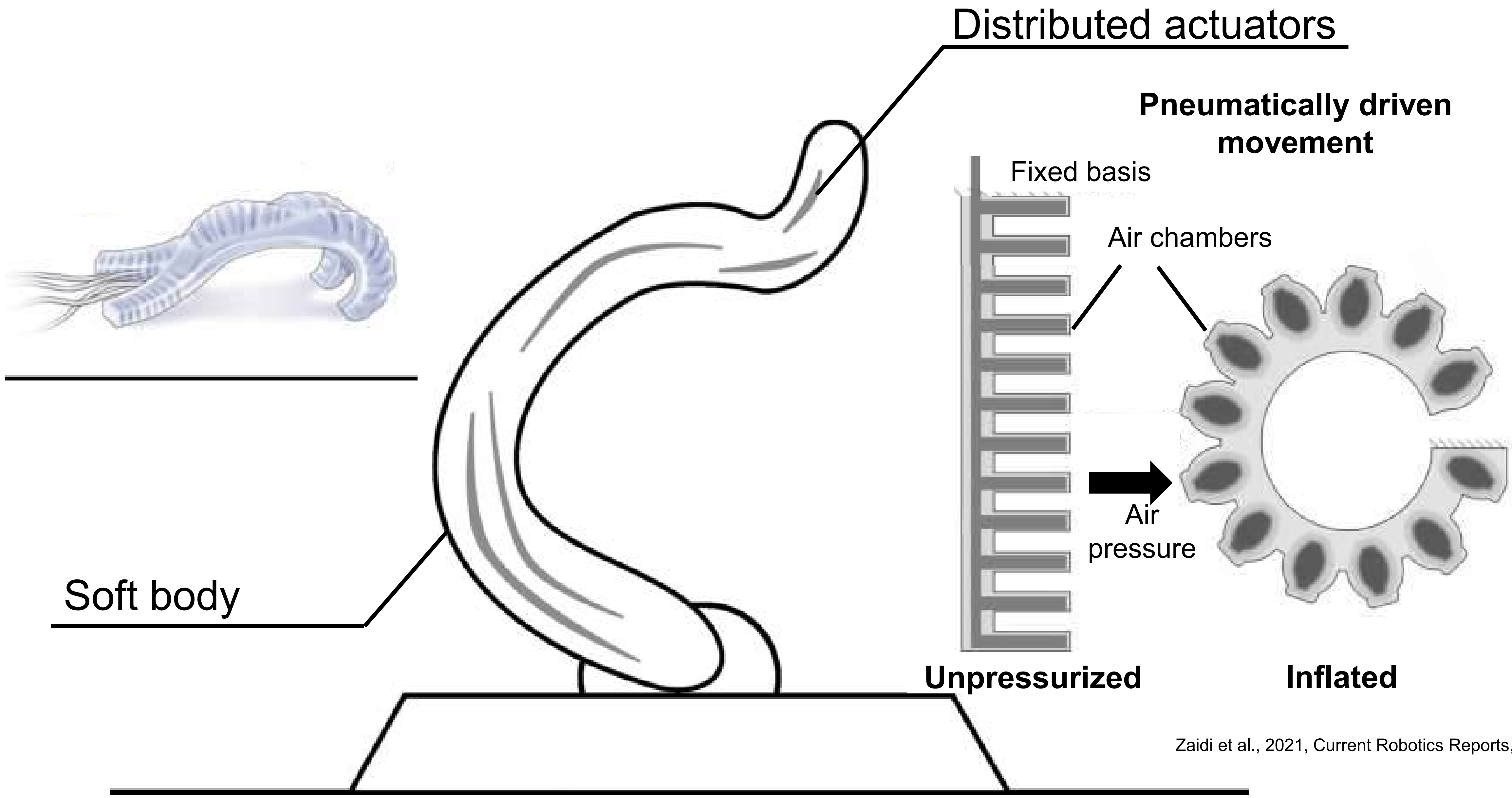
Distributed actuators
Soft body



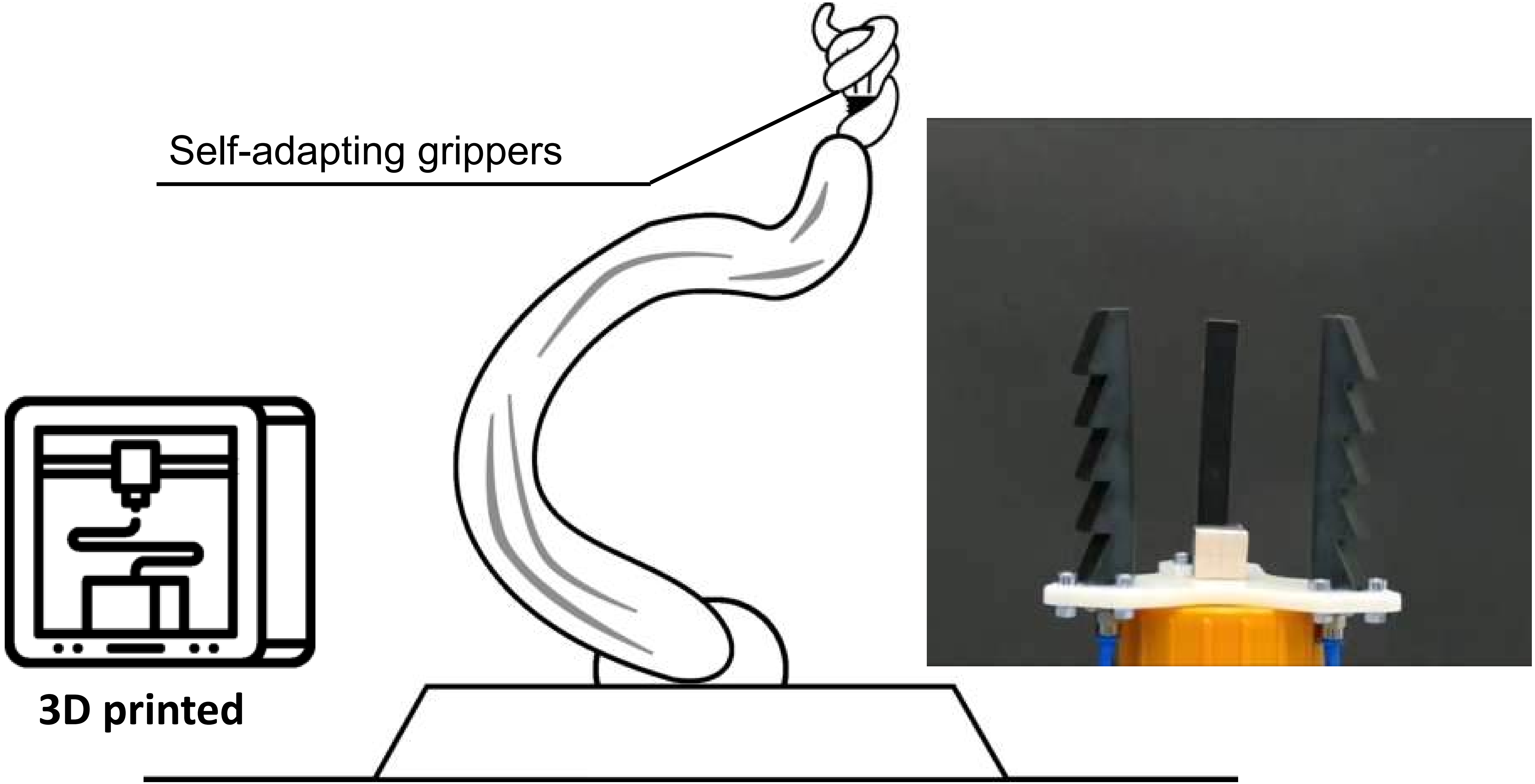
Zaidi et al., 2021, Current Robotics Reports, 2 (3)



Zaidi et al., 2021, Current Robotics Reports, 2 (3)



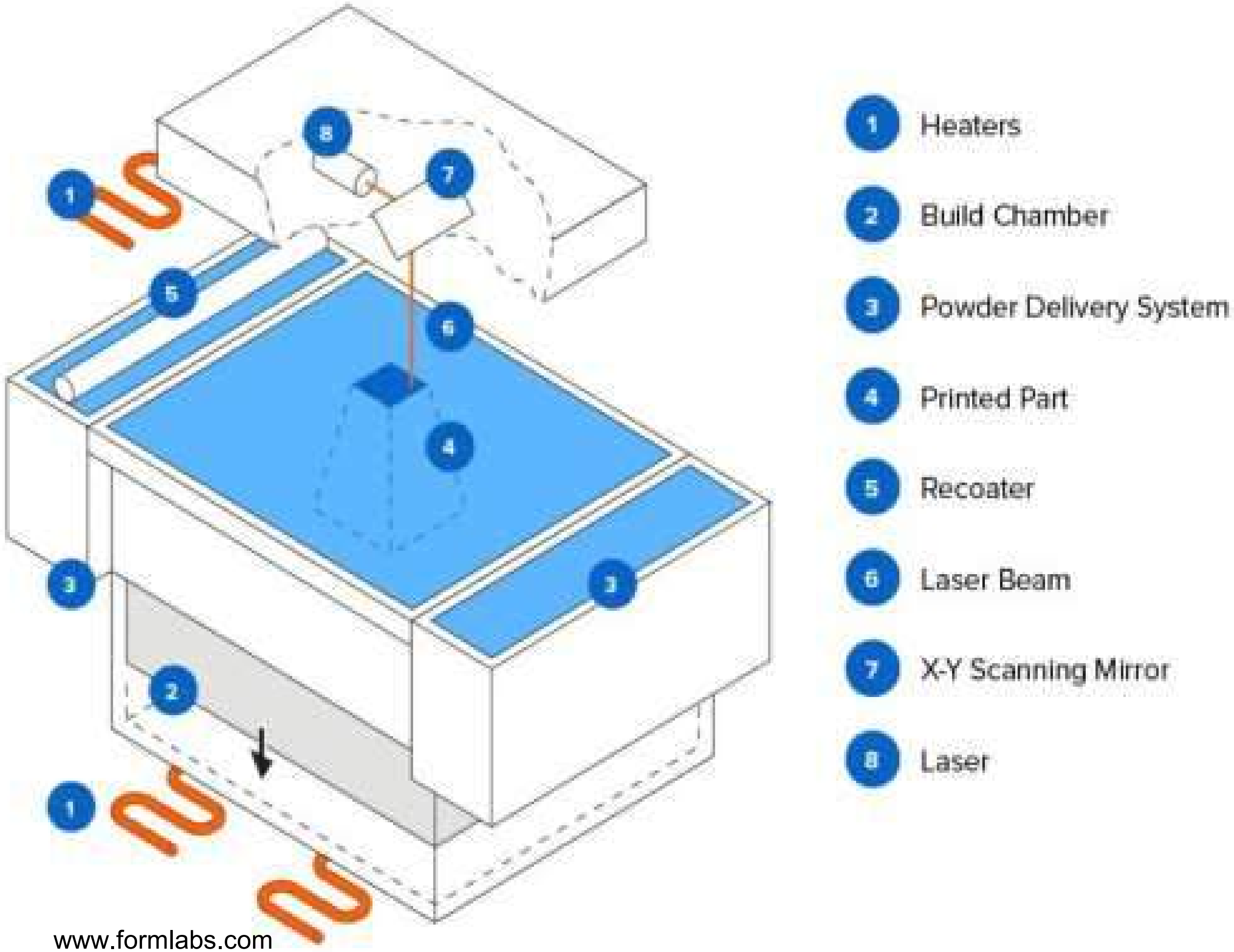
Zaidi et al., 2021, Current Robotics Reports, 2 (3)


Self-adapting grippers
3D printed

How do you print these?

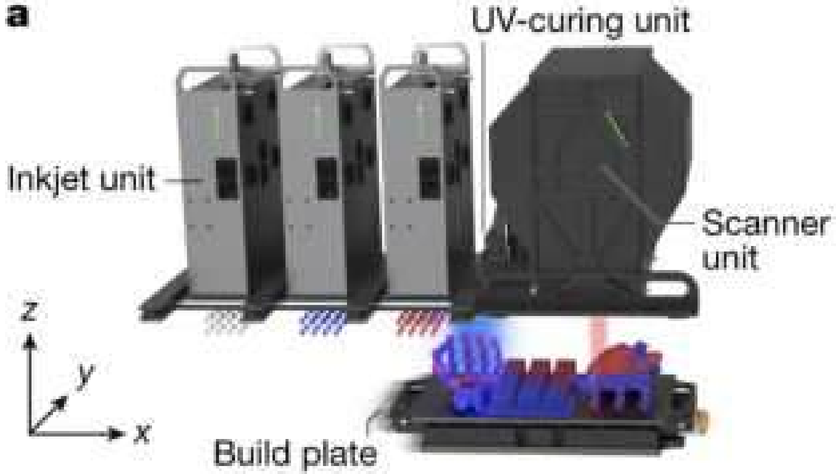
Overview of 3D printing technologies for soft robots

SLS – Selective laser sintering



www.formlabs.com

VCJ – Vision controlled jetting



Buchner et al. (2023) Nature 623

Overview of 3D printing technologies for soft robots

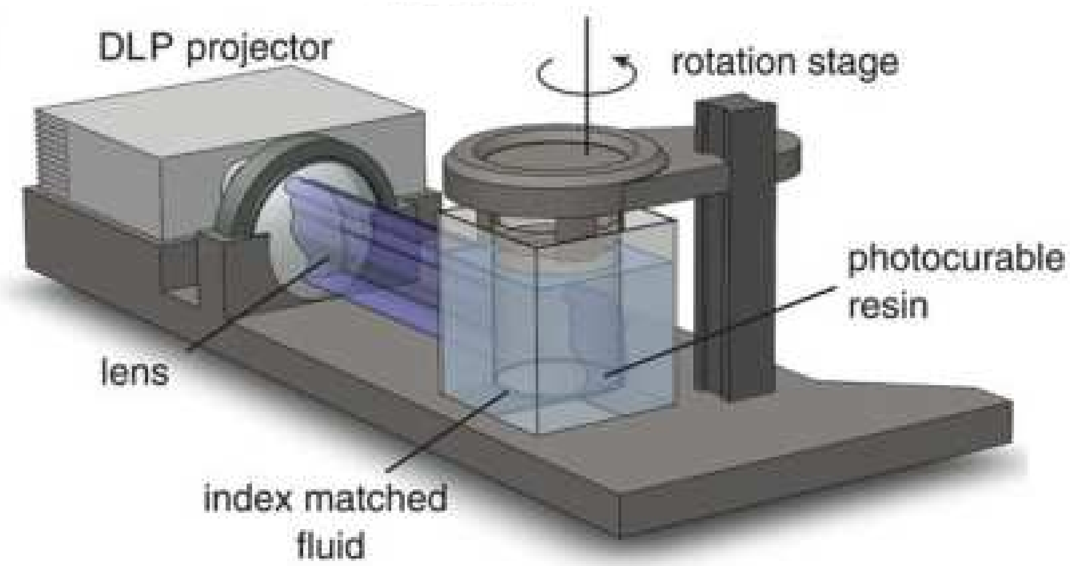
SLA/DLP/MSLA – light curable resin

www.formlabs.com

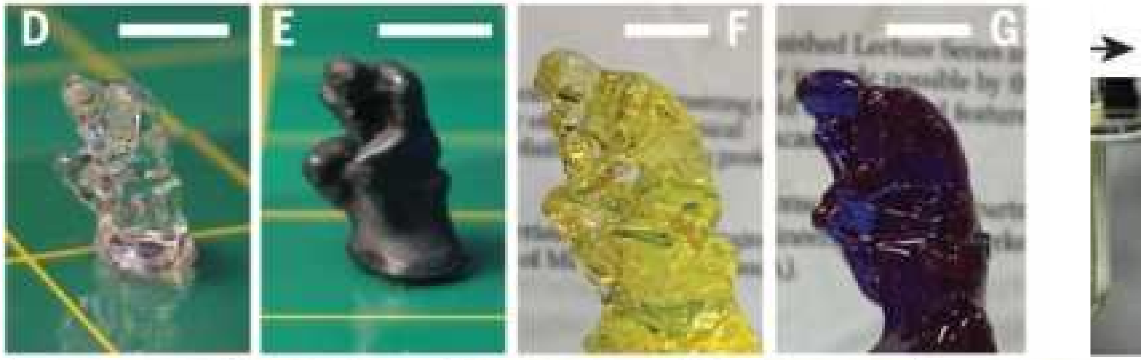
By Dsazer25 CC BY-SA 4.0

Volumetric 3D printing

A



C



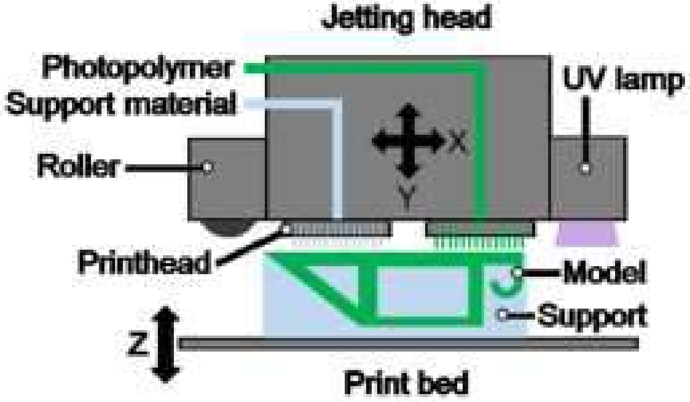
Kelley et al. (2019) Science 363 (6431)

Overview of 3D printing technologies for soft robots

Polyjet/Inkjetting + UV light

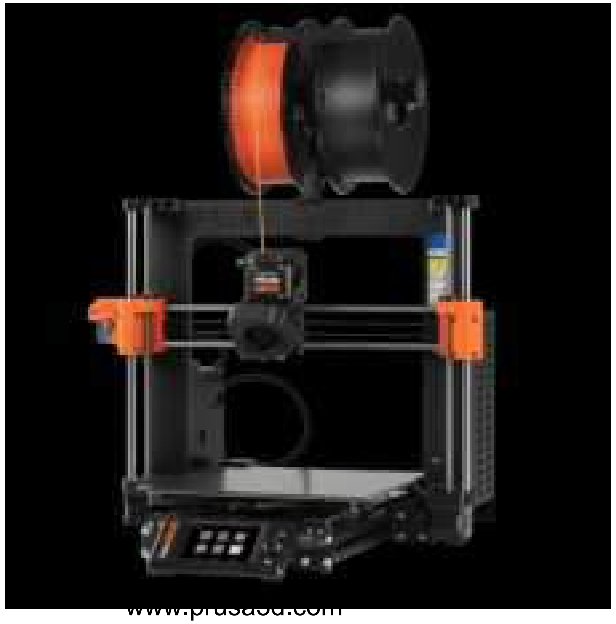
www.stratasys.com

Tauber et al. (2023) LNCS 14157



Knorr et al. (2024) Scientific Reports 14 (14157)

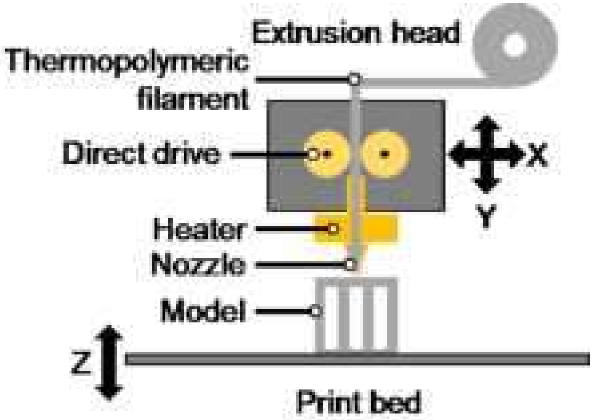
Fused filament fabrication



www.prusa3d.com

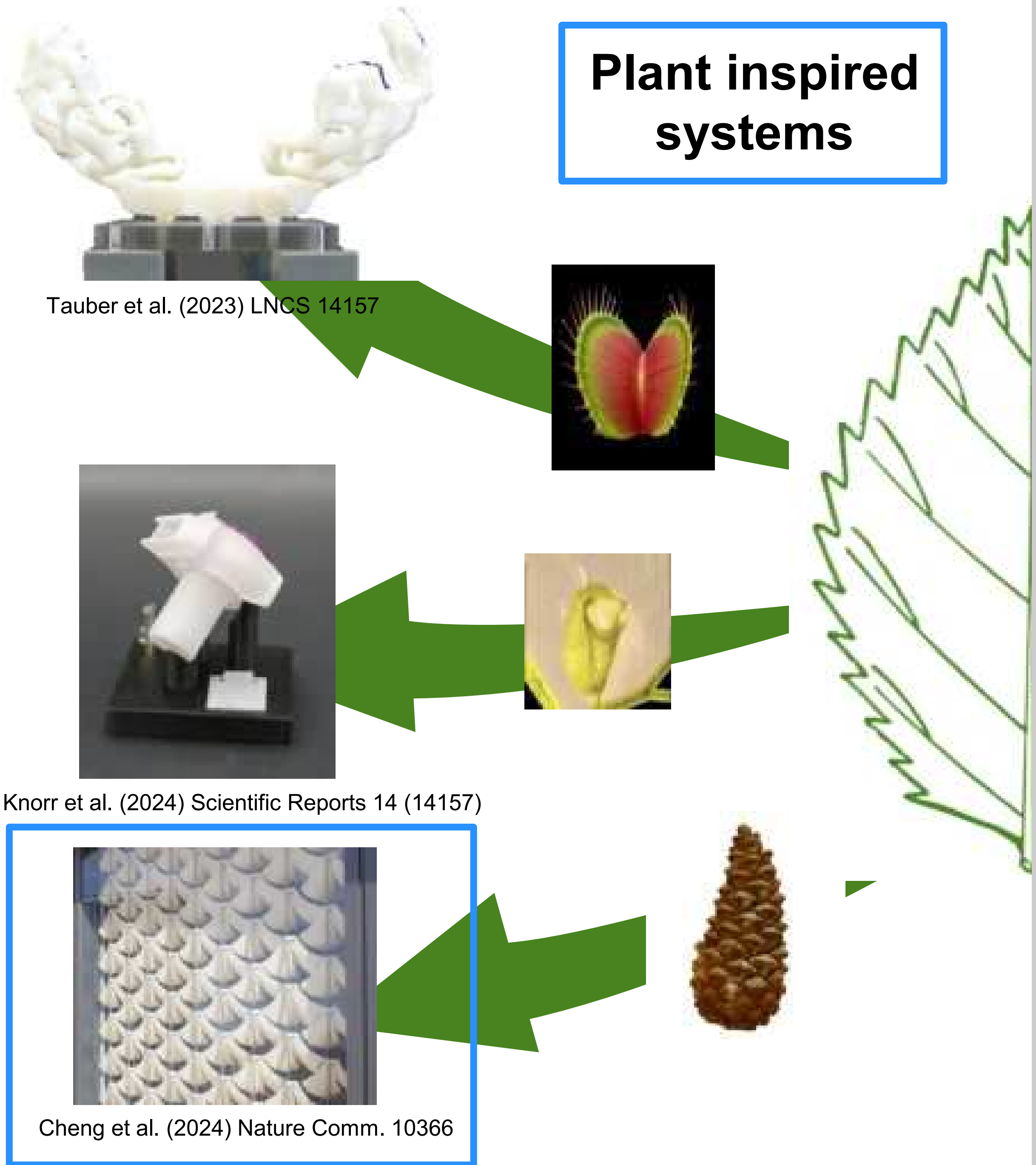
Cheng et al. (2024) Nature Comm. 10366

Conrad et al. (2024) Sci. Robotics 9 (86)




Inspired by nature

Plant inspired systems



Tauber et al. (2023) LNCS 14157

Knorr et al. (2024) Scientific Reports 14 (14157)

Cheng et al. (2024) Nature Comm. 10366

How can plant like motions be transferred into soft machines?

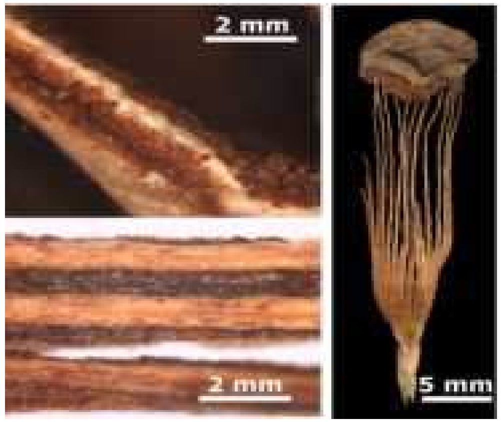
livMatS BioElast

Hygroscopic autonomous motions in plants

BGF universität freiburg

Pinus nigra

Pinus jeffreyi



Time laps camera analyses:
Movie over several hours

Ulrich et al. (2024): Bioinsp. & Biomim. 19(4): 046009 // T. Speck et al. (2023) *MRS Bulletin*, 48: 1-16 Eger et al. (2022) Advanced Science: 202200458. // Horstmann et al. (2022) Frontiers in Plant Science // Correa et al. (2020) Philosophical Transactions of the Royal Society London A, 378 (2167): 20190445. // Poppinga et al. (2020) Integrative and Comparative Biology: 60(4): 886-895.

Technical transfer and development of demonstrators

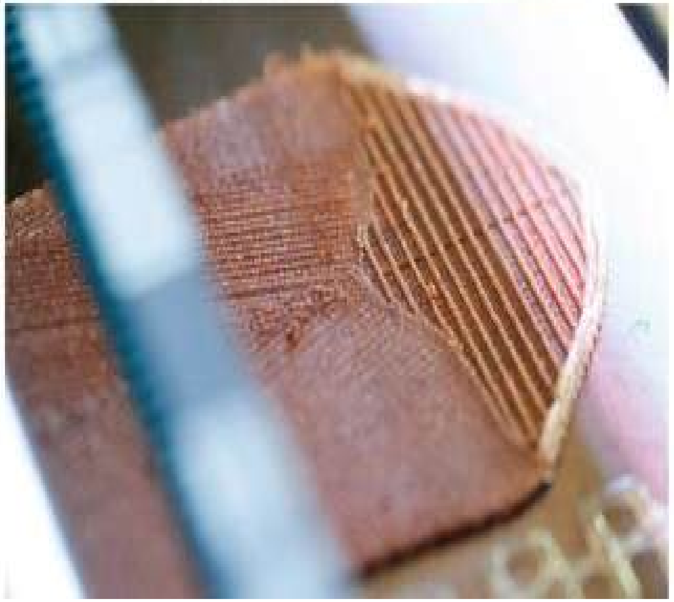
Technical transfer by FFF printing
into multi-material structures which are

- mechanically robust
- functionally integrated
- environmentally responsive
- and show multi-phase motions
  without consumption of external energy

Materials:

Copolyester with embedded cellulose fibers

Acrylonitrile butadiene styrene = ABS plastic



D. Correa & A. Menges (2017) In Fabricate - Rethinking Design and Construction, UCL Press, 190-195 // Correa et al. (2020) Philosophical Transactions of the Royal Society A 378 (2167): 20190445.

livMatS BioElast

Responsive autonomous surface structures inspired by passive multi-phase plant movements

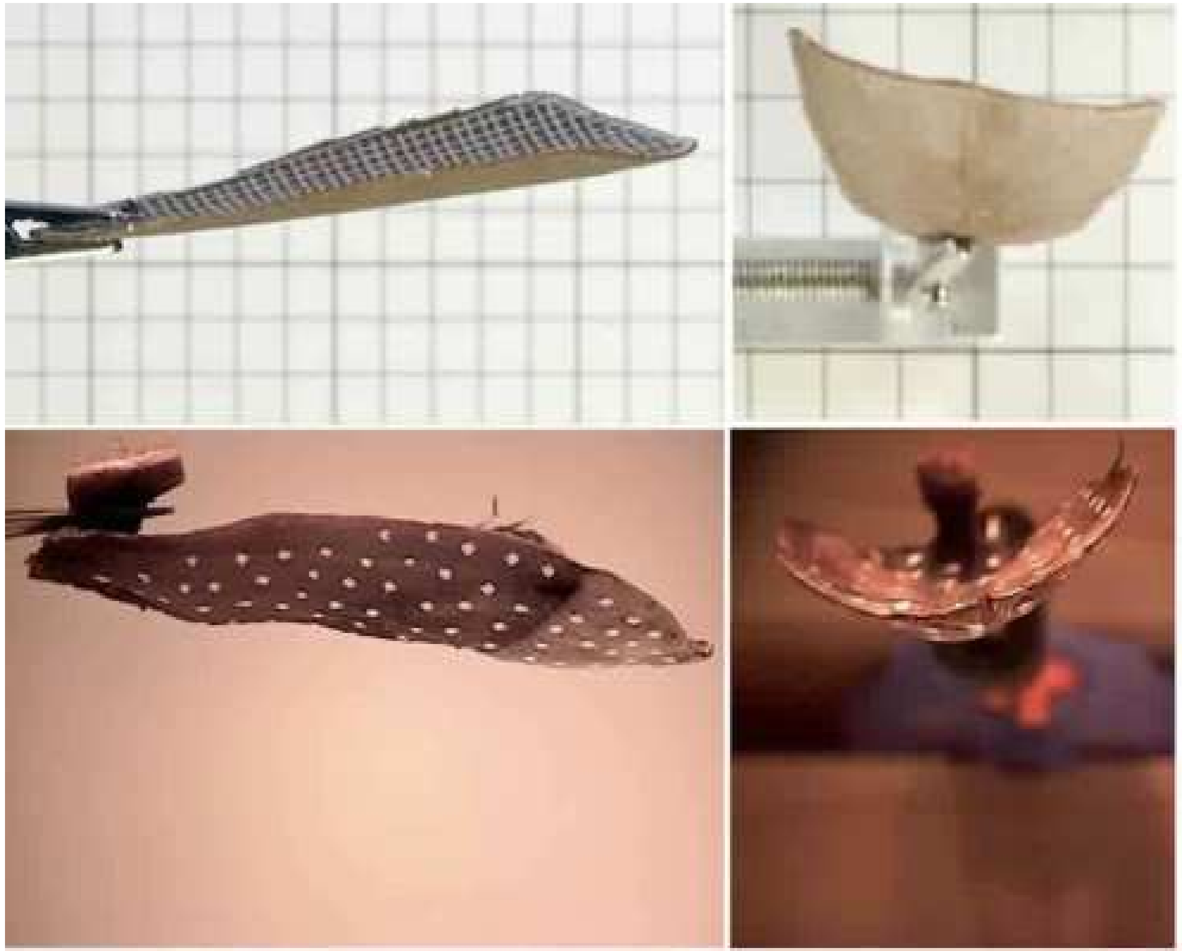
BGF universität freiburg

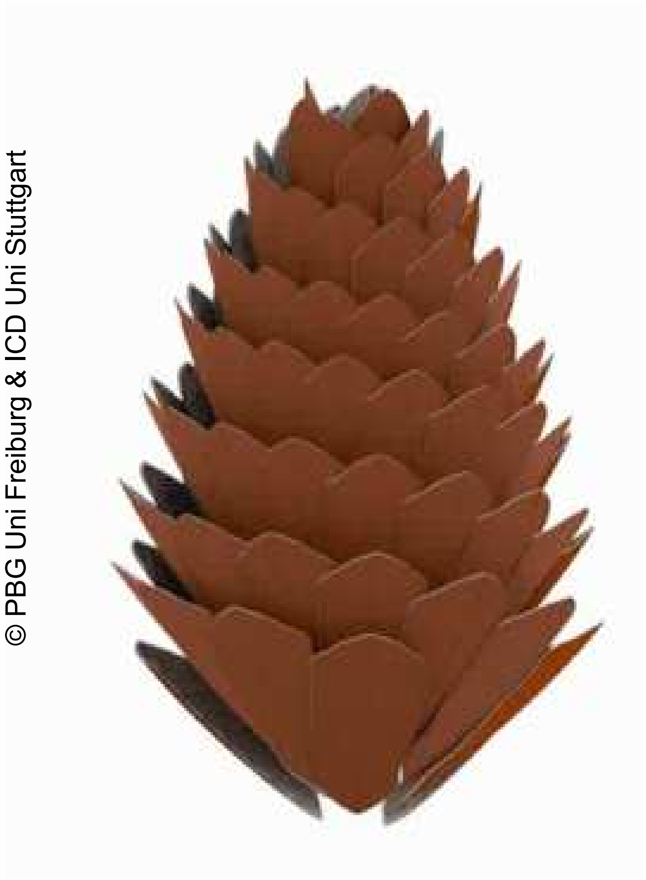
Materials: Copolyester with embedded cellulose fibers

Acrylonitrile butadiene styrene = ABS plastic

Biomimetic 4D-printed scale

Natural pine cone scale (*Pinus wallichiana*)



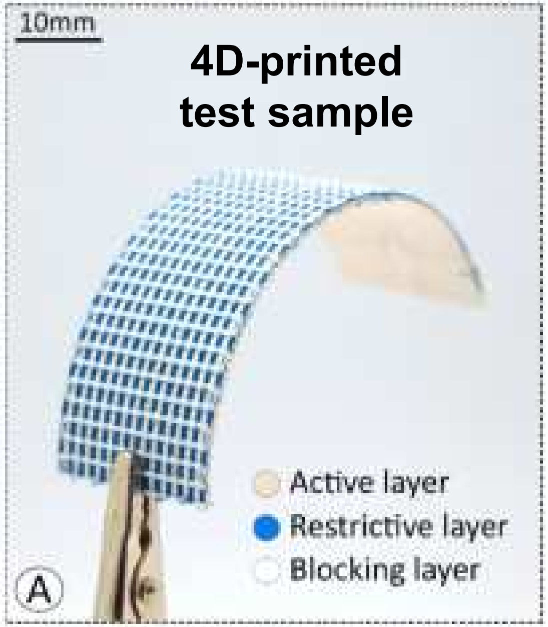


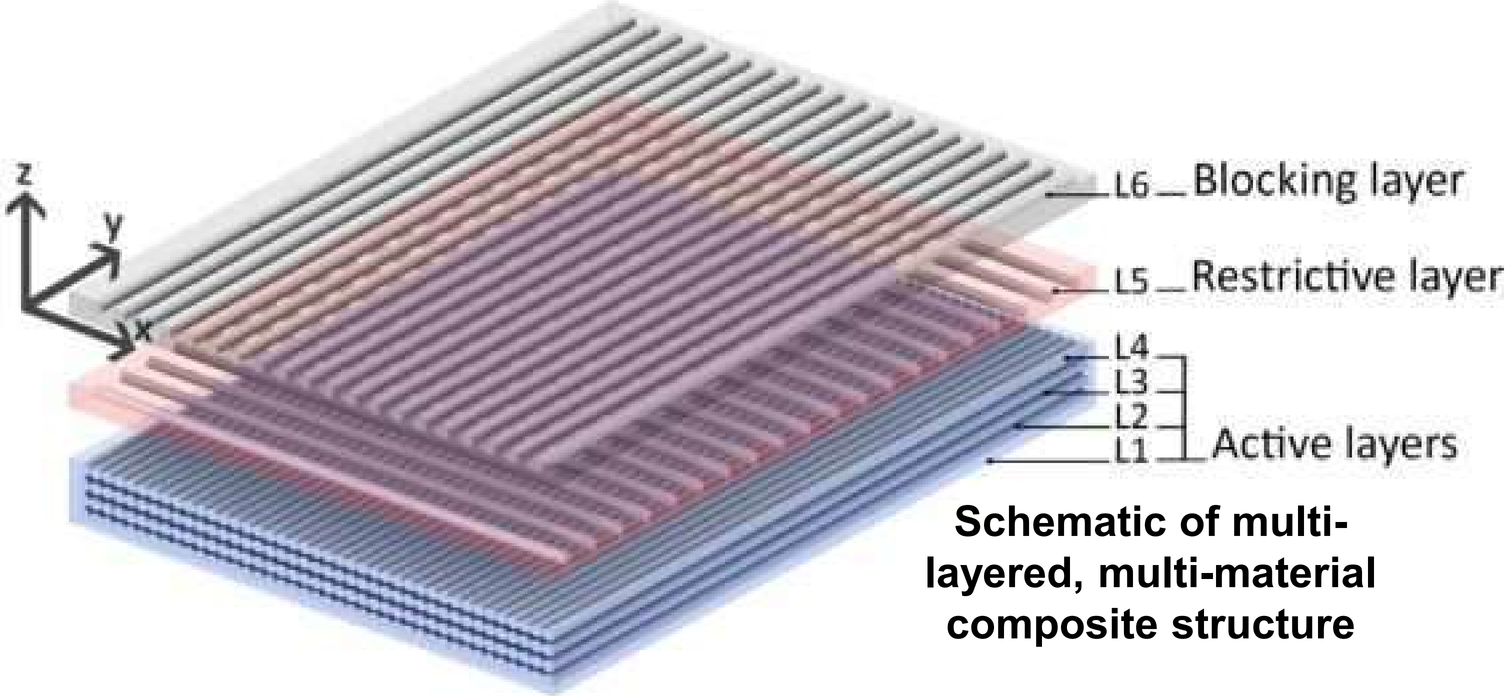
Proof of concept: Technical implementation of bi-axial two-phase motion pattern

Correa et al. (2020): Philosophical Transactions of the Royal Society London A, 378 (2167): 20190445.

4D-printed hygroscopic soft machines with complex shape-change & sequential motion

Programming of timescale in bioinspired 4D-printed materials systems:





Schematic of multi-layered, multi-material composite structure

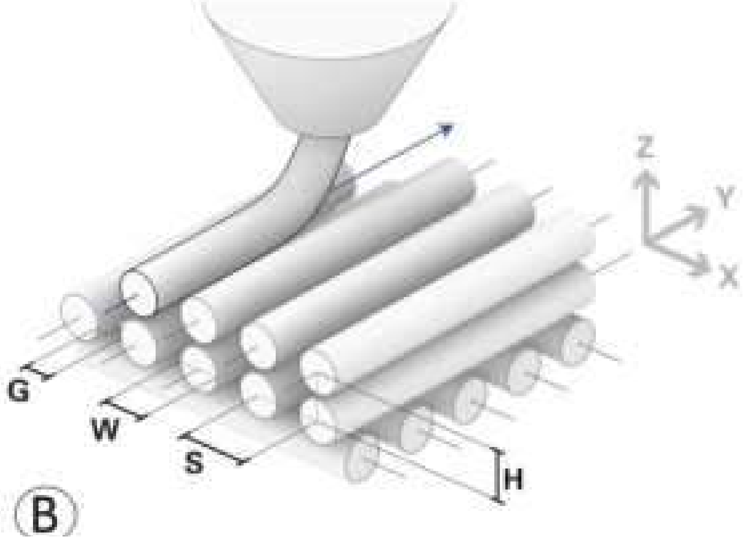
Mesostructured 4D-printed hygroscopic materials system consisting of functional multilayers with water permeability anisotropy inspired by structure and function of the involucral bracts of the silver thistle (*Carlina acaulis*) and scales of pine cones (*Pinus* spp.).

Tahouni et al. (2021) Bioinspiration and Biomimetics, 16: 055002

4D-printed hygroscopic soft machines with complex shape-change & sequential motion

Programming of timescale in bioinspired 4D-printed materials systems:

Parameters	Active layer (hygroscopic bio-composite LAYWOOD)	Restrictive layer (PLA)	Blocking layer (TPC)
Layer height	0.2 mm	0.2 mm	0.2 mm
Number of printed layers	2–10	1	1
Orientation (*X*–*Y* plane)	0°–90°	90°–0°	0°–90°
Spacing (*X*–*Y* plane)	0.3–0.7 mm	0.5–3 mm	0.5–3 mm
Nozzle temperature	210 °C	210 °C	220 °C
E-value (volume of filament/mm)	0.040	0.033	0.033
Feed rate	1200 mm min^{-1}	1200 mm min^{-1}	1200 mm min^{-1}

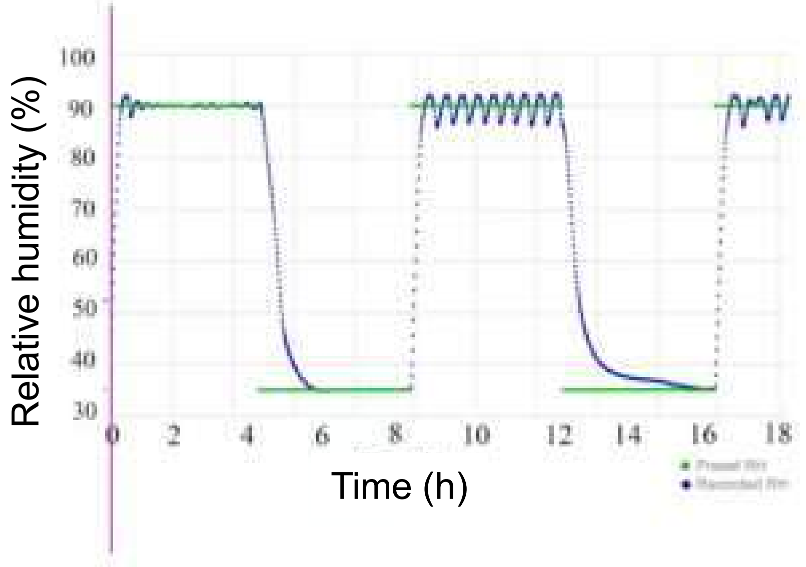


Parametric toolpath design to enable air gaps for better permeability.
Printed on a dual extruder FFF printer.

Tahouni et al. (2021) Bioinspiration and Biomimetics, 16: 055002

4D-printed hygroscopic soft machines with complex shape-change & sequential motion

Hygro-responsive form change in a bioinspired ventilation flap



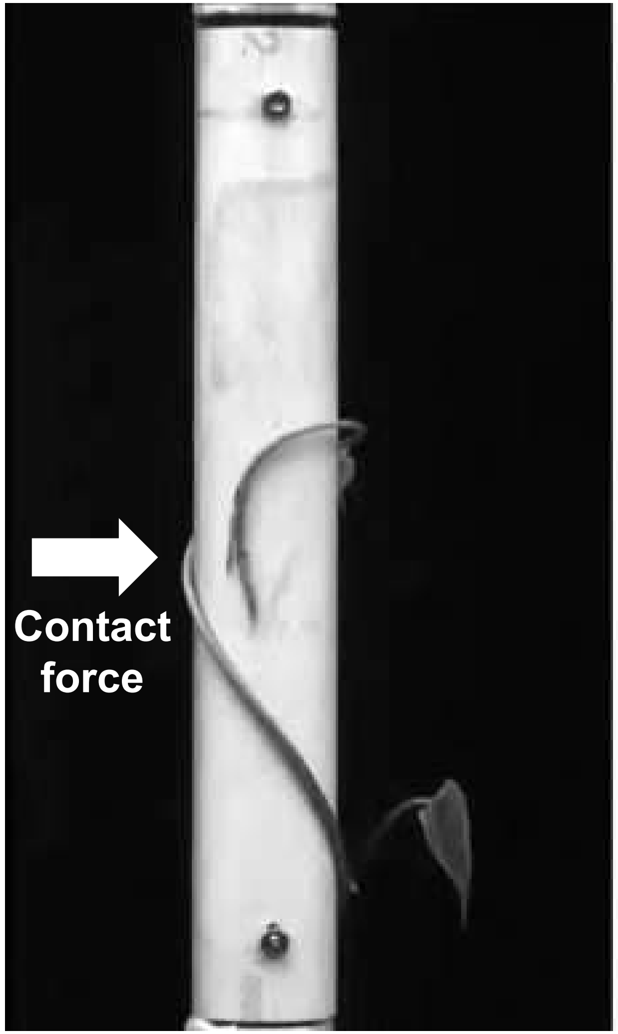
Tahouni et al. (2021) Bioinspiration and Biomimetics, 16: 055002 // Speck et al. (2023) MRS Bulletin, 48: 1-16

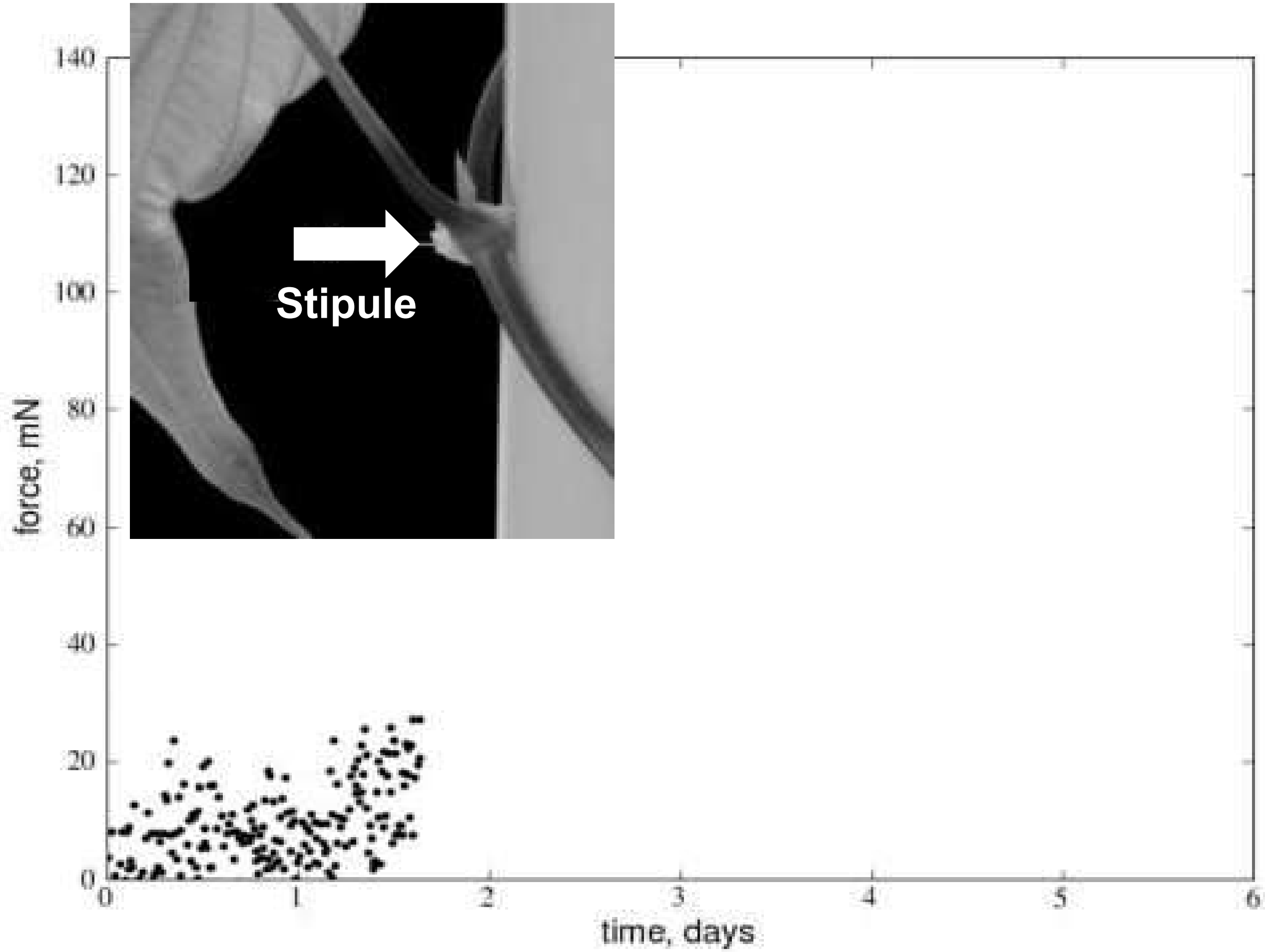
Solar Gate *Skylight*, *liv*MatS
Biomimetic Shell @ FIT

Cheng et al. (2024) Nature Communication 10366

Twining lianas: From role model to a 4D-printed wearable system

Pre-programmed self-adaptive attachment systems in stem twining lianas



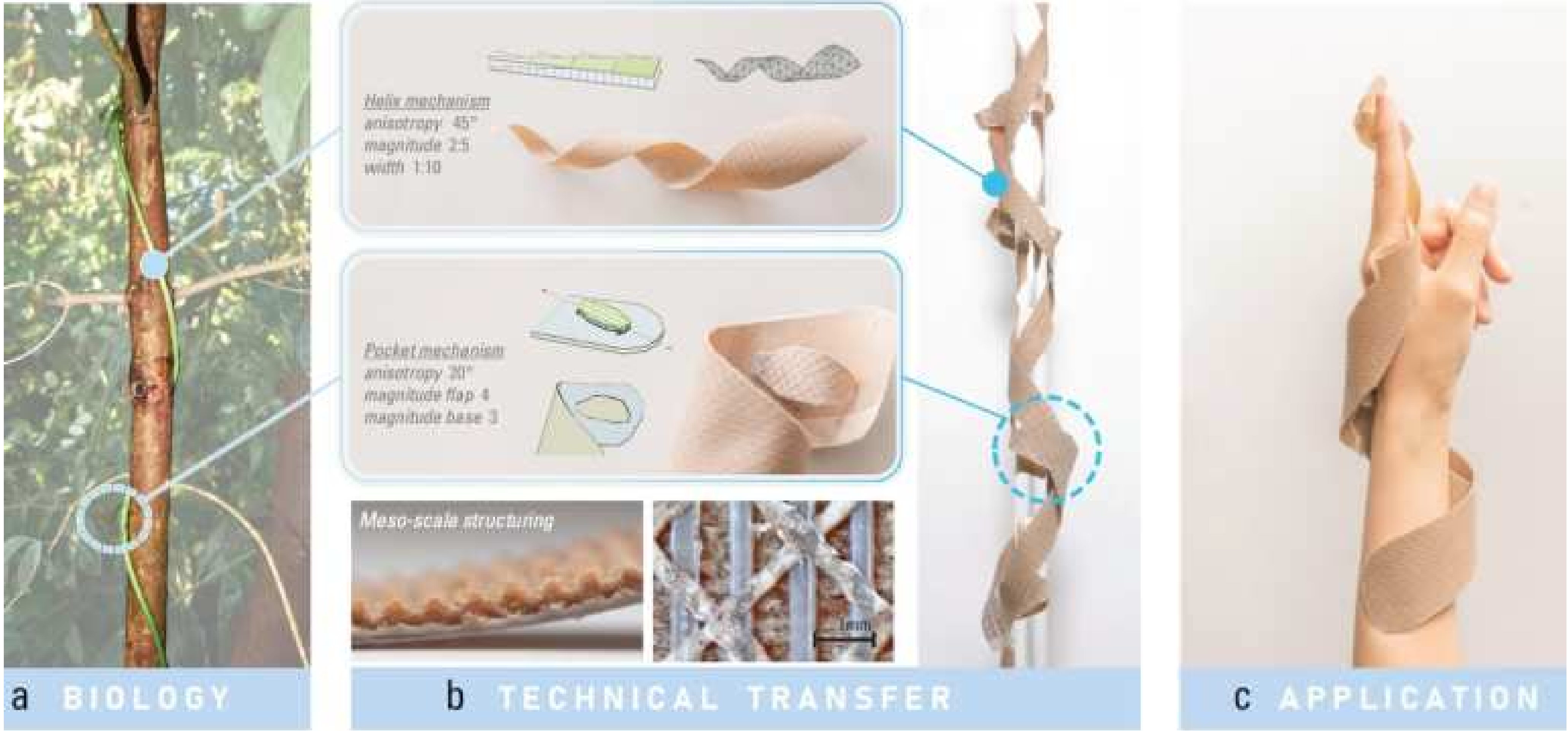


Cheng et al. (2021) Applied Science, 8(13): 2100411 DOI: 10.1002/advs.202100411

4D-MultiMats

[redacted]

Twining lianas: From role model to a 4D-printed wearable system



Biomimetic approach: (a) *Dioscorea bulbifera*: force generation by twining & stipules, (b) abstraction of functional principles & transfer to computational design methods as basis for multifunctional 4D-printed material systems, (c) Implementation: development of a first working prototype of an orthotic device.

Cheng et al. (2021) Applied Science, 8(13): 2100411 DOI: 10.1002/advs.202100411

livMatS Living, Adaptive and Energy-autonomous Materials Systems Cluster of Excellence

4D-MultiMats

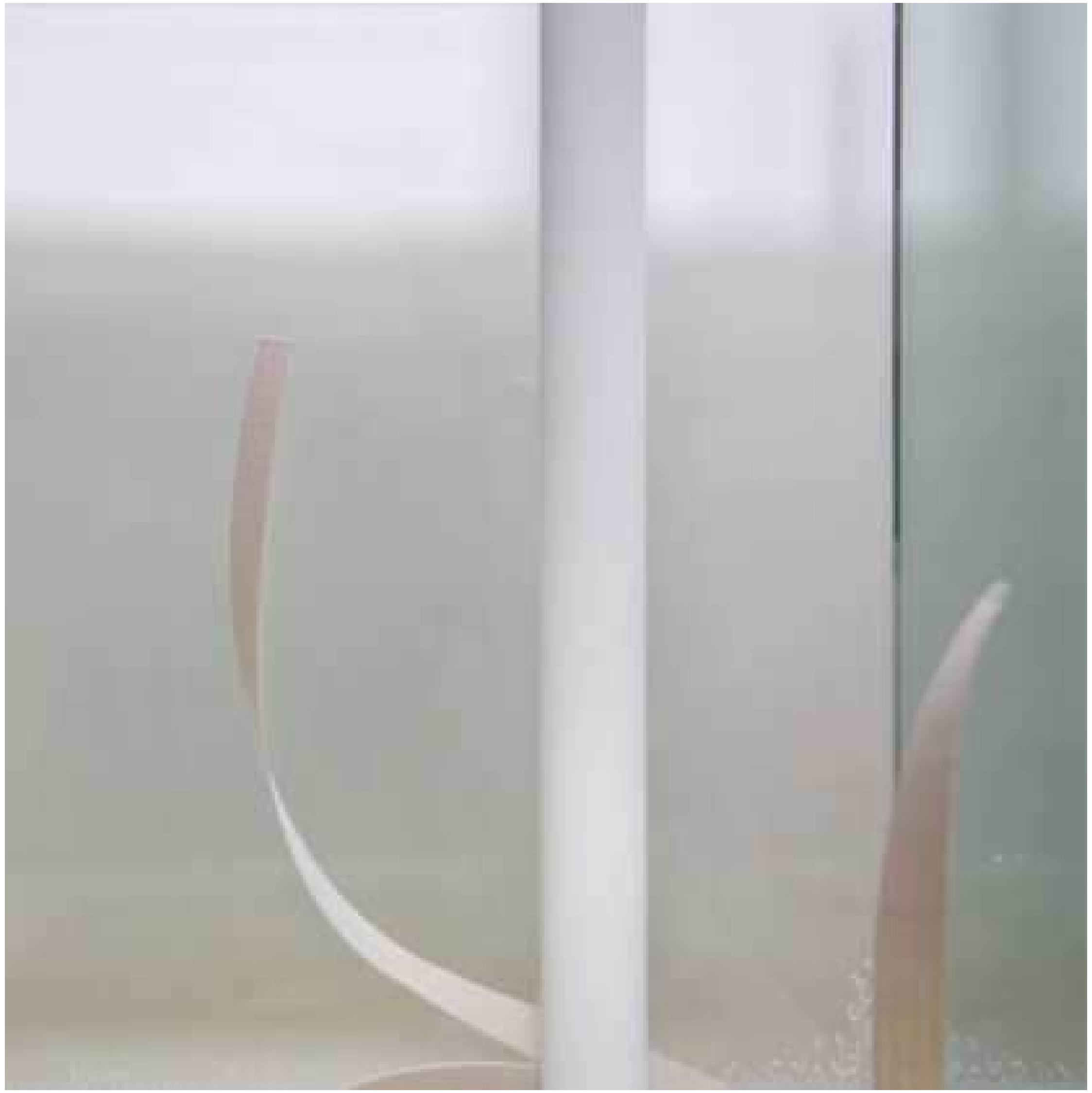
[redacted]

Baden-Württemberg

Twining lianas: From role model to a 4D-printed wearable system

BGF Botanischer Garten Freiburg

UNI FREIBURG

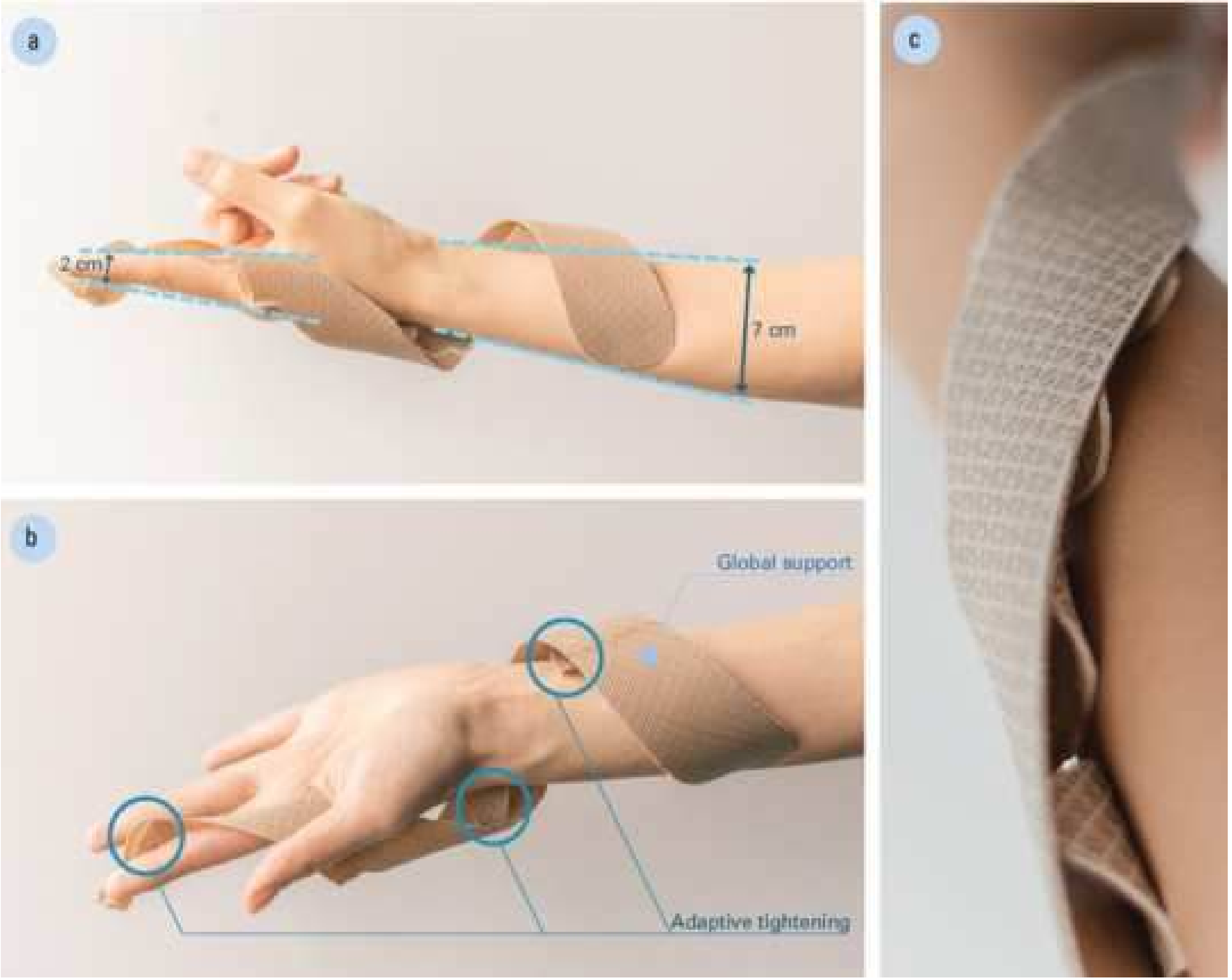


Cheng et al. (2021) Applied Science, 8(13): 2100411 DOI: 10.1002/advs.202100411

livMatS 4D-MultiMats [redacted] Baden-Württemberg

BGF Botanischer Garten Freiburg UNI FREIBURG

Twining lianas: From role model to a 4D-printed wearable system



Prototype of the bioinspired orthotic device: an adaptive wrist-forearm splint

The helix mechanism is designed to wrap the body from forearm to finger.

Serves as primary structure for global support, while the pocket mechanisms self-tighten the structure.

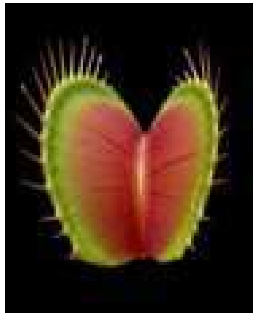
Close-up view of the pocket mechanisms placed at the interface between helix mechanism and skin.

Cheng et al. (2021) Applied Science, 8(13): 2100411 DOI: 10.1002/advs.202100411

How can plant like motions be transferred into soft machines?

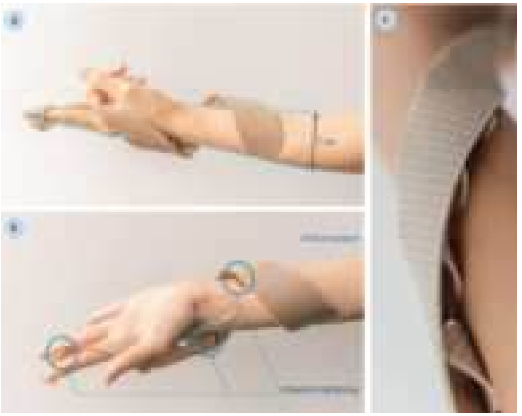
Summary plant inspired systems

Through compliant mechanisms soft systems can be created from hard materials.

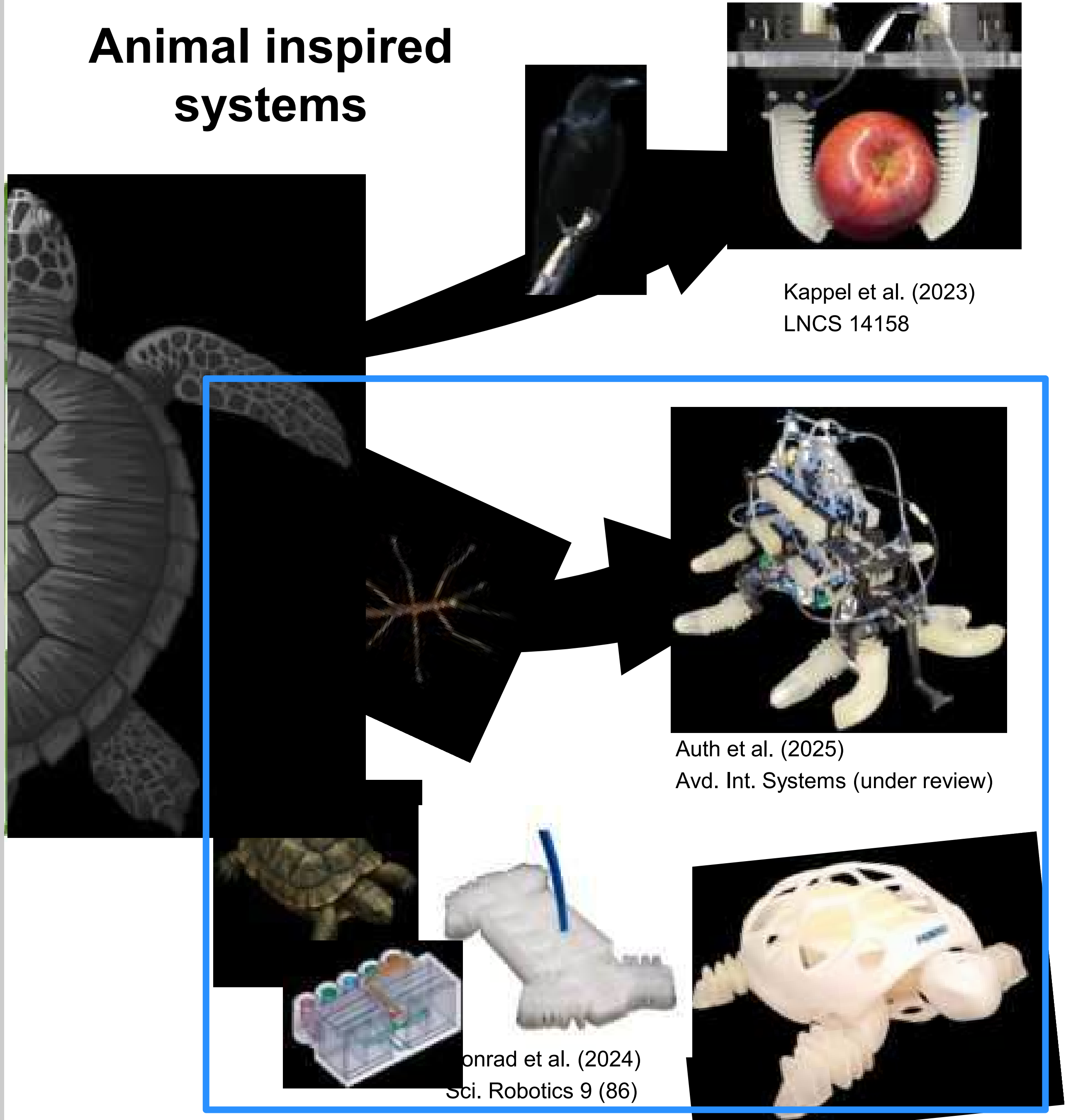


Environmentally responsive systems for building hulls and Architecture shading systems.

Energy free medical devices.



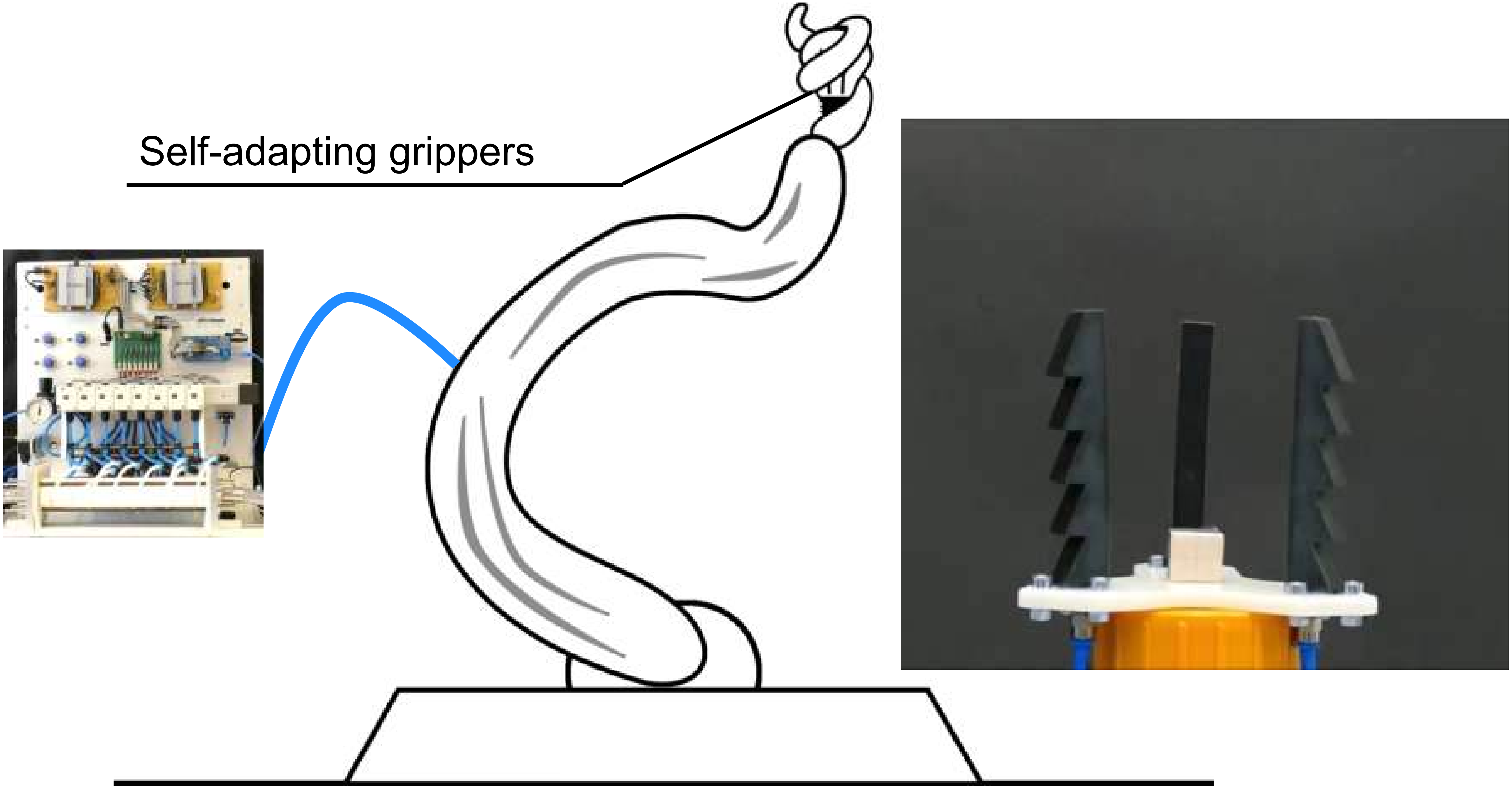
Animal inspired systems

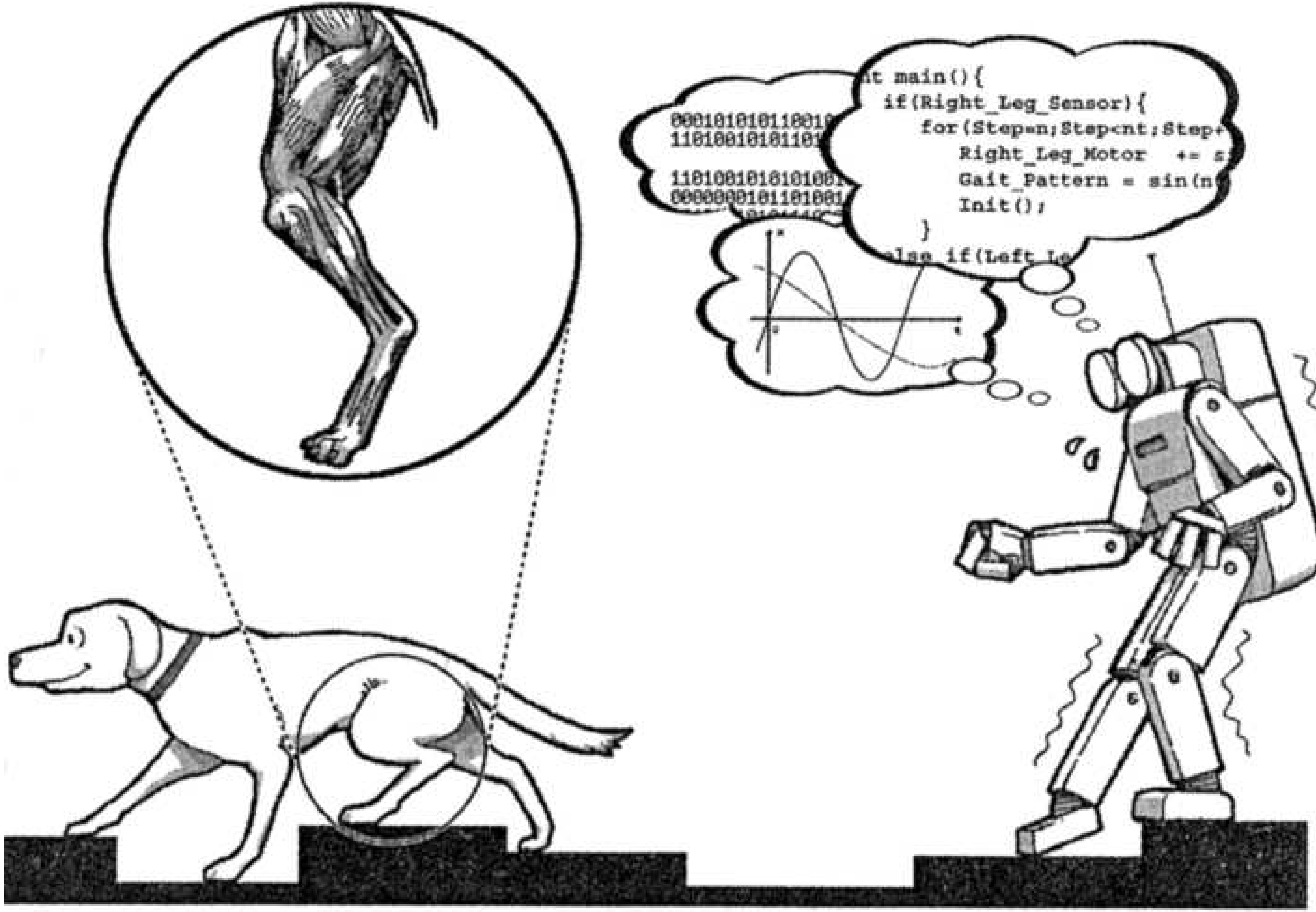


Kappel et al. (2023)
LNCS 14158

Auth et al. (2025)
Avd. Int. Systems (under review)

onrad et al. (2024)
Sci. Robotics 9 (86)


Self-adapting grippers



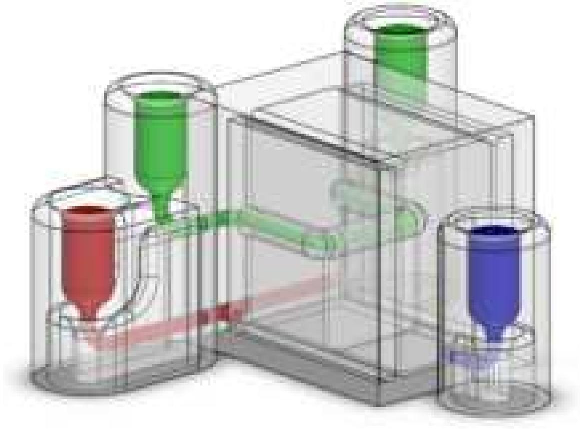
Pfeifer & Bongard (2006) How the Body Shapes the Way We Think. MIT Press.

How can we built entirely electronic free autonomous soft robots?

OR

How can the kinking of a tube control a soft robot?

Electronic free control systems



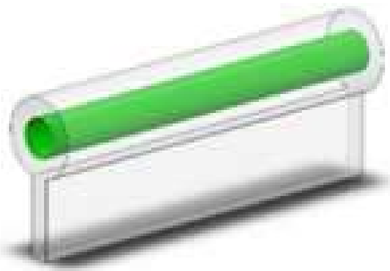
3D printed pneumatic logic gates

NOT, AND, OR gates to create control circuits

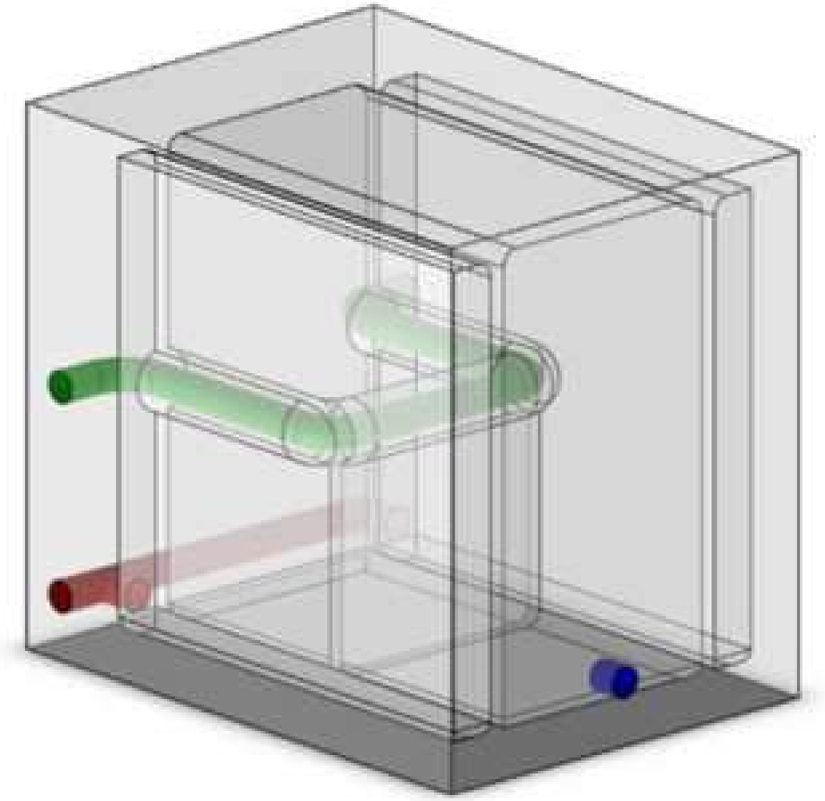
Enable complex motion without complex control

Conrad et al. (2024) Science robotics 9 (86) eadh4060

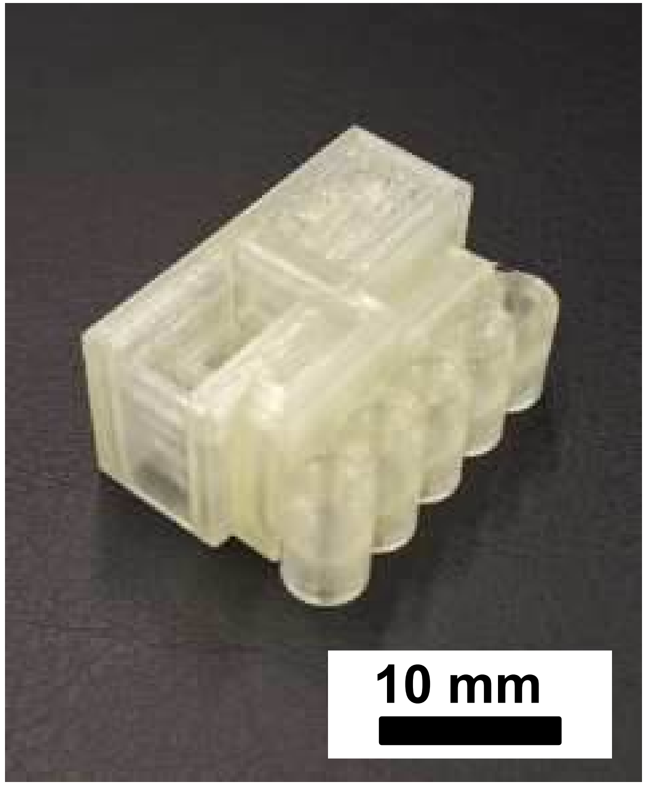
3D printed pneumatic transistors



Bendable round 1 mm channel

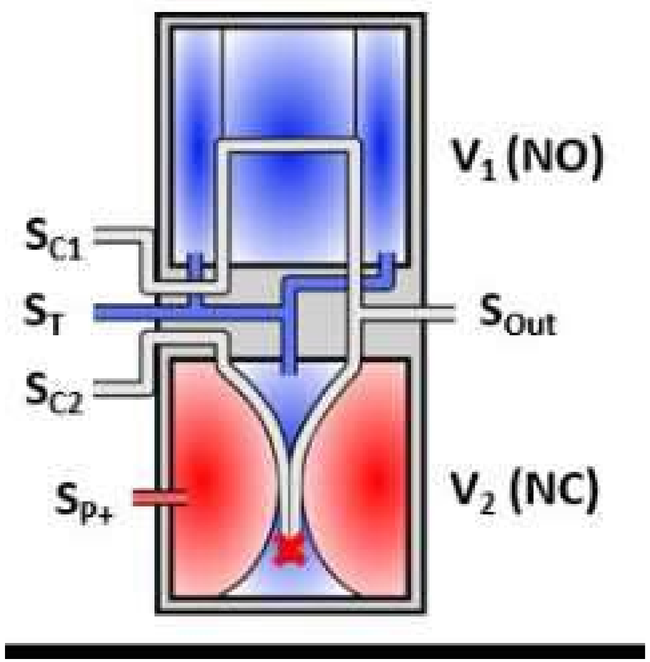


Bendable channel leading through multi-chamber system



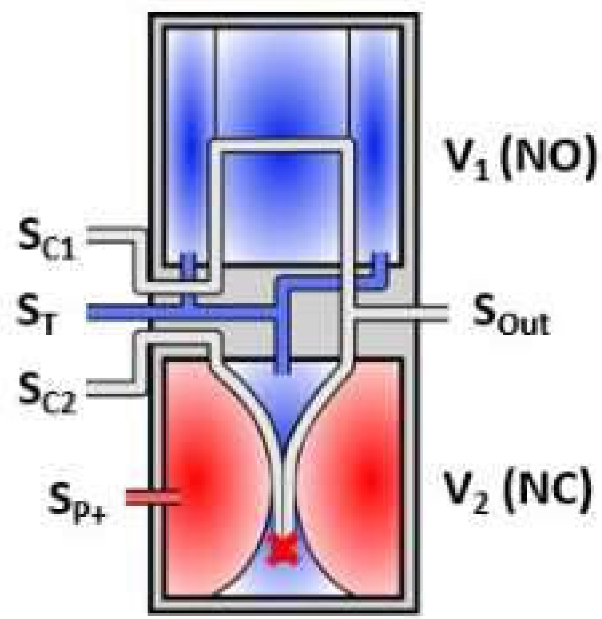
Conrad et al. (2024) Science robotics 9 (86) eadh4060

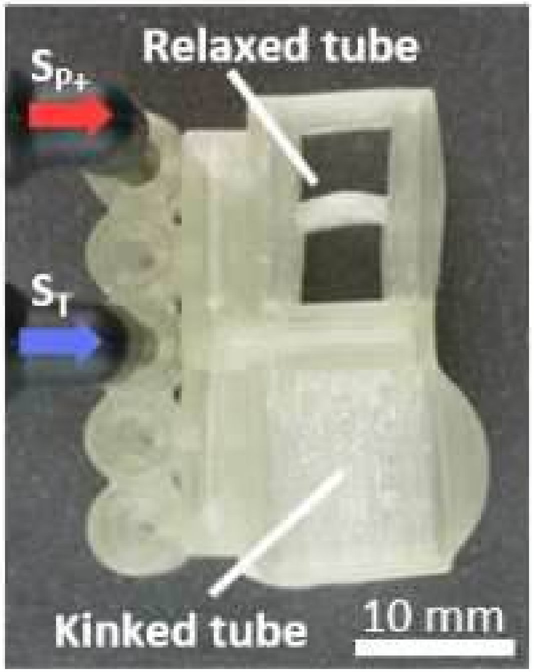
3D printed pneumatic logic gates



Conrad et al. (2024) Science robotics 9 (86) eadh4060

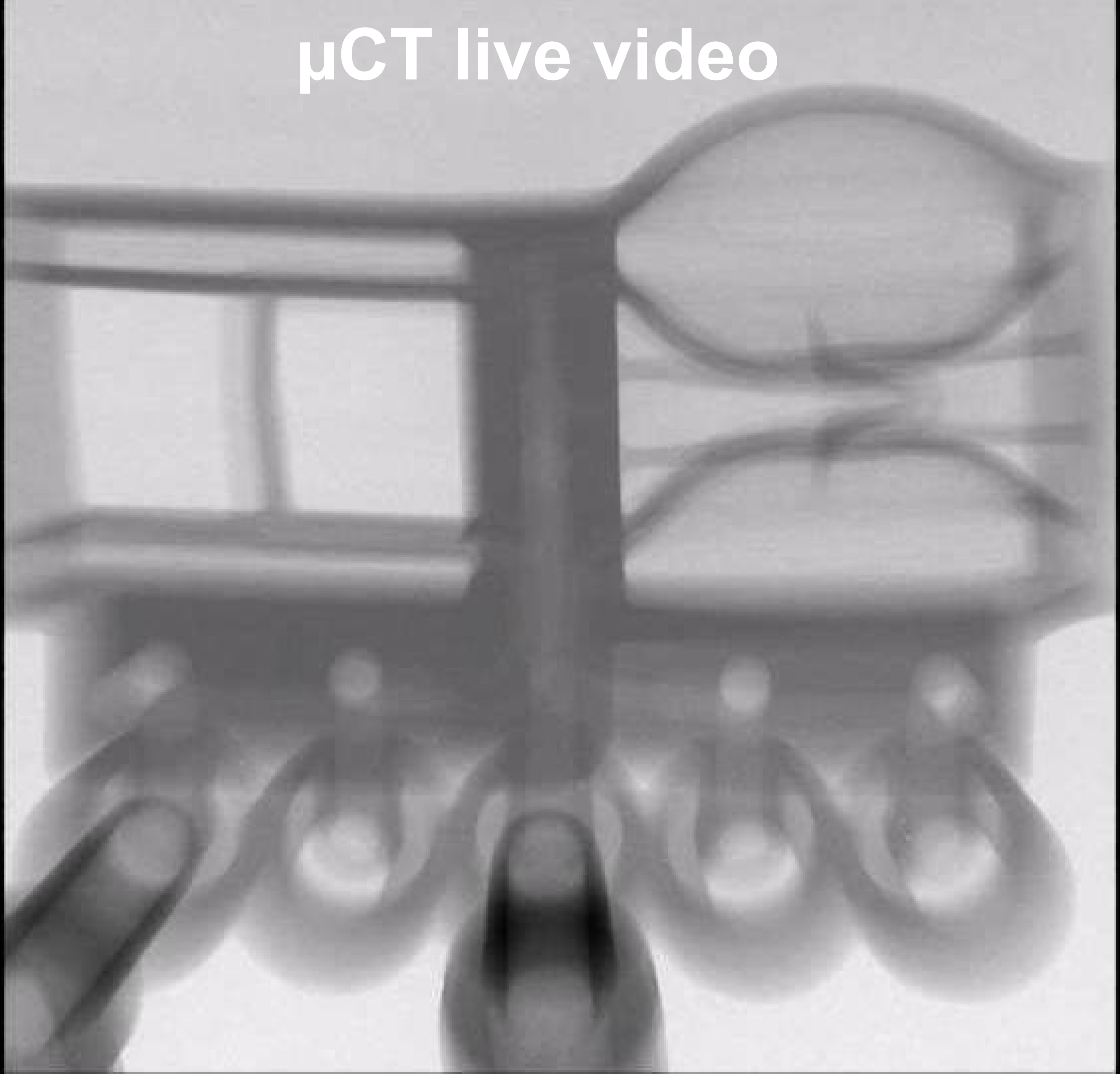
3D printed pneumatic logic gates



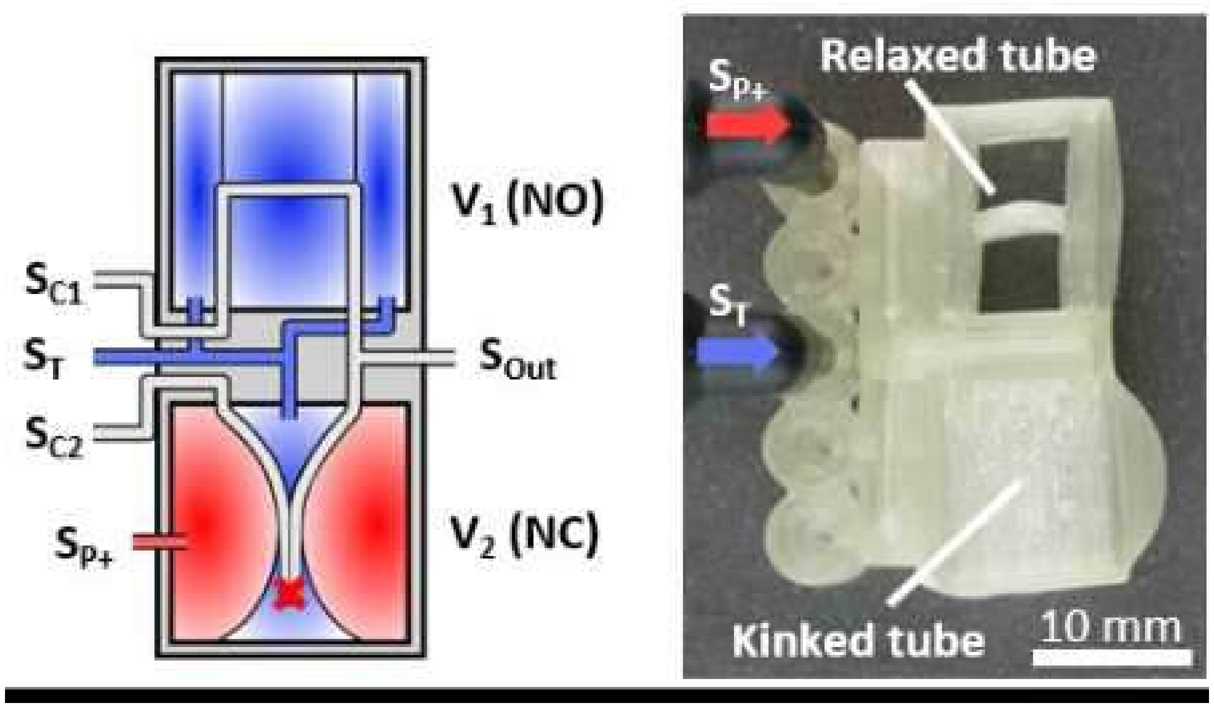


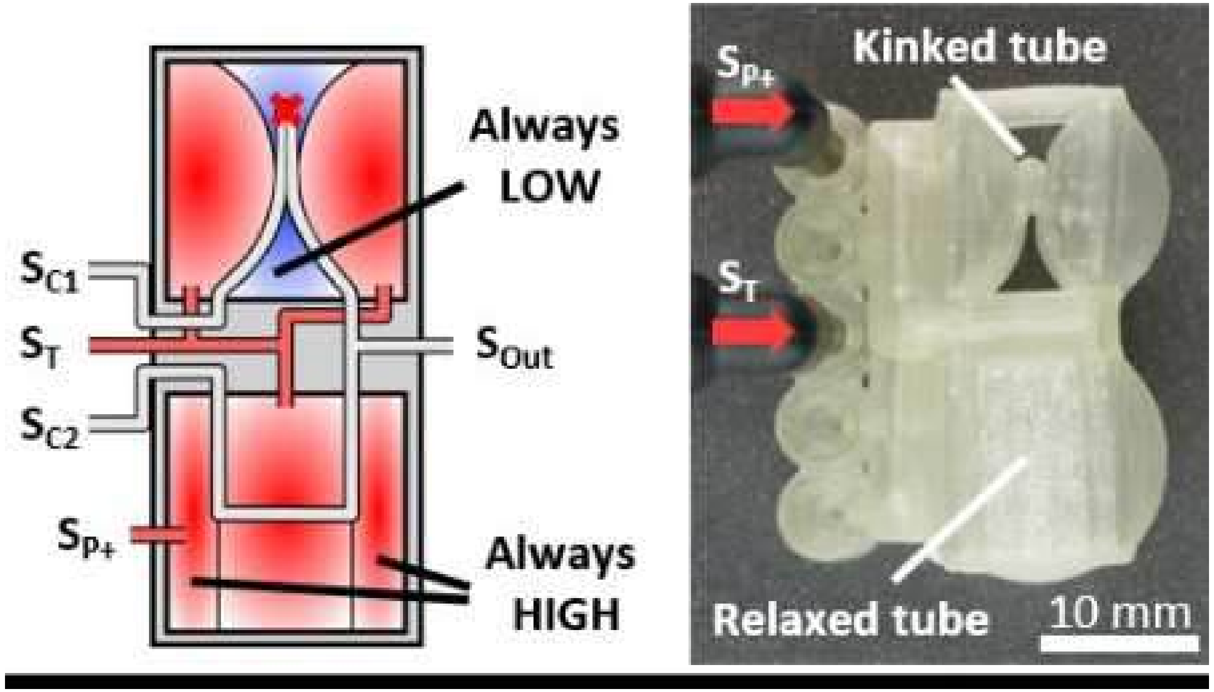
Conrad et al. (2024) Science robotics 9 (86) eadh4060

µCT live video

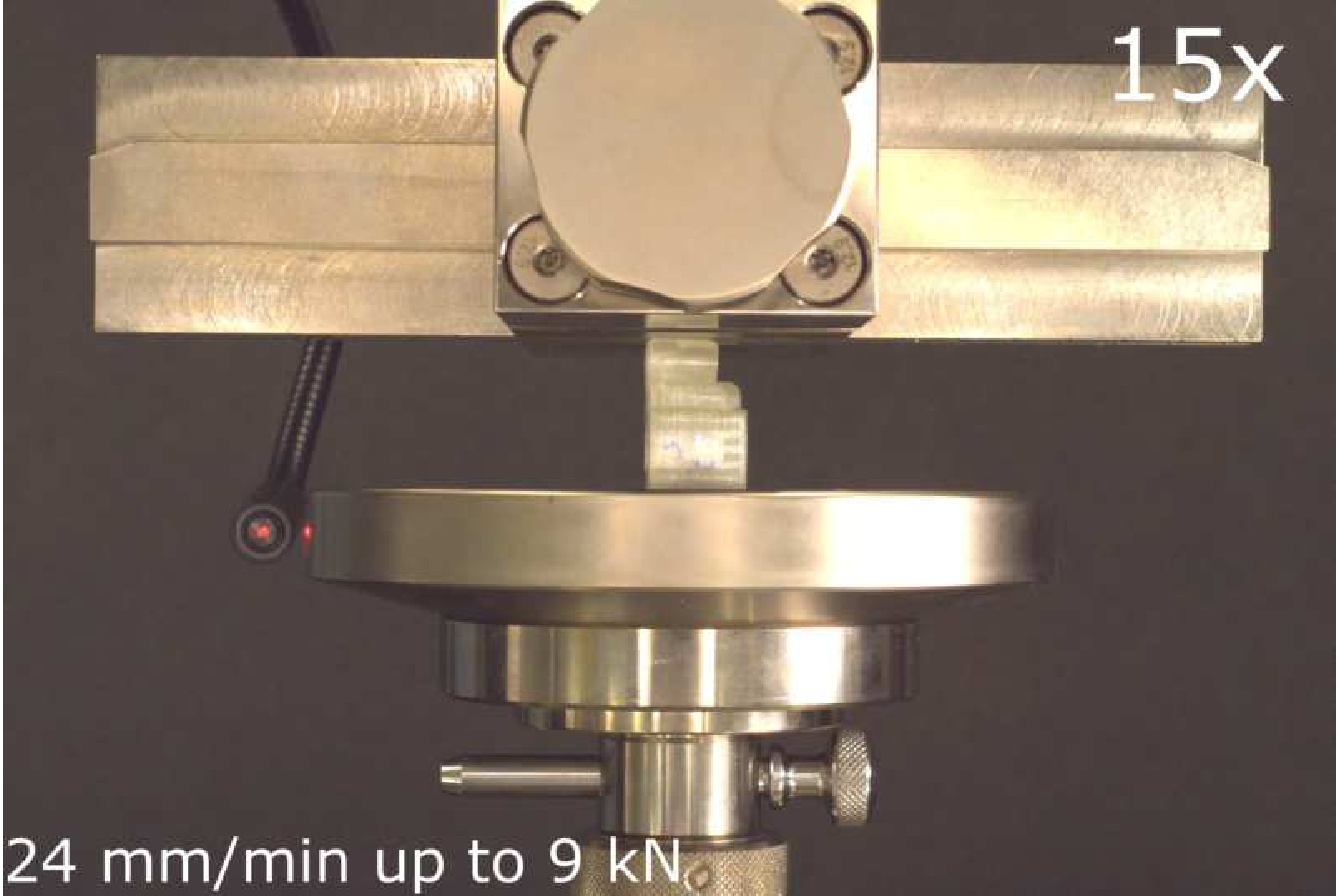


3D printed pneumatic logic gates



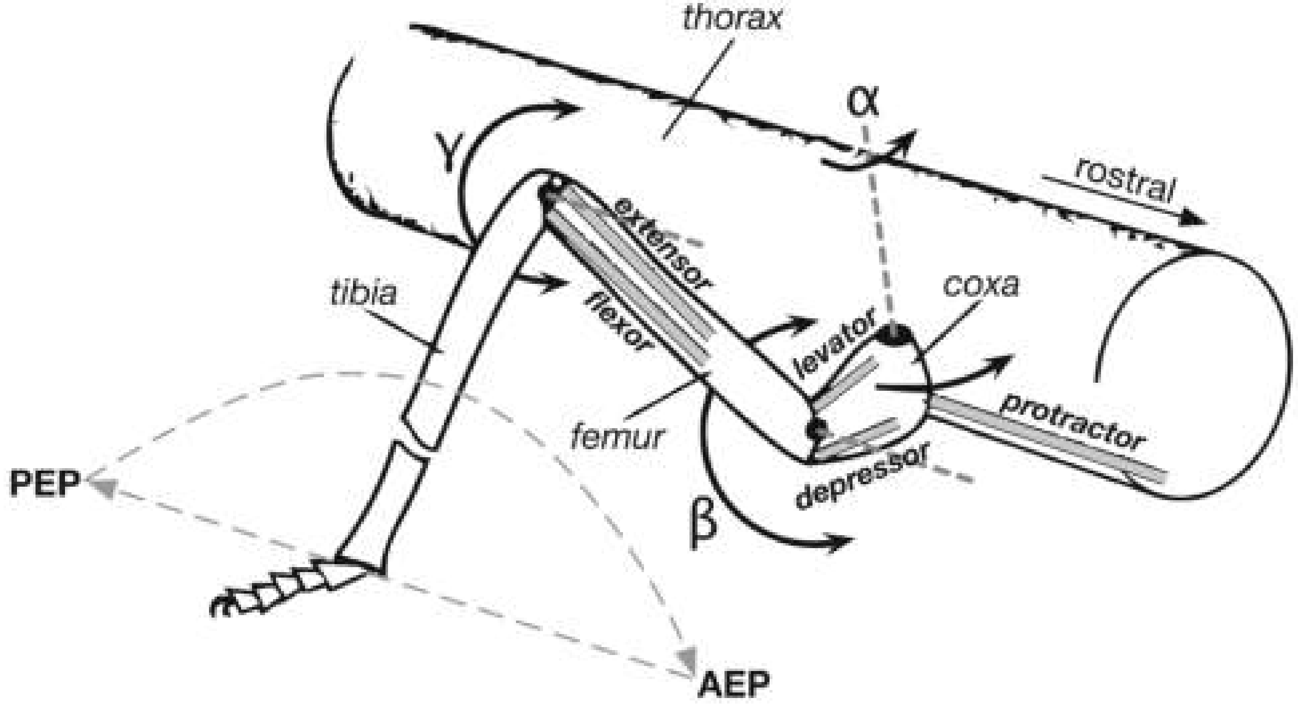


Conrad et al. (2024) Science robotics 9 (86) eadh4060


15x
24 mm/min up to 9 kN

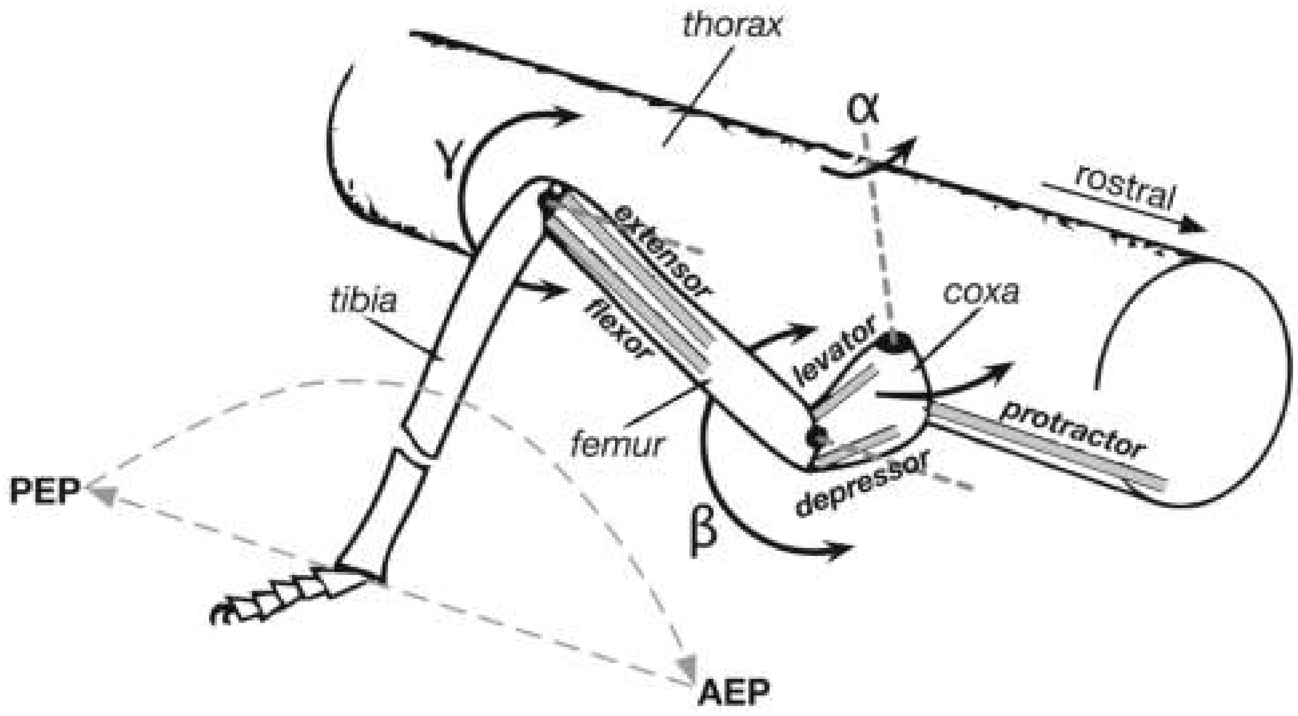
Create complex motion without complex control…

Walk like a stick insect

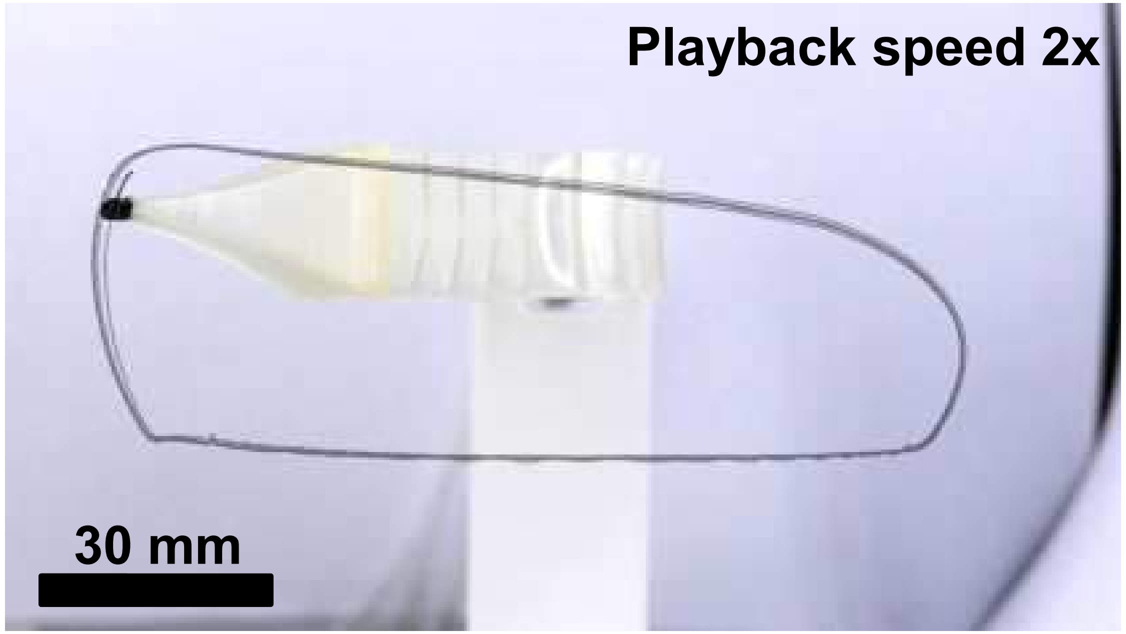


Cruse et al. (2007) Philos. Trans. A Math. Phys. Eng. Sci. 365

Walk like a stick insect

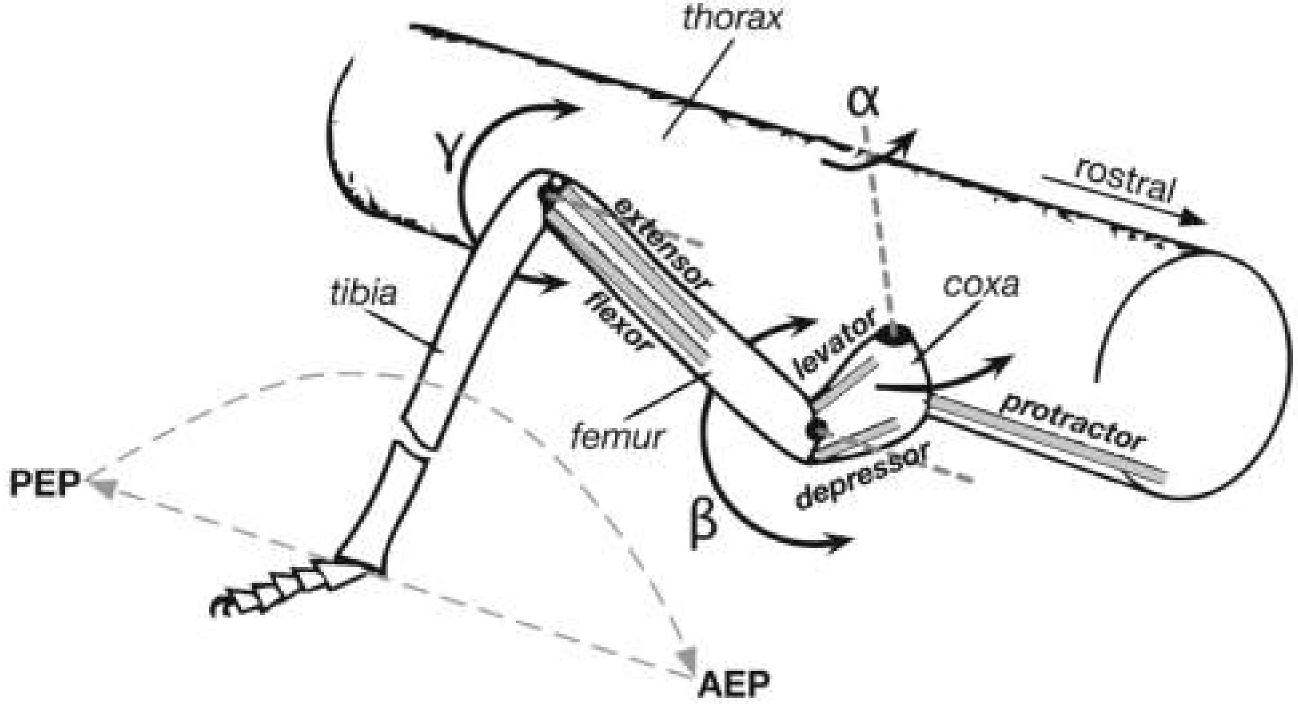


Cruse et al. (2007) Philos. Trans. A Math. Phys. Eng. Sci. 365



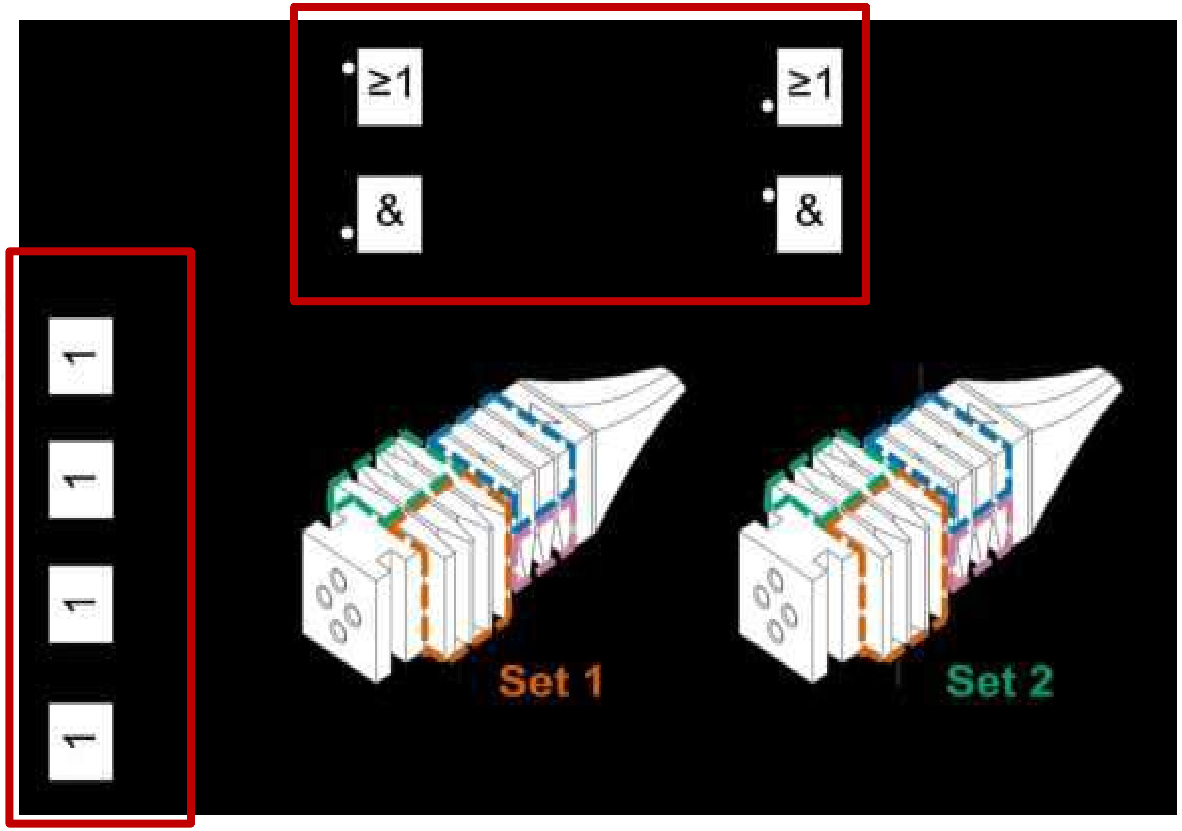
Teichmann et al. (2023) Biomimetic and Biohybrid Systems, LNAI 14157

Walk like a stick insect



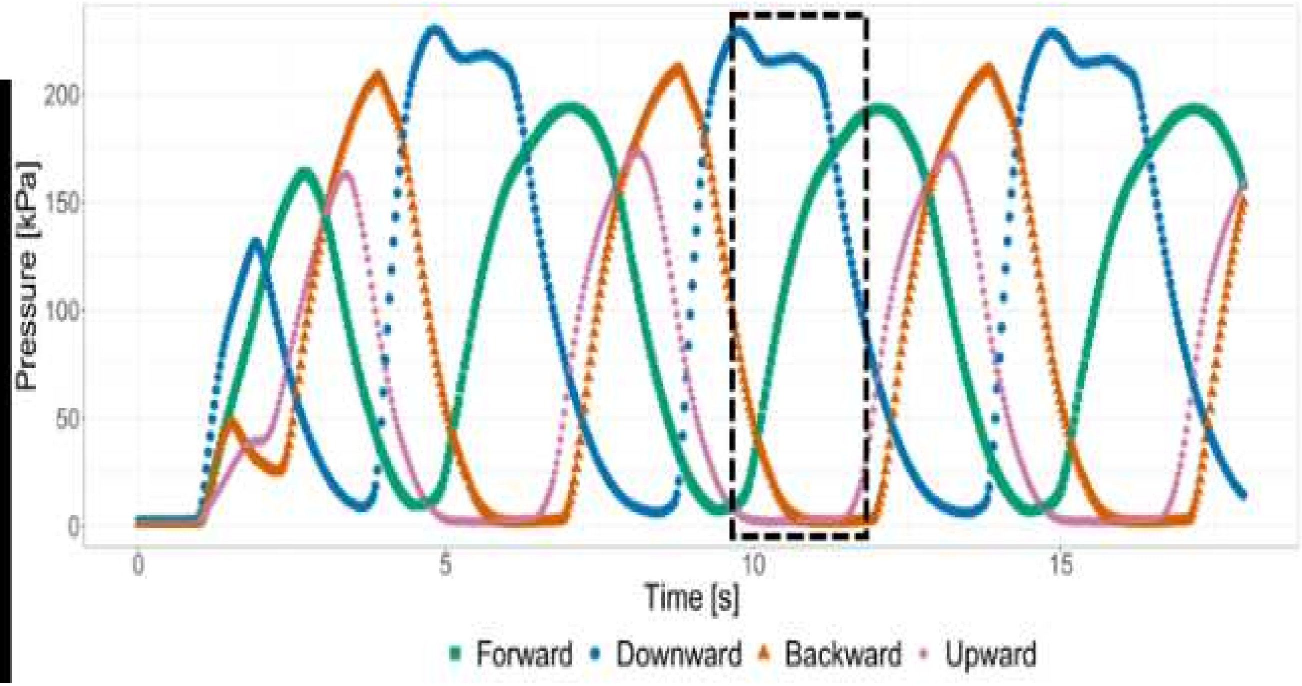
Cruse et al. (2007) Philos. Trans. A Math. Phys. Eng. Sci. 365

Signal Adjuster

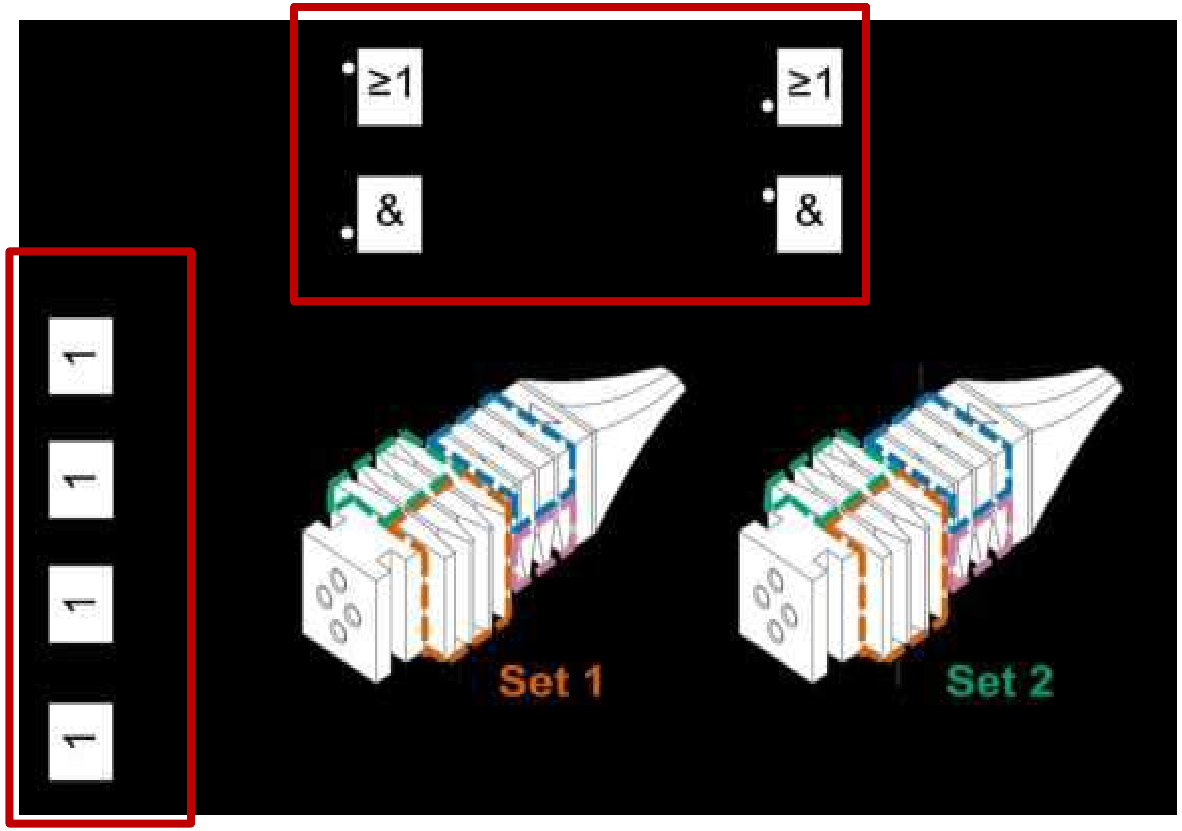


Oscillator

Walk like a stick insect



Signal Adjuster

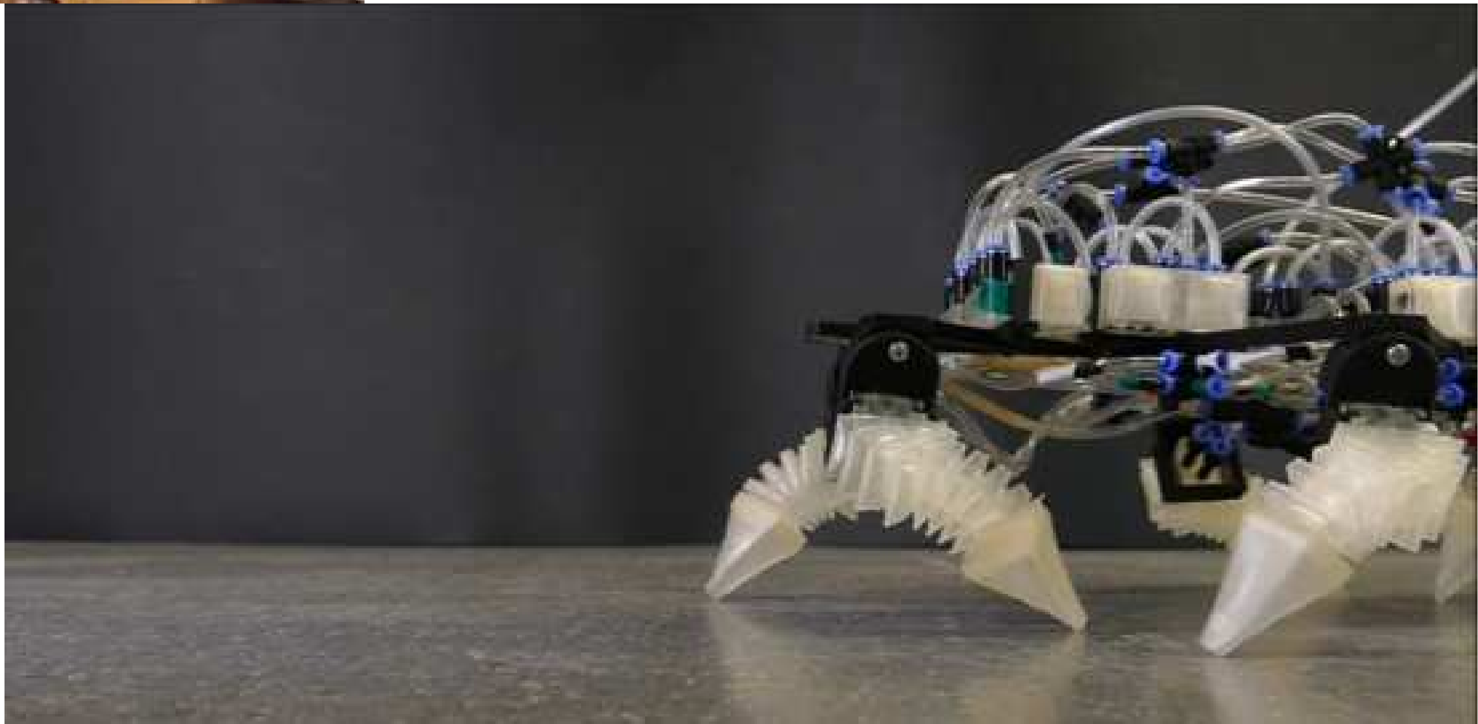


Oscillator


0.16 BLs/s or 0.06 m/s
at 10 l/min & 225 kPa

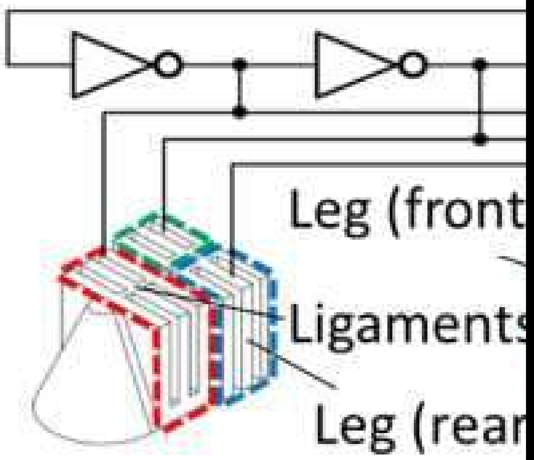
Motion principle

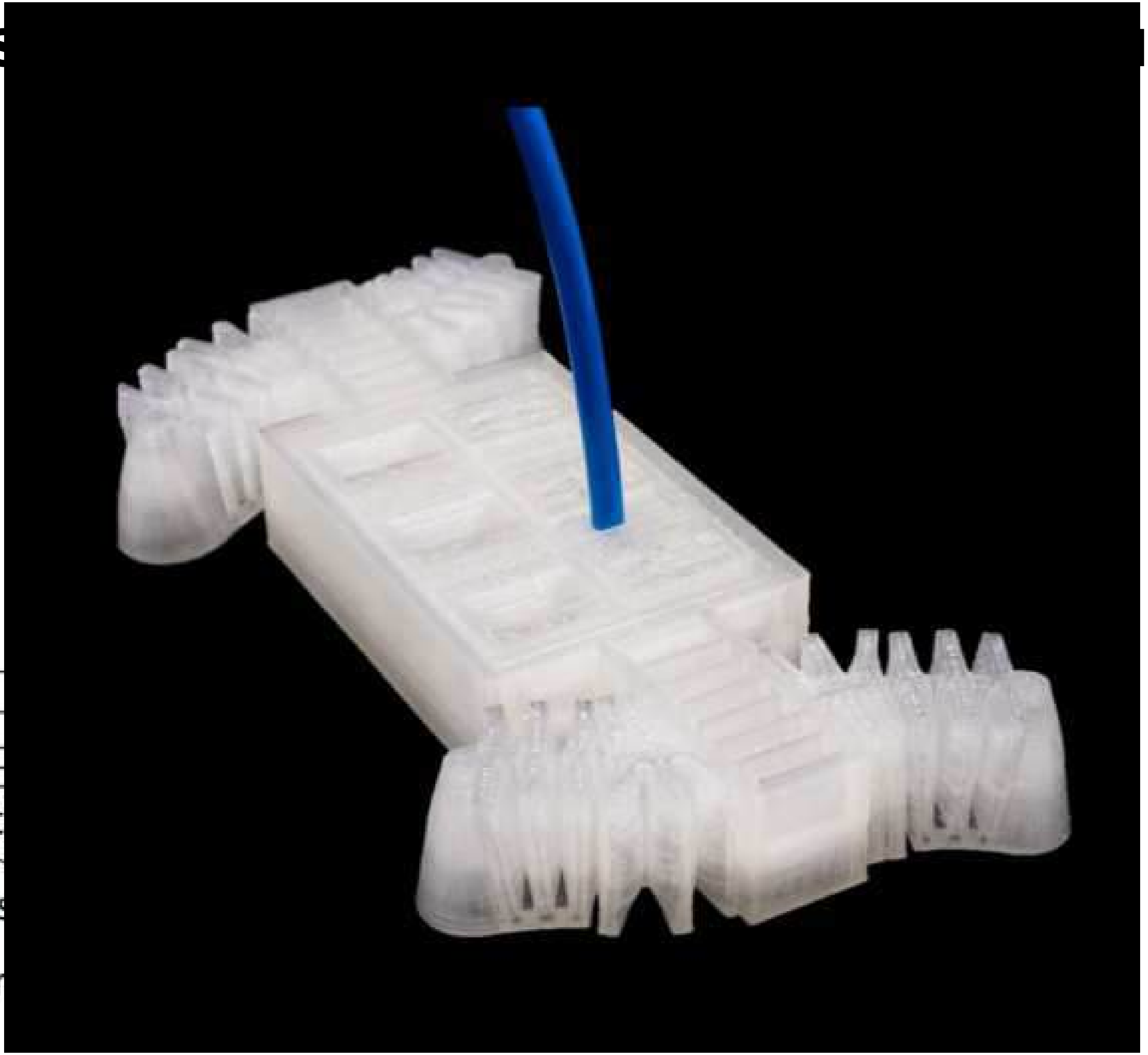
Transfer



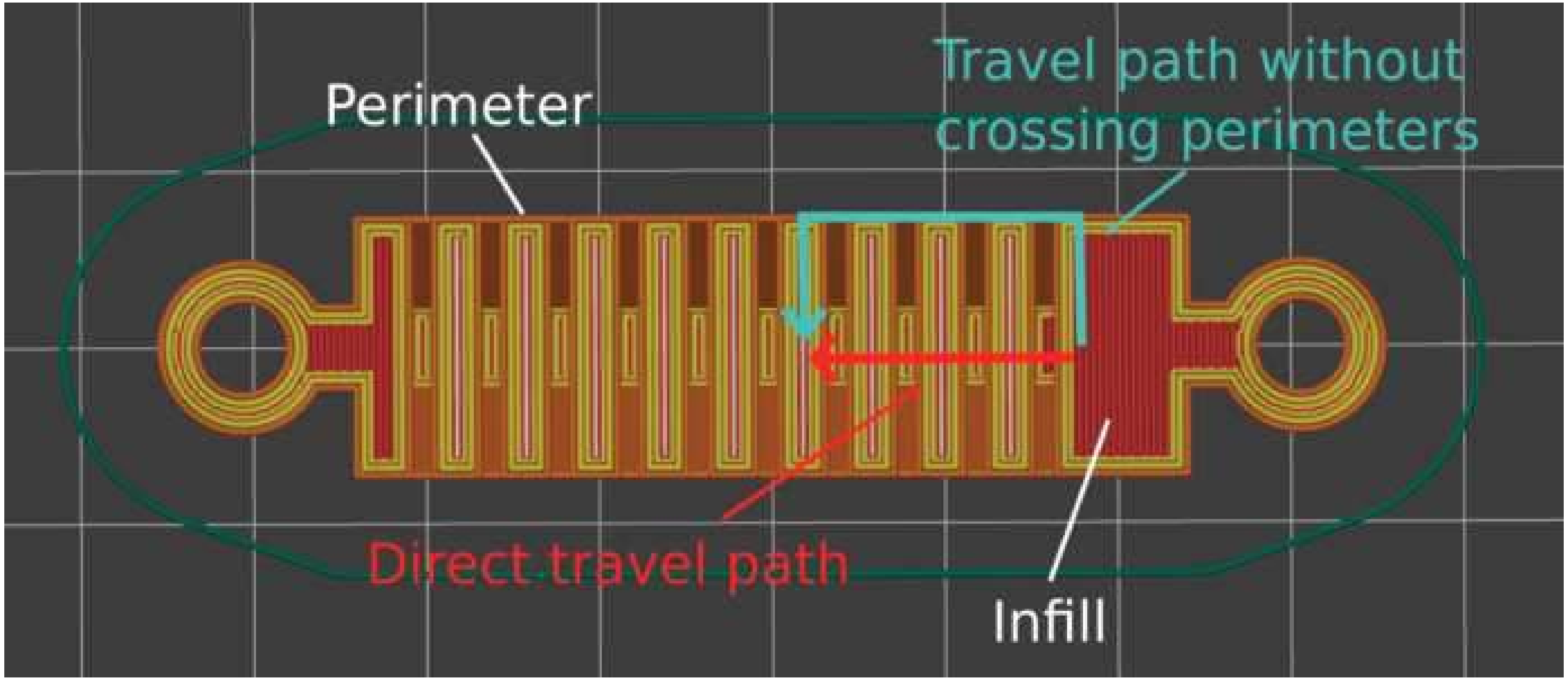
Motion

Fully s it



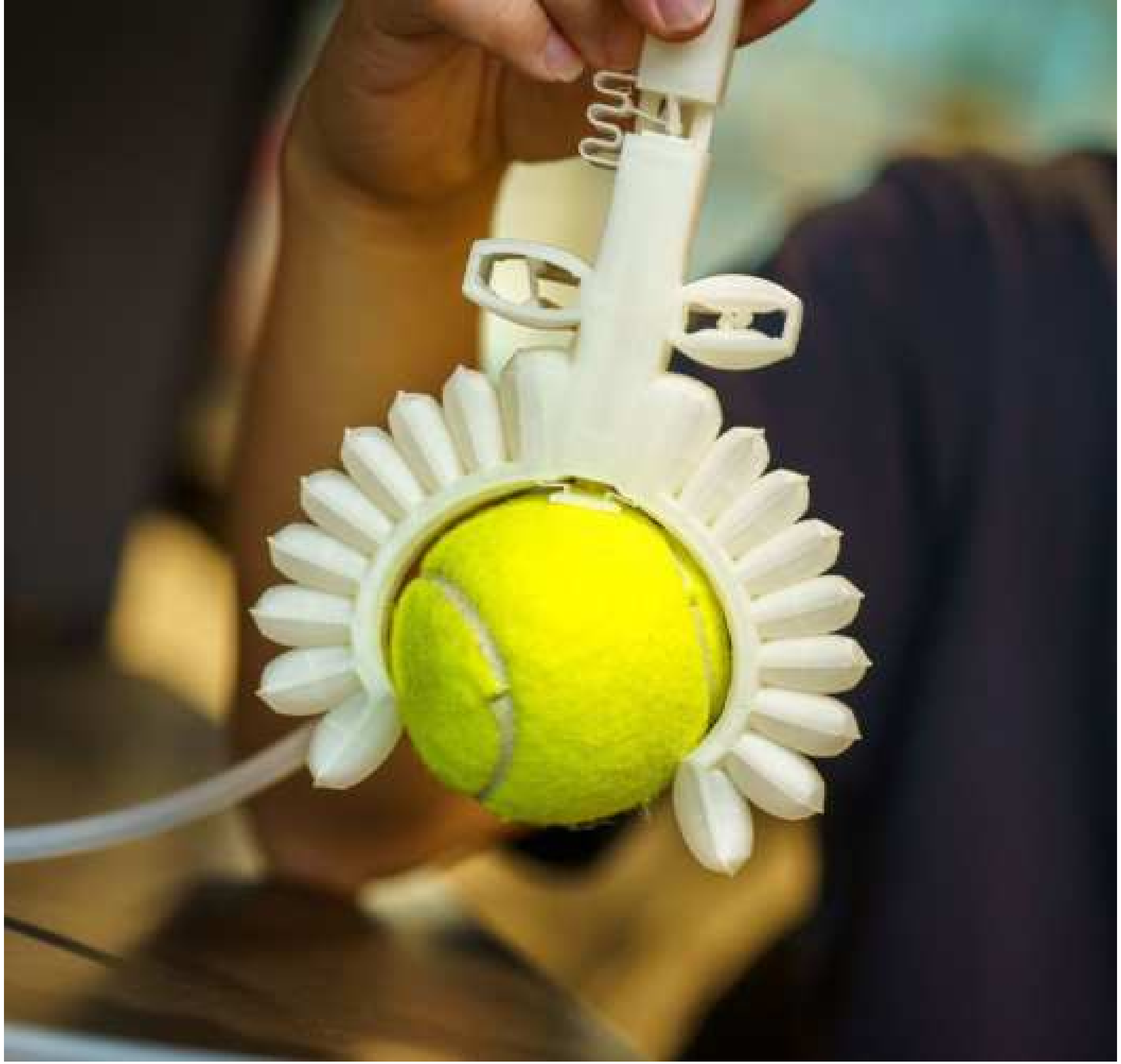


How do you print this?



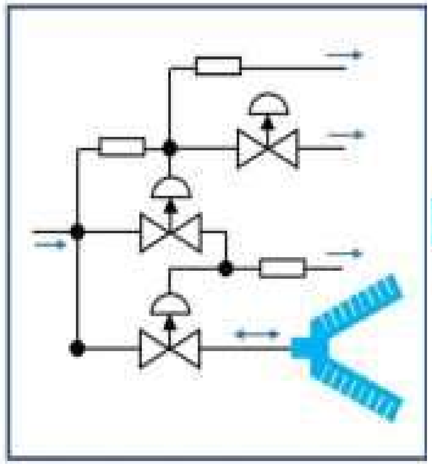
One continous print path for airtight structures

Conrad et al. (2021) Bioinspiration and Biomimetics 16 (5)

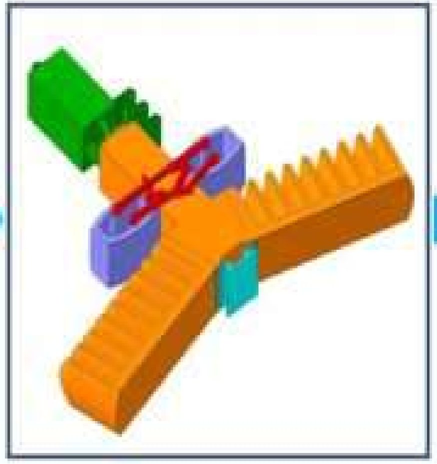


Bioinspired Robotics and Design Lab

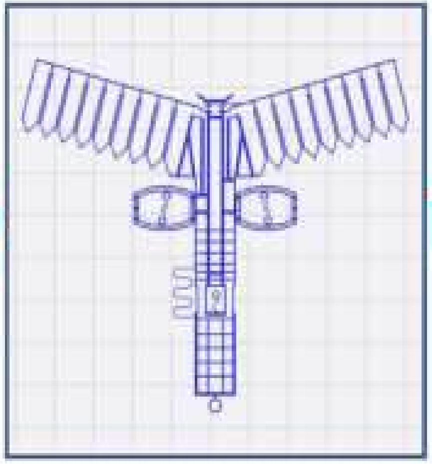
Zhai et al. (2023) Science Robotics 8 (79)



1. Conceptual design of soft robot and control circuit



2. Combination into a single design

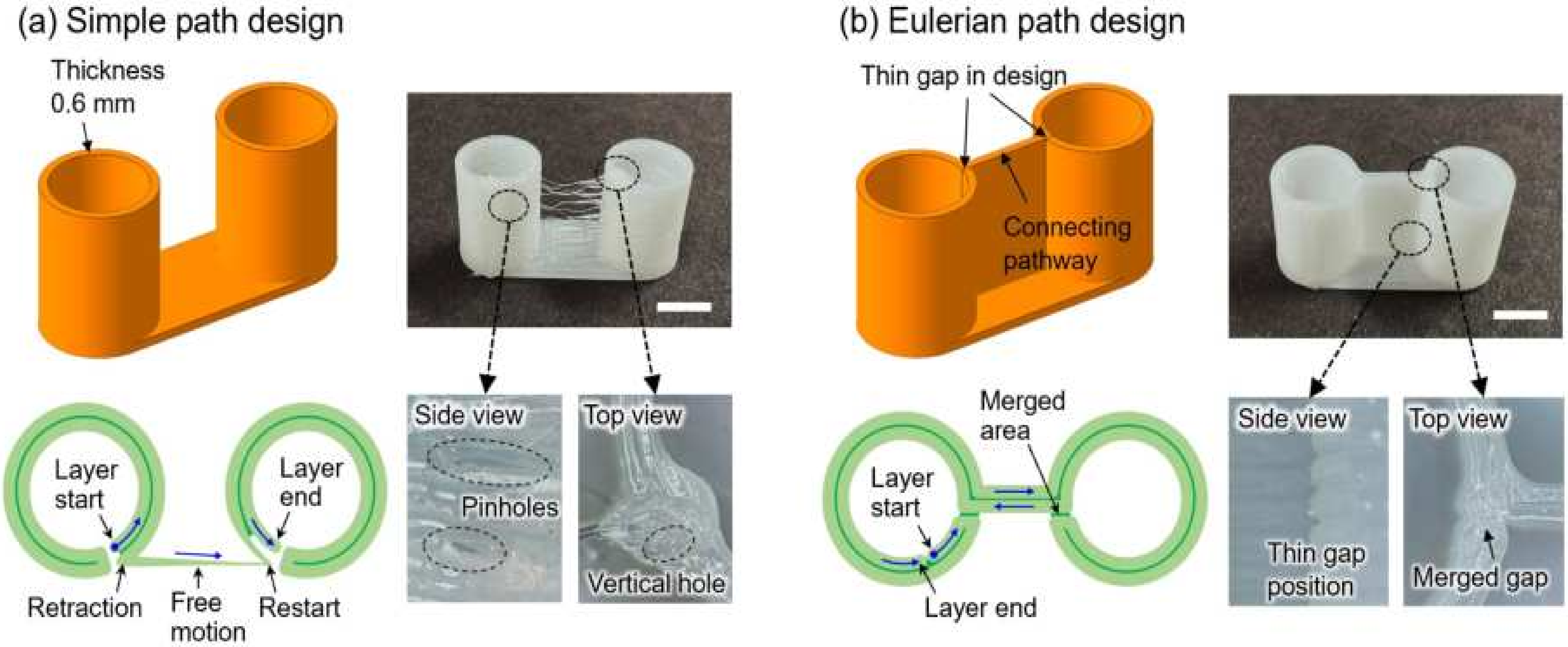


3. Generation of toolpath for airtight structures

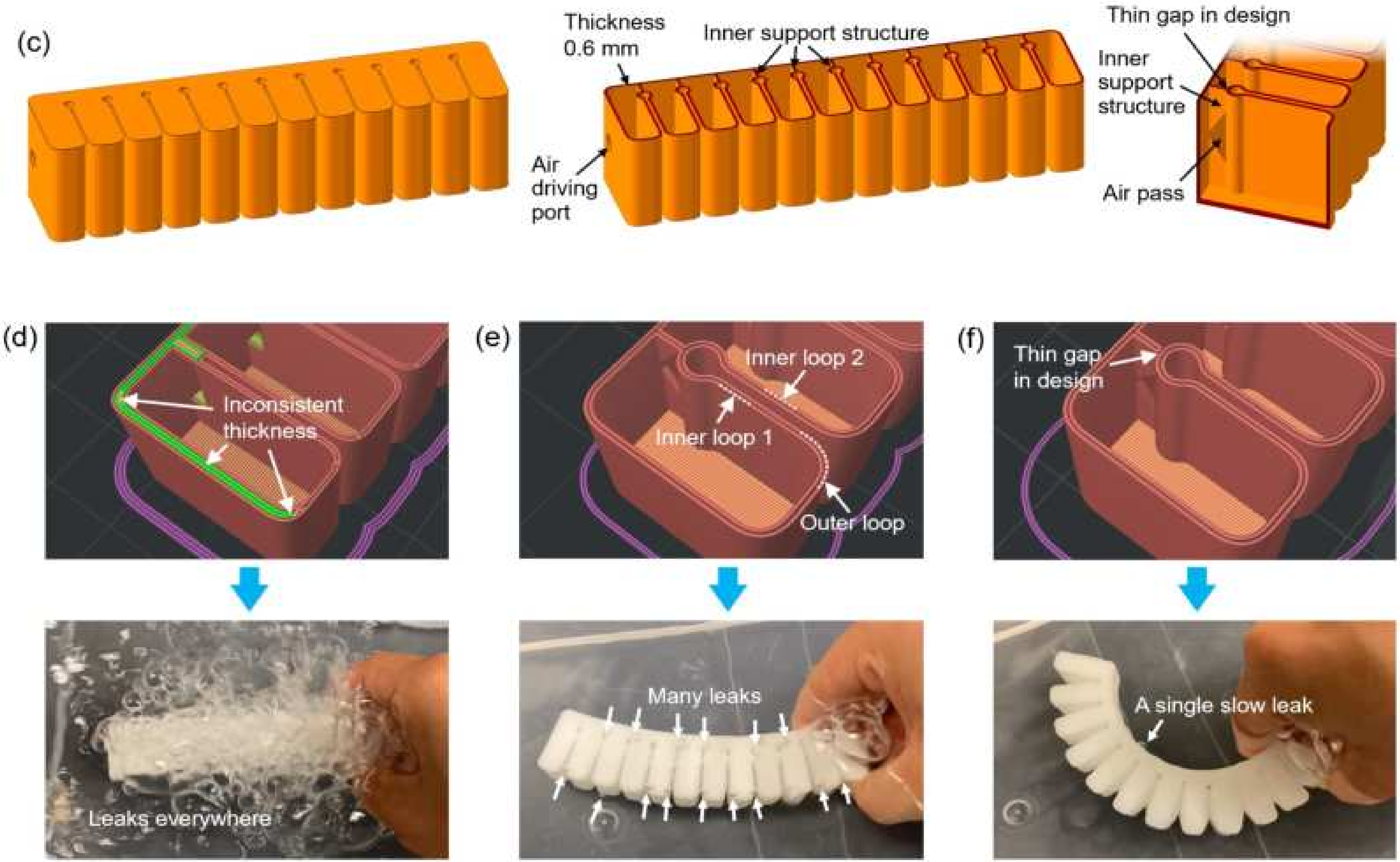
4. Printing of monolithic device

5. Electronics-free operation

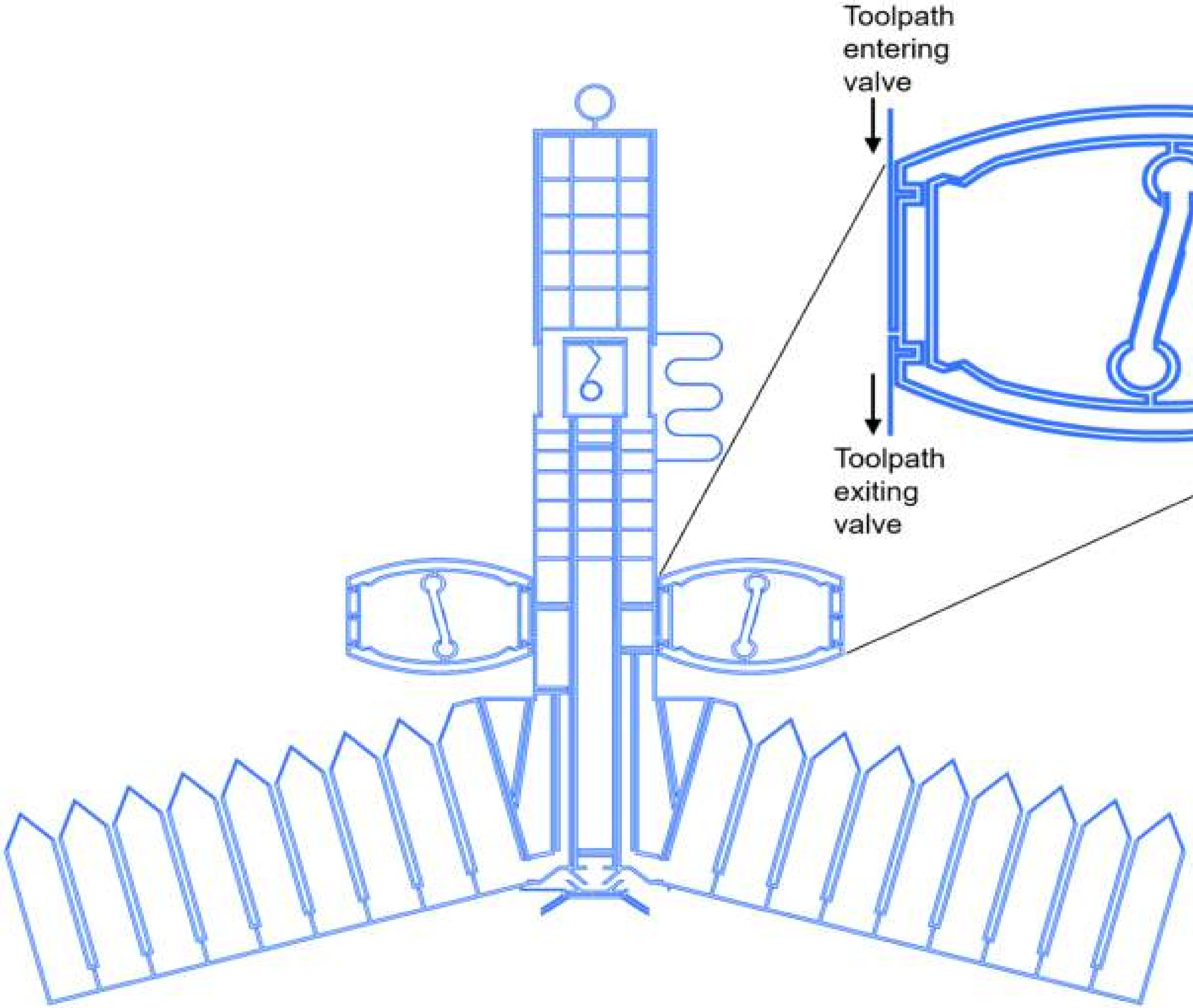
Zhai et al. (2023) Science Robotics 8 (79)



Zhai et al. (2023) Science Robotics 8 (79)



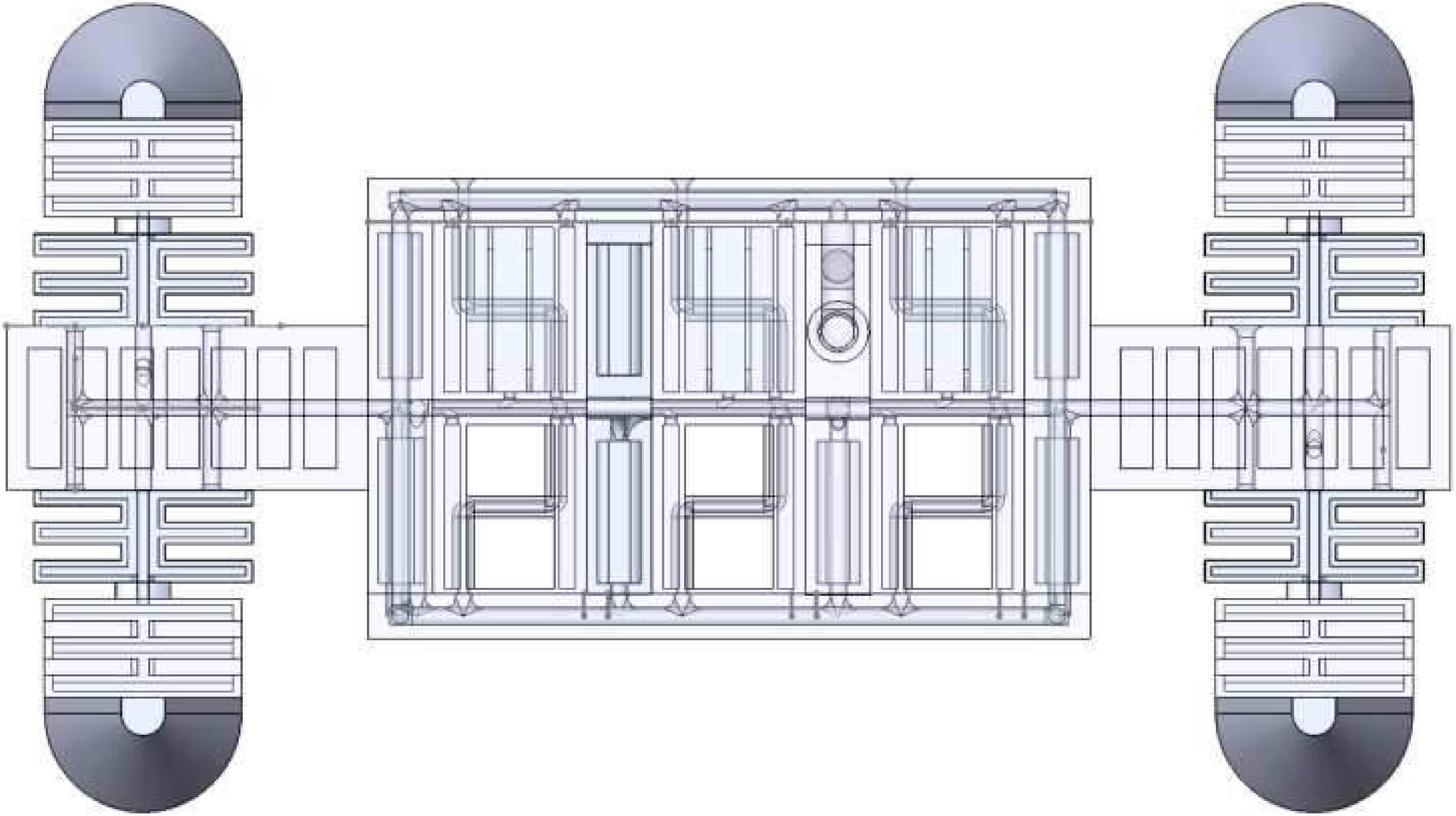
Zhai et al. (2023) Science Robotics 8 (79)



Designed bottom/top solid infill thickness	0.8-1.0 mm	
Designed vertical wall thickness	0.6 mm	
Actual printed vertical wall thickness	0.8 mm	
Layer of vertical walls	2	
Line width (nozzle size)	0.3 mm	
Layer height	0.1 mm	
Printing speed	25 mm/s everywhere	
Nozzle temperature and cooling fan power	layer 1 230°C 0% fan	≥layer 7 235°C 40% fan
Global flow rate multiplier	135%	
Solid infill line width multiplier	85%	
Solid infill flow rate multiplier	79%	

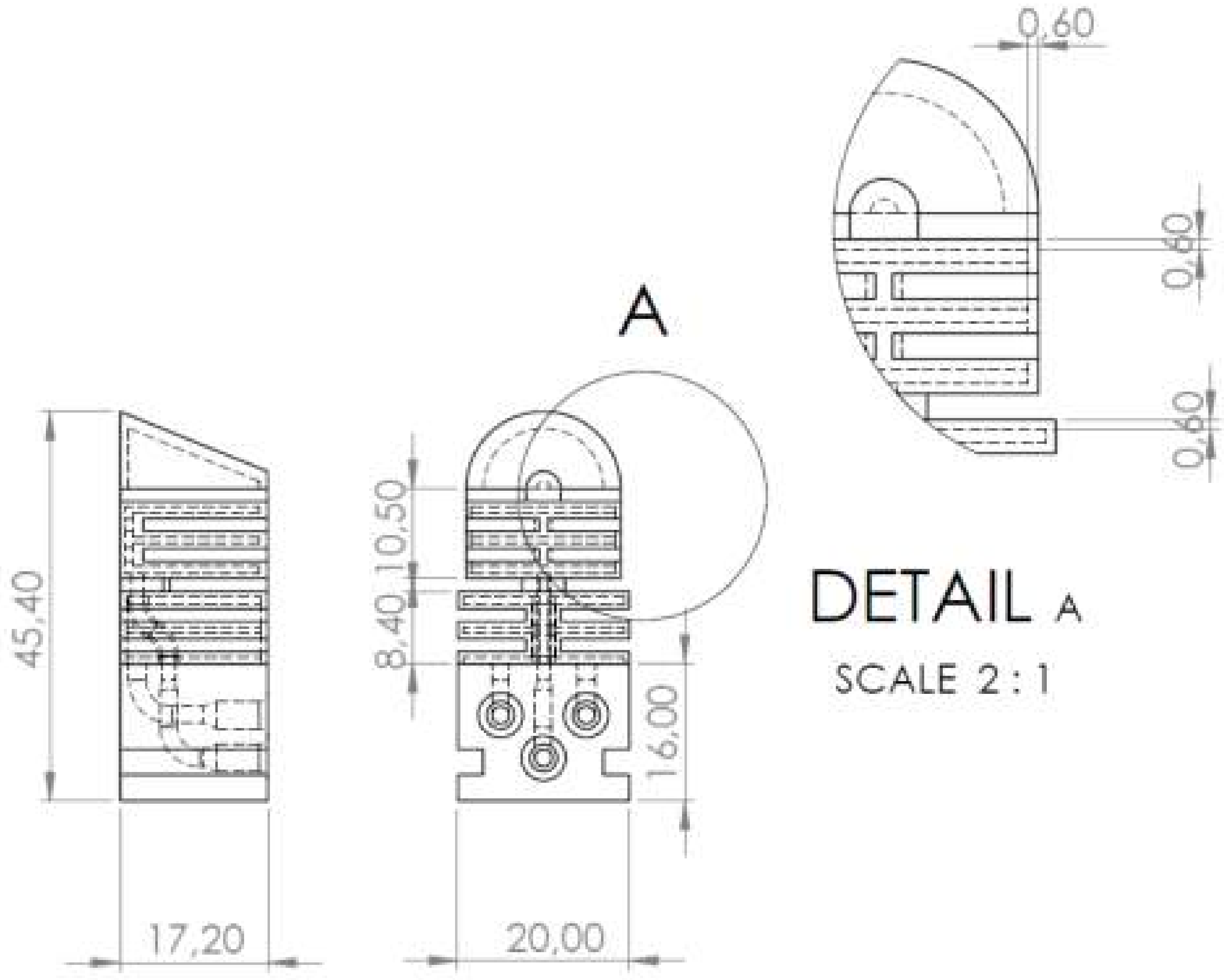
Zhai et al. (2023) Science Robotics 8 (79)

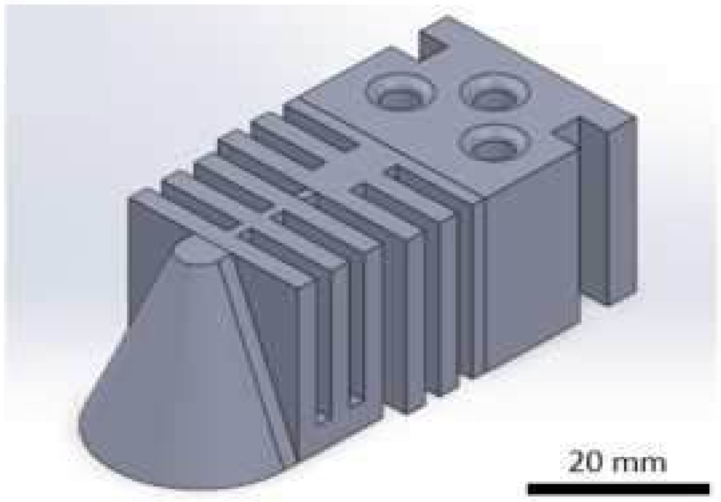
Design requirements



Conrad et al. (2024) Science robotics 9 (86) eadh4060

Design requirements



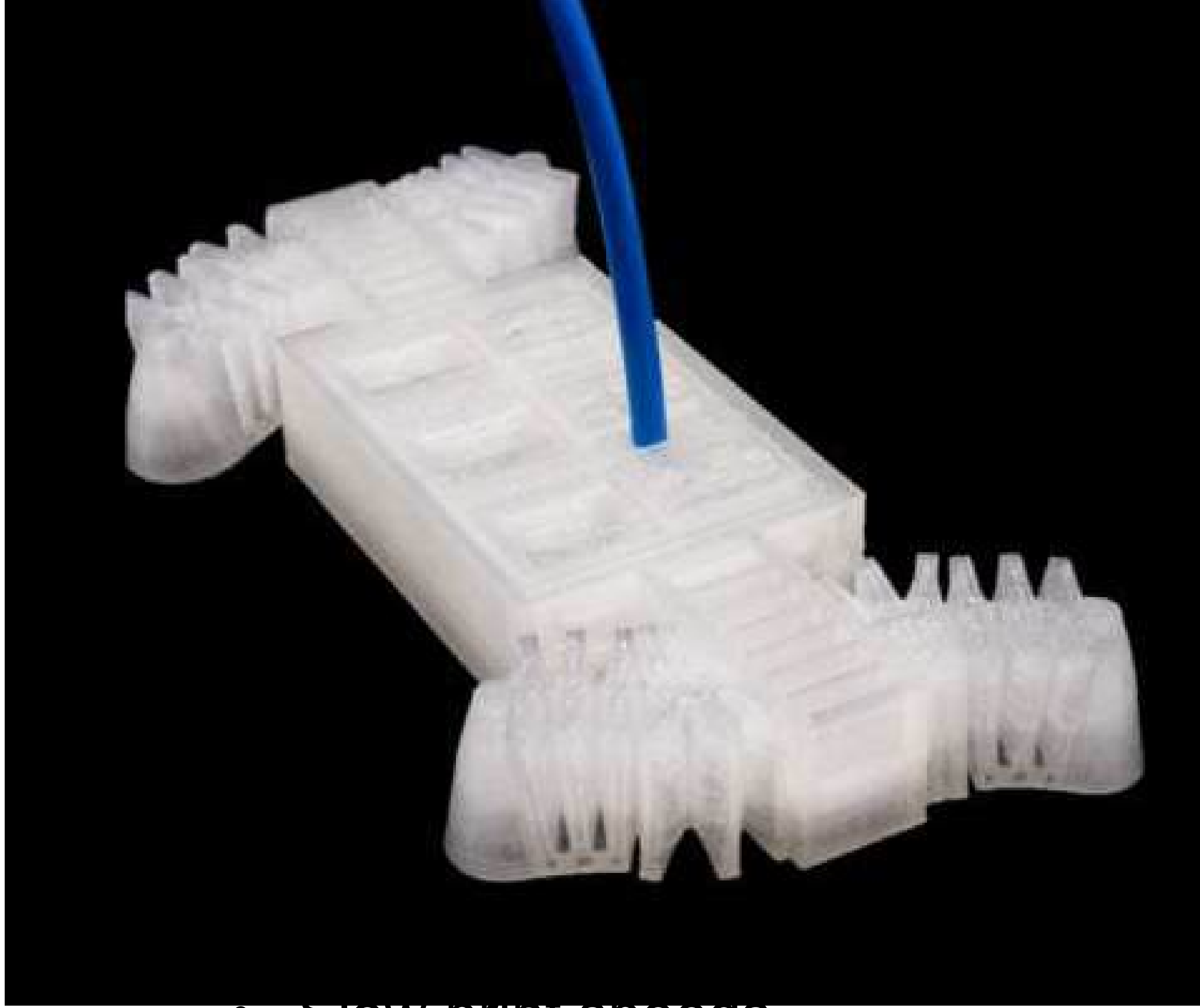


- Thin walls: 0.6 mm per membrane
- One continuous line, avoid crossing parameters

Conrad et al. (2024) Science robotics 9 (86) eadh4060

Print settings

Parameters	Value
Nozzle diameter	0.3 mm
Print temperature	220 °C
Bed temperature	60 °C
Part cooling	0 %
Layer height	0.1 mm
Perimeters	2
Top/bottom layers	10
Infill density	95 %
Print speed	10 mm/s
Infill-perimeter overlap	25 %
Extrusion multiplier perimeters	115 %
Extrusion multiplier infill	100 %
Extrusion multiplier bridge	80 %



- Slow print speeds
- Dry material

Conrad et al. (2024) Science robotics 9 (86) eadh4060

Material drying

TPU printing

- Highly hygroscopic material
- Up to 6h storage in an oven at 60° C
- At least 1-2h before printing
- Print from filaments dryer
- Dryers have settings for flexmaterials

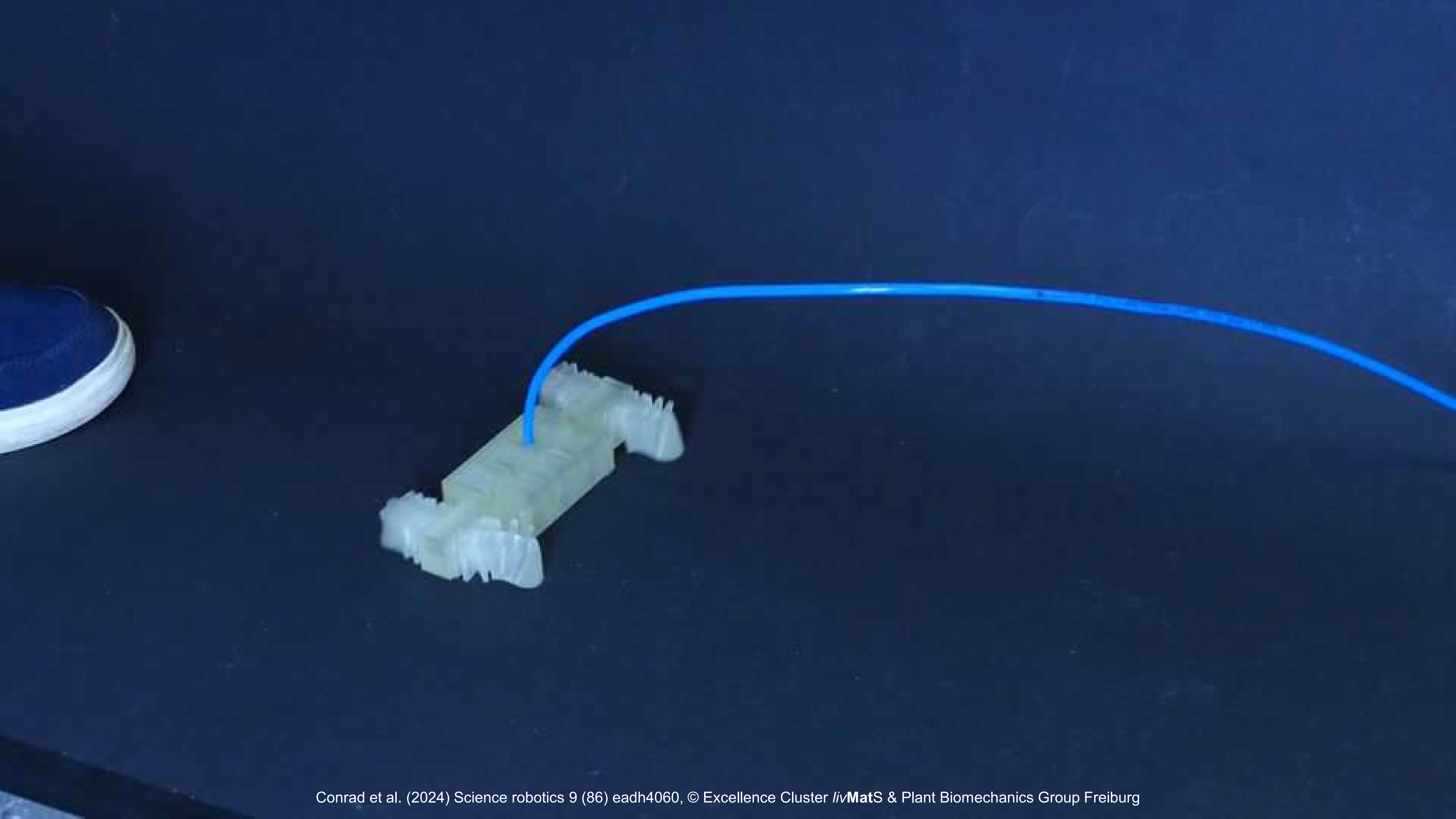
Overall printing time: **50 hours**
Manual assembly: **0 hours**

Conrad et al. (2024) Science robotics 9 (86) eadh4060,

0.25 BL/s or 0.04 m/s at 3.44 l/min & 175 kPa

Weight: 76.5 g

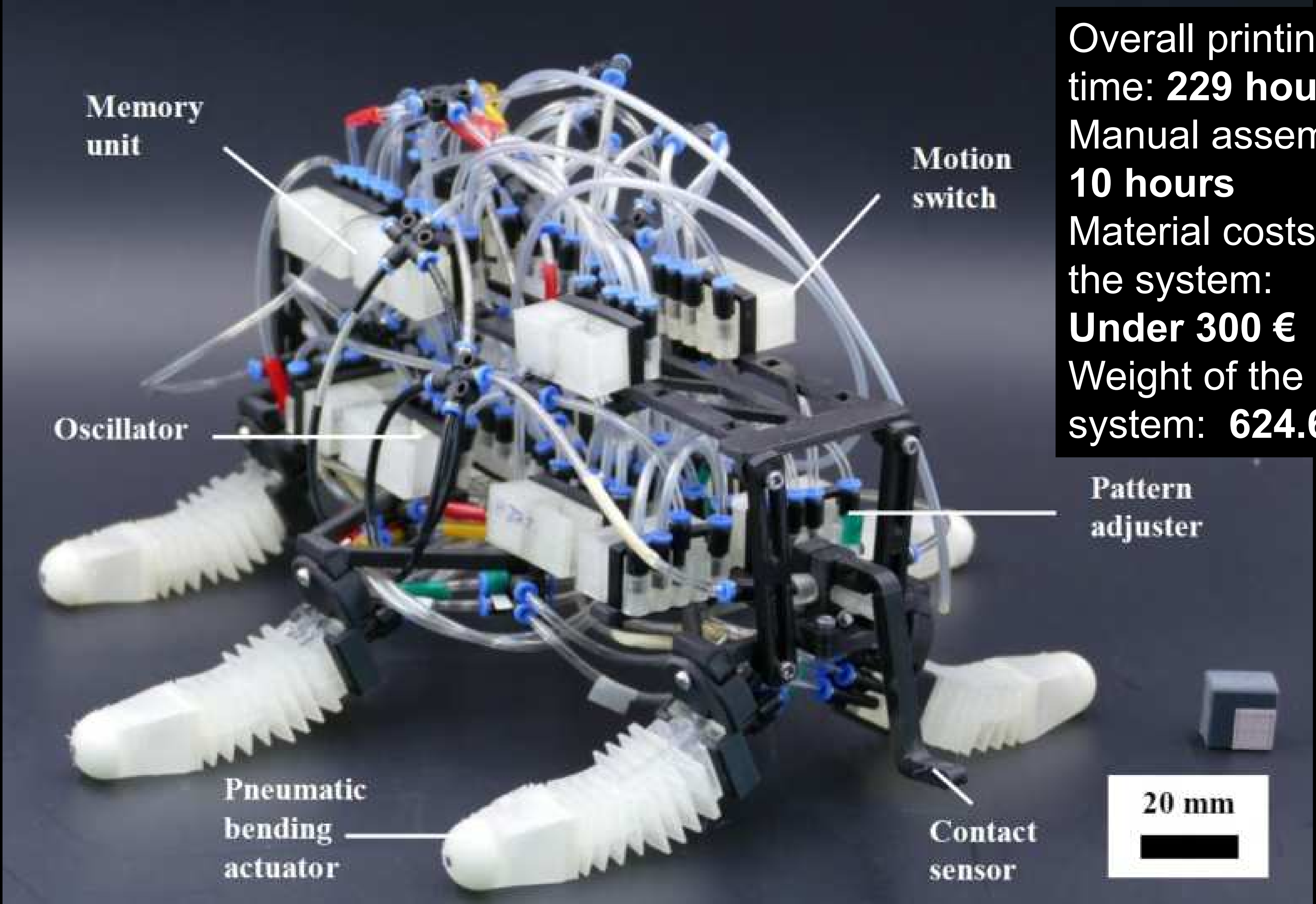
Material cost: 7€




0.25 BL/s or 0.04 m/s
at 3.44 l/min & 175 kPa

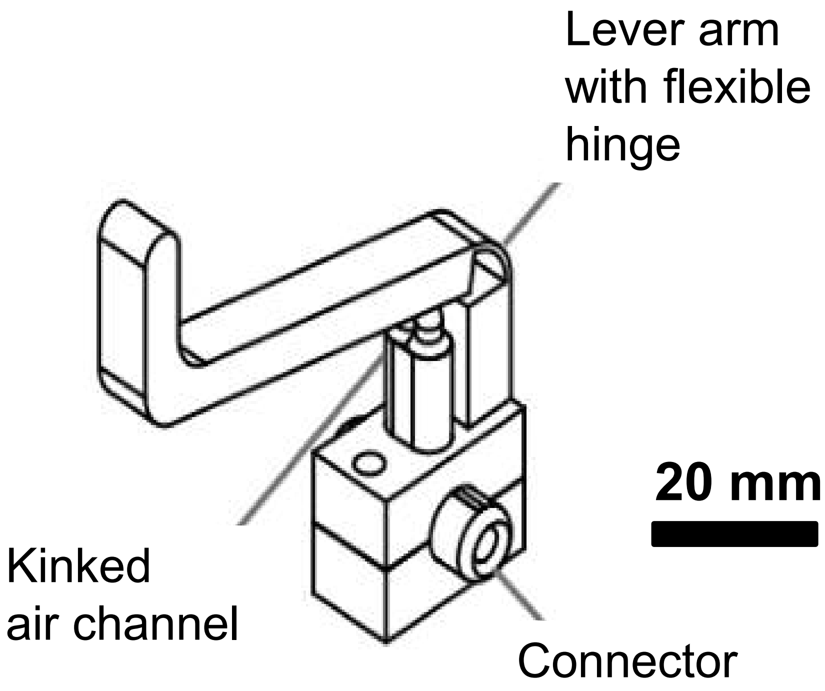
Conrad et al. (2024) Science robotics 9 (86) eadh4060, © ZDF moma Future

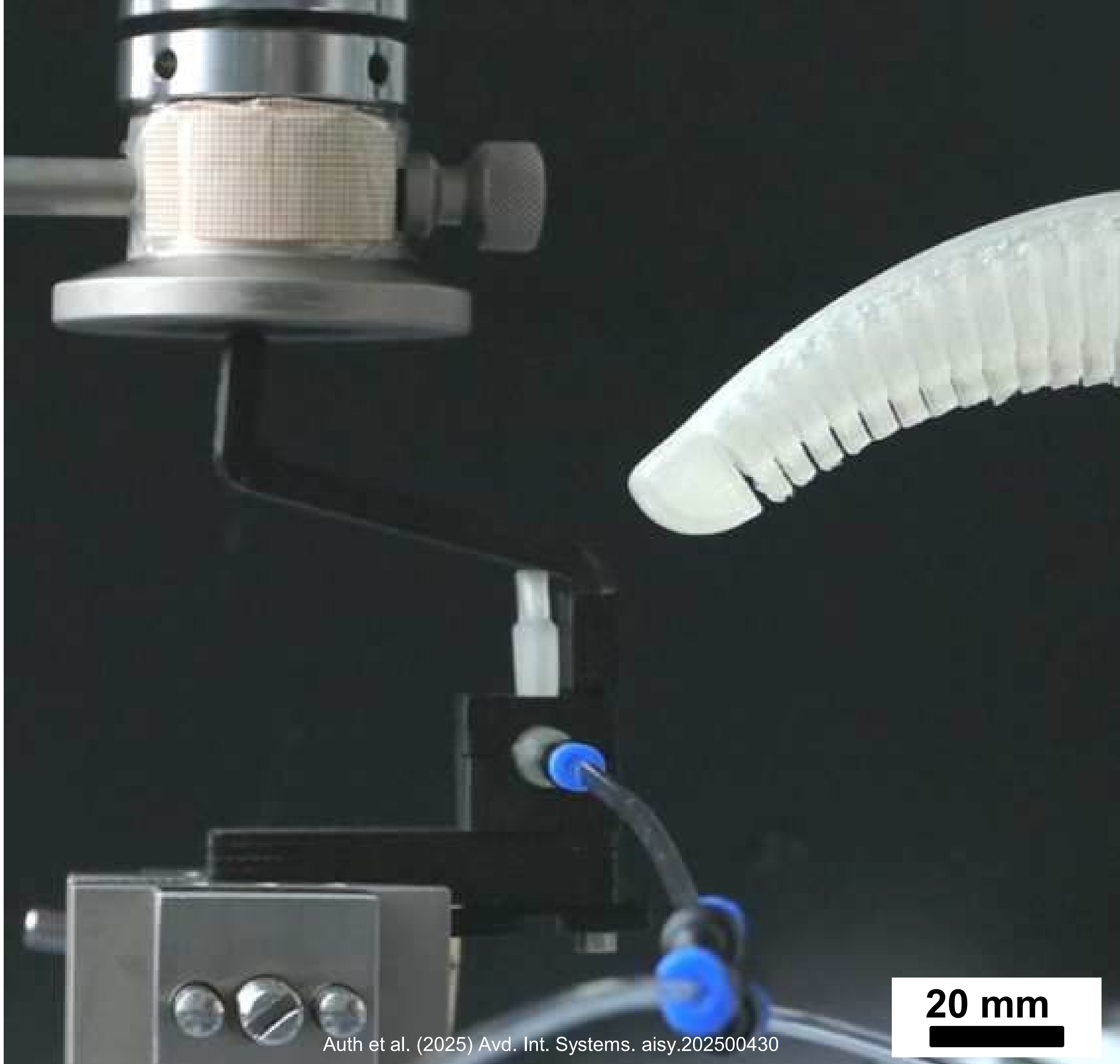
How can it orient itself in the environment?



Overall printing time: **229 hours**
Manual assembly: **10 hours**
Material costs of the system: **Under 300 €**
Weight of the system: **624.6 g**

Soft sensor

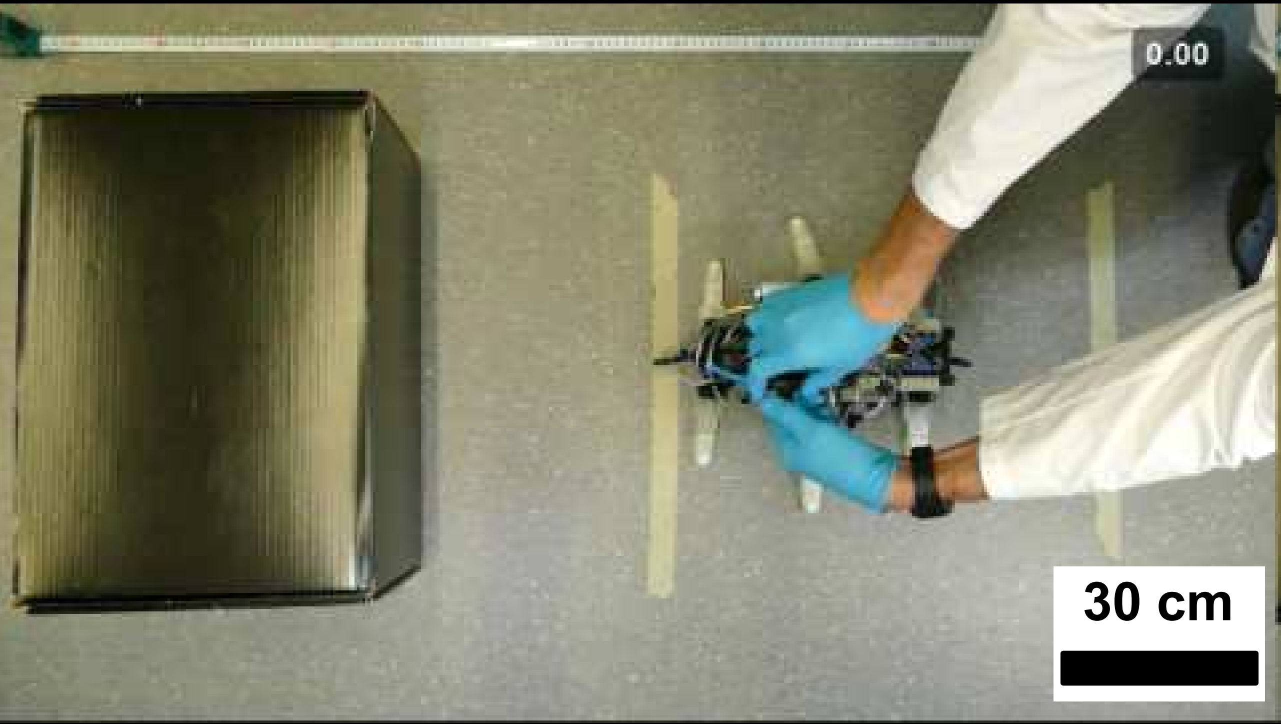


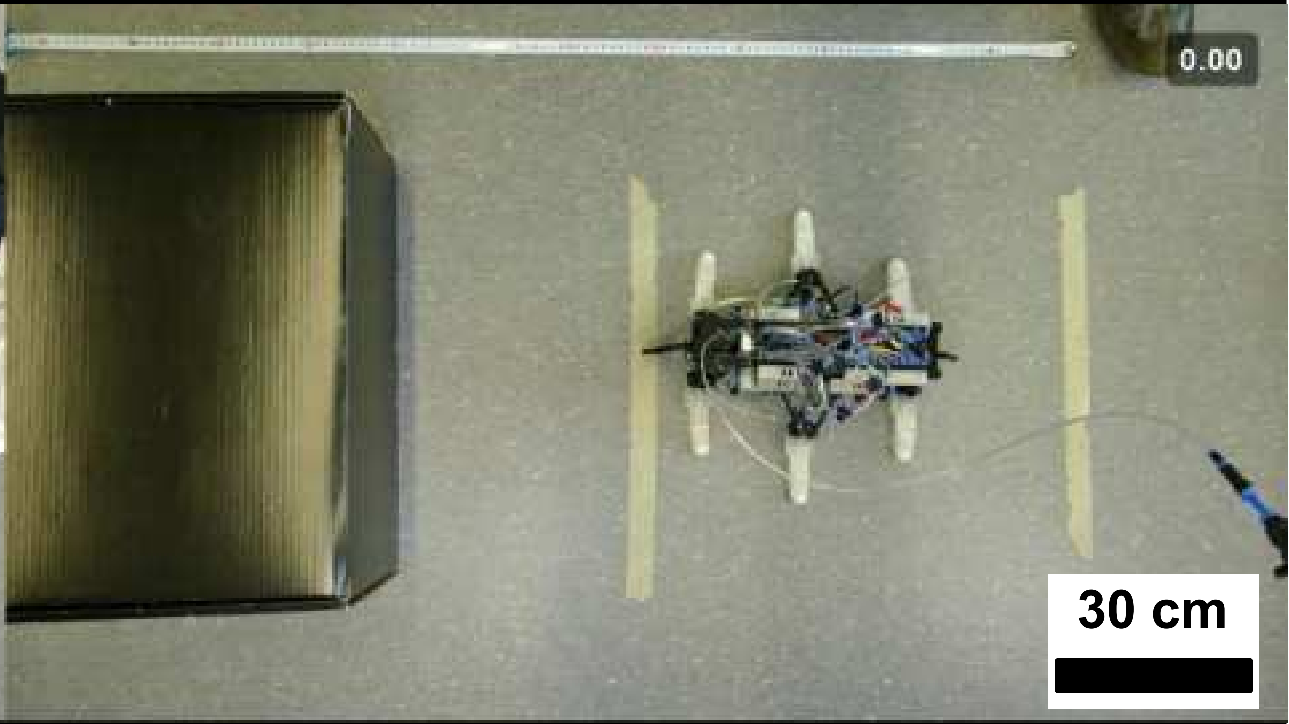


Auth et al. (2025) Avd. Int. Systems. aisy.202500430


livMatS

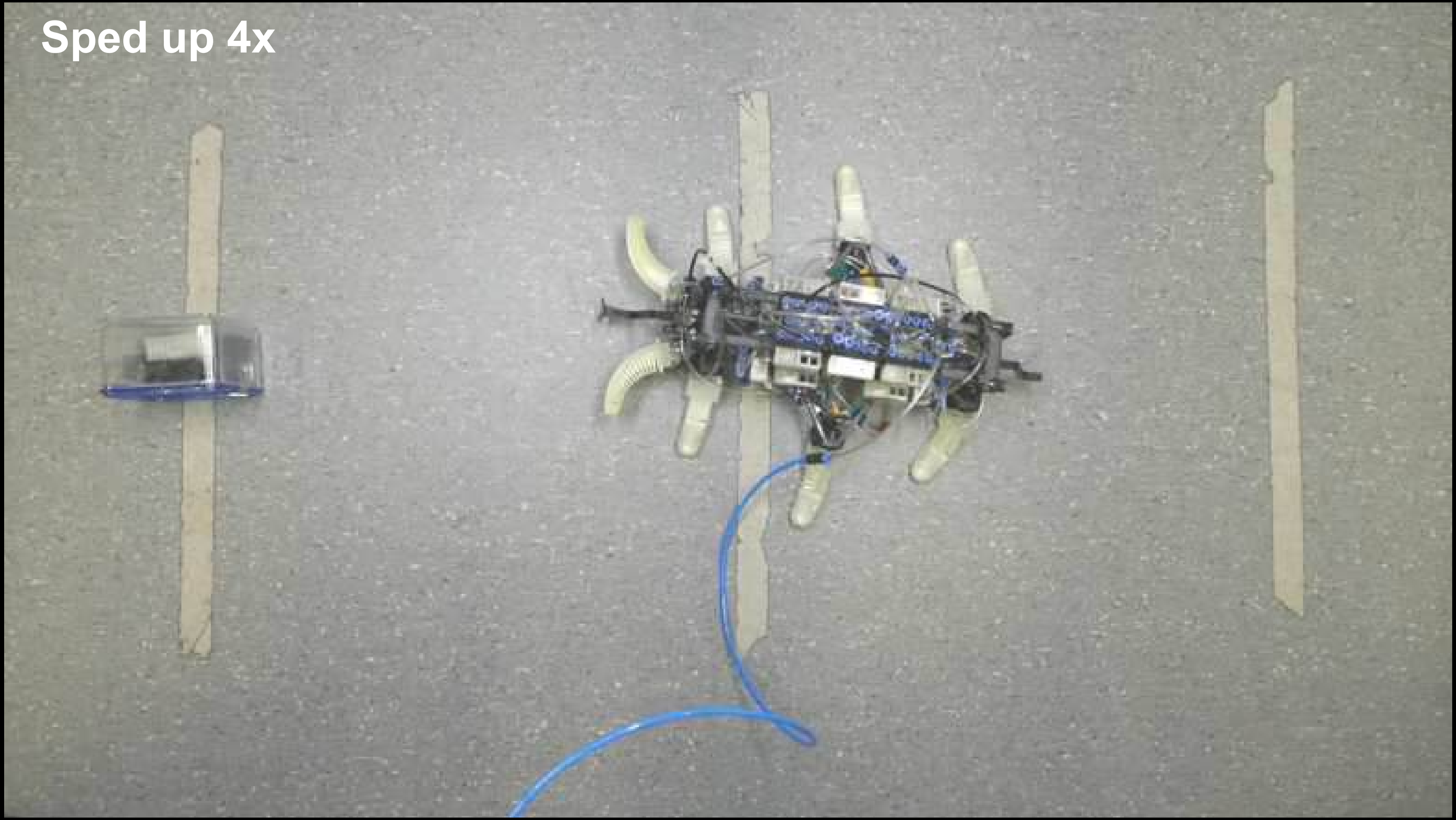
Autonomous vs. tethered





How can it interact with the environment?

Future Combination of Ligament Grippers with Walker

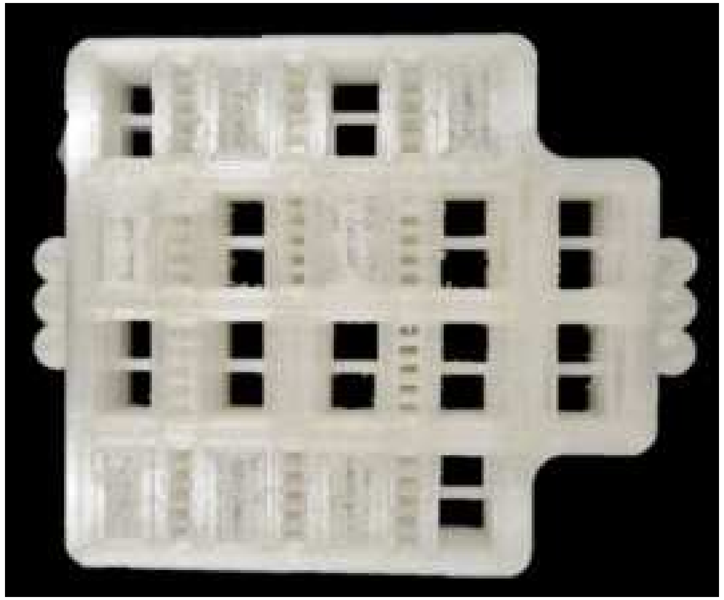


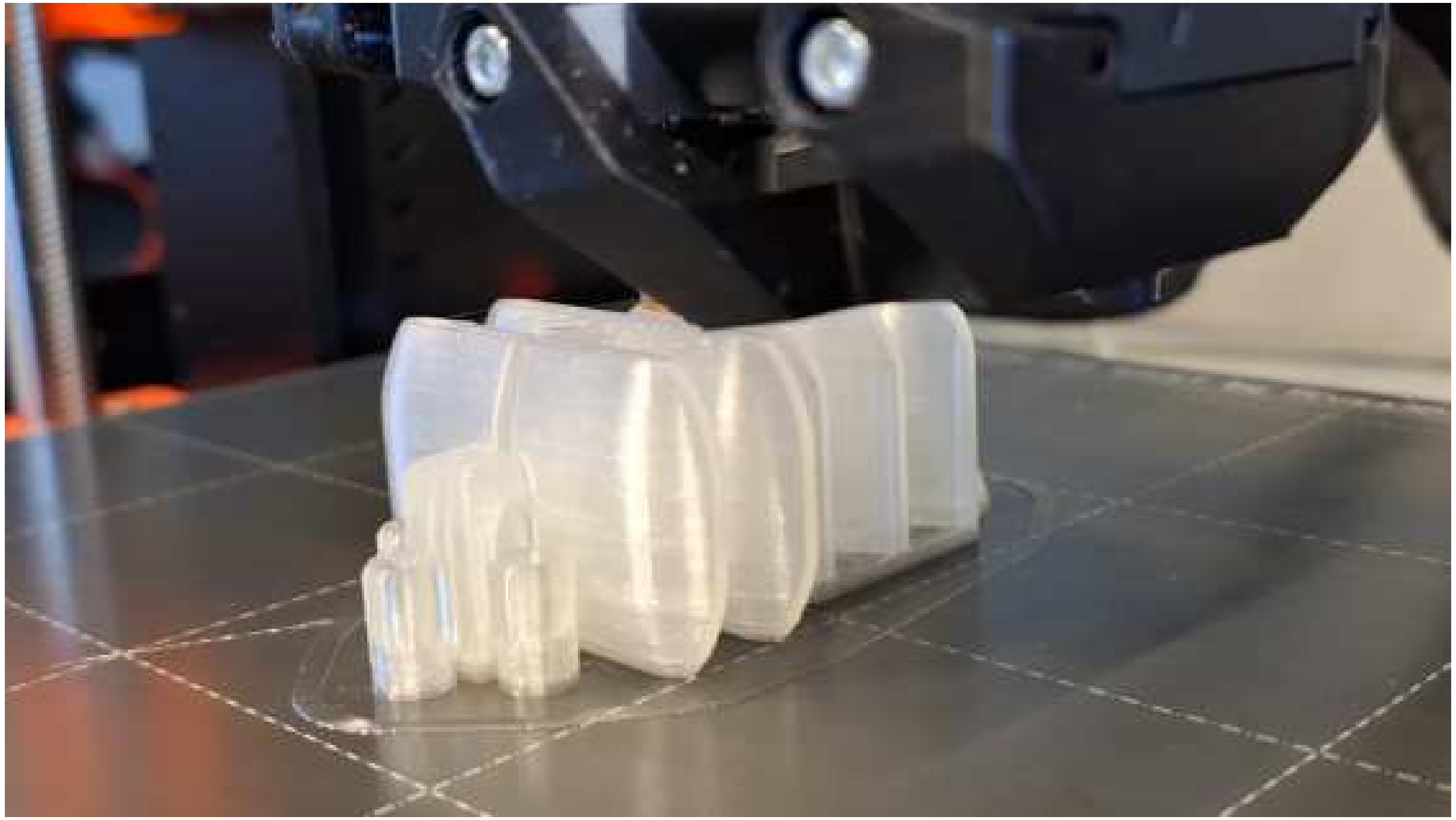
Auth et al. (2025) Avd. Int. Systems. aisy.202500430 © Excellence Cluster *liv***Mat**S & Plant Biomechanics Group Freiburg

Can we now integrate and improve this again?

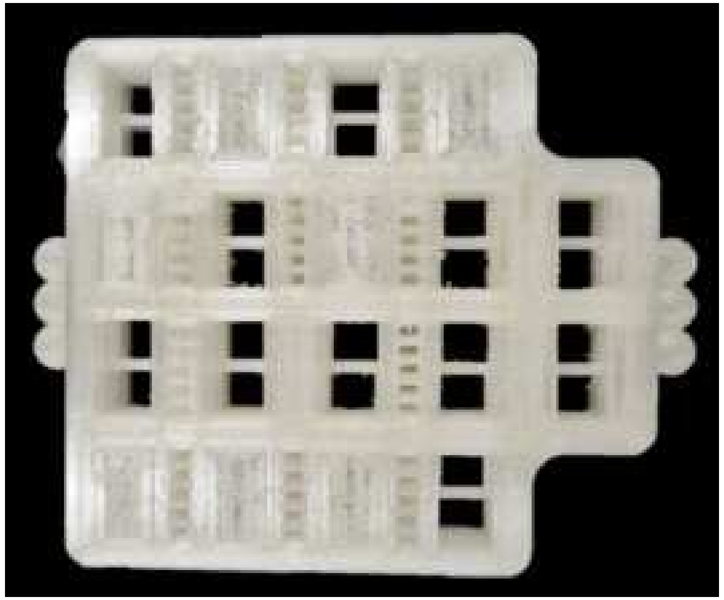
Advanced circuit for complex motions

No photos/
No videos

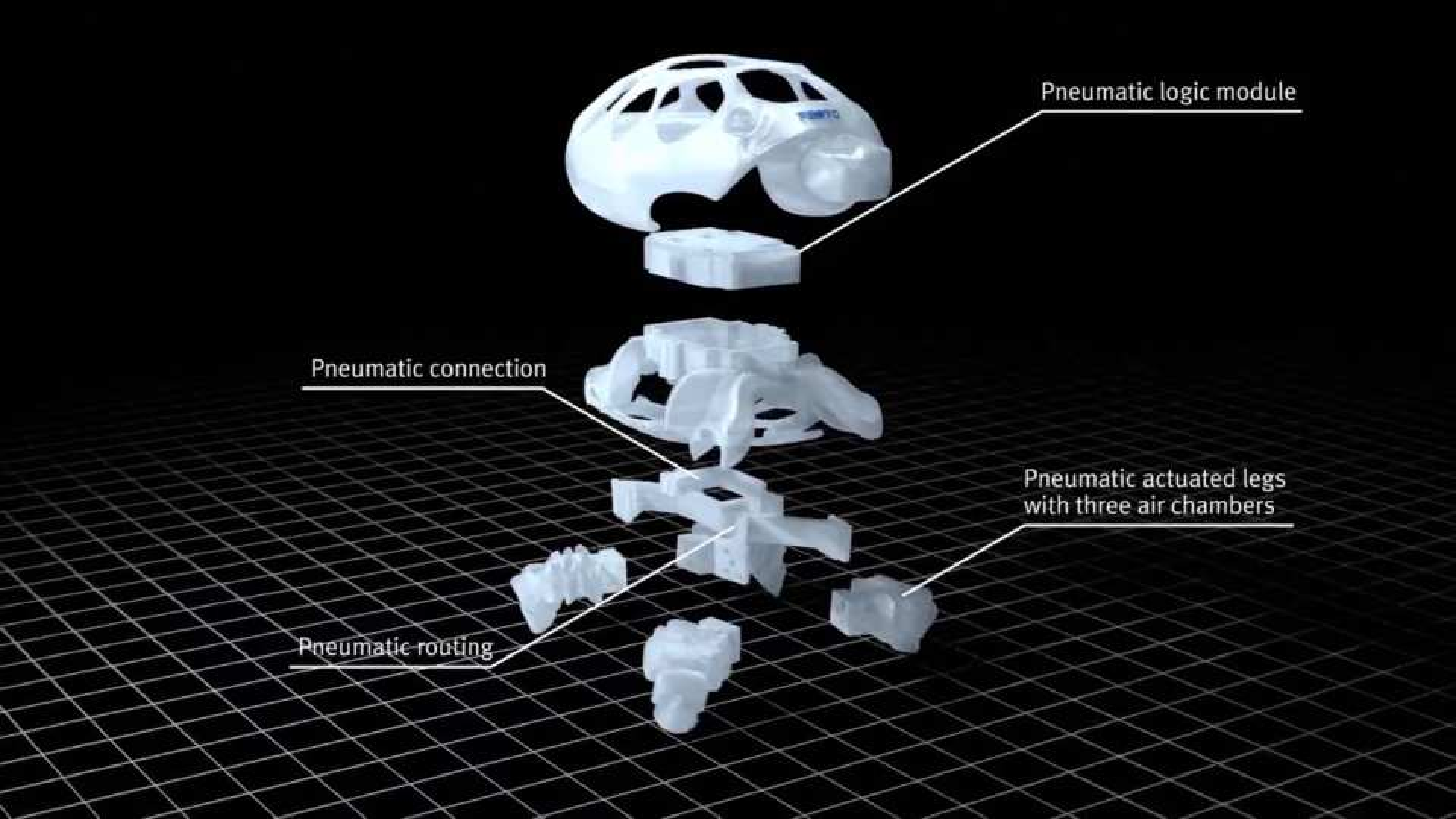




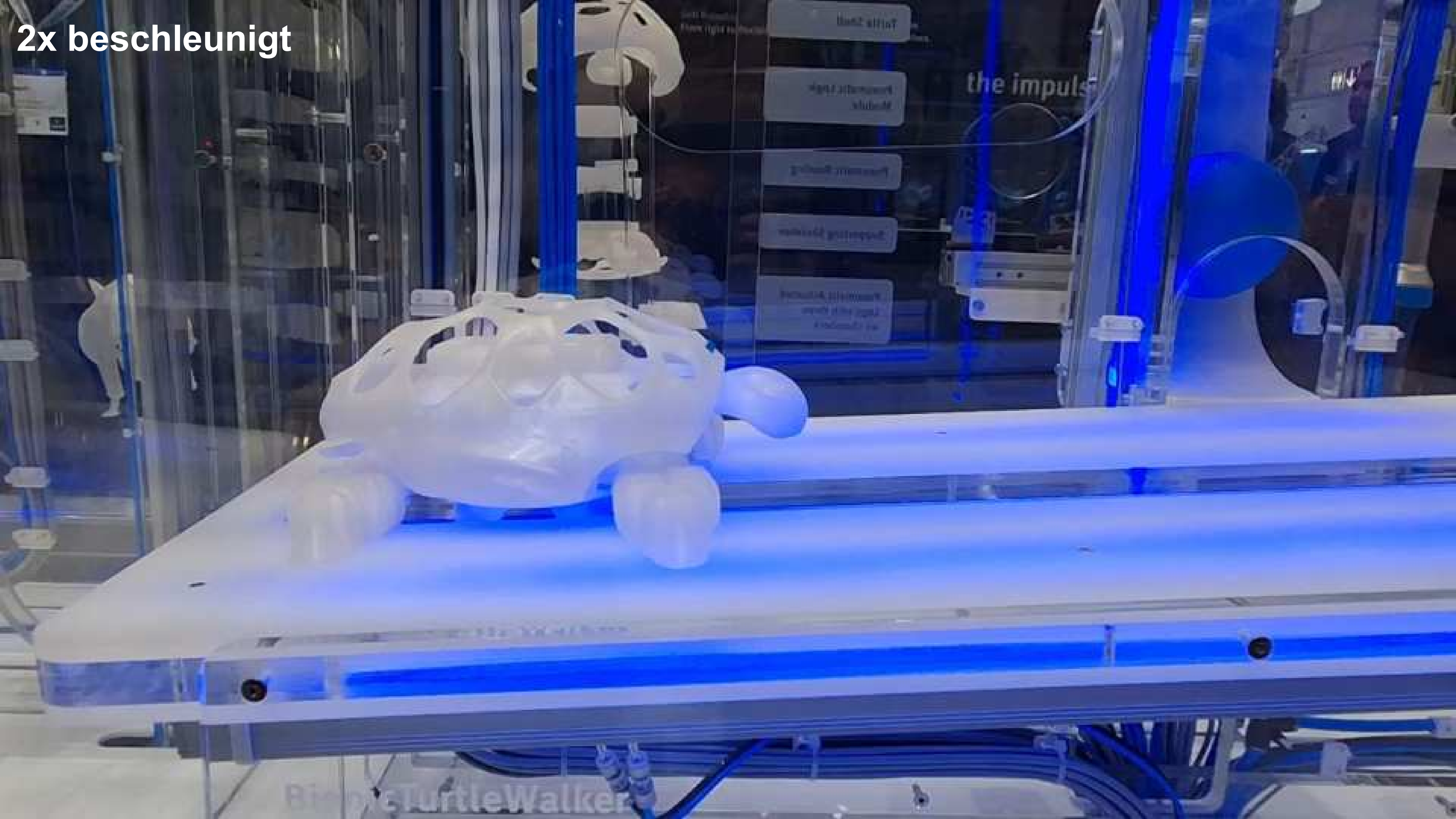
Advanced circuit for complex motions



Overall printing time: **111 hours**
Manual assembly: **20 min**
Material costs of the system: **32 €**
Weight of the system: **352 g**


Pneumatic logic module
Pneumatic connection
Pneumatic actuated legs
with three air chambers
Pneumatic routing

2x beschleunigt



What next for 3D printing of soft robots?

Upside-down printing

- Open-source platform
- Utilizes gravity for flex material printing
- 2.85 mm Ø filament reduces buckling

Flex Printer:
- Open-source platform.
- Costs <$500.
- Fits on any desktop.
- Prints previously impossible geometries.

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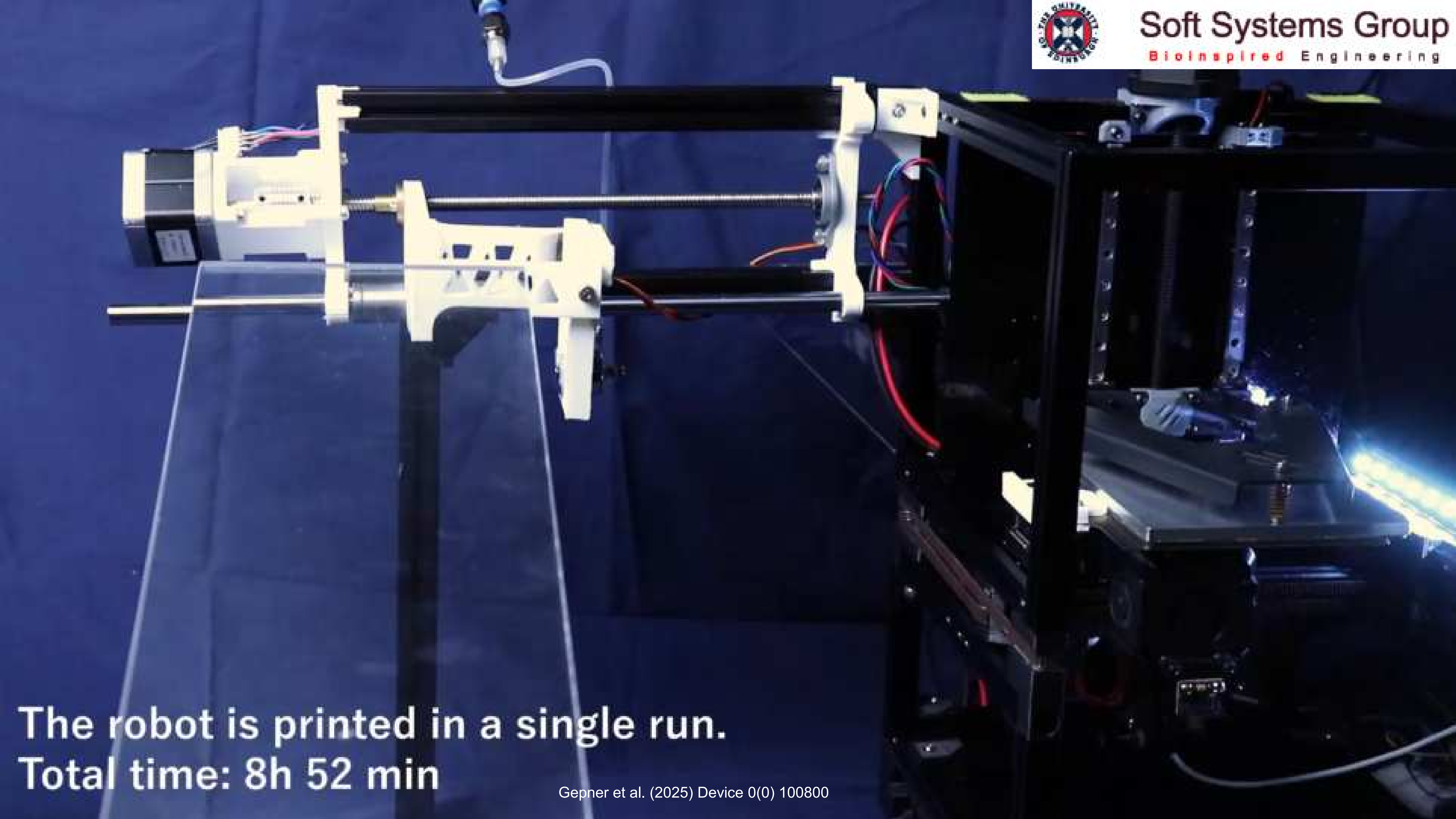
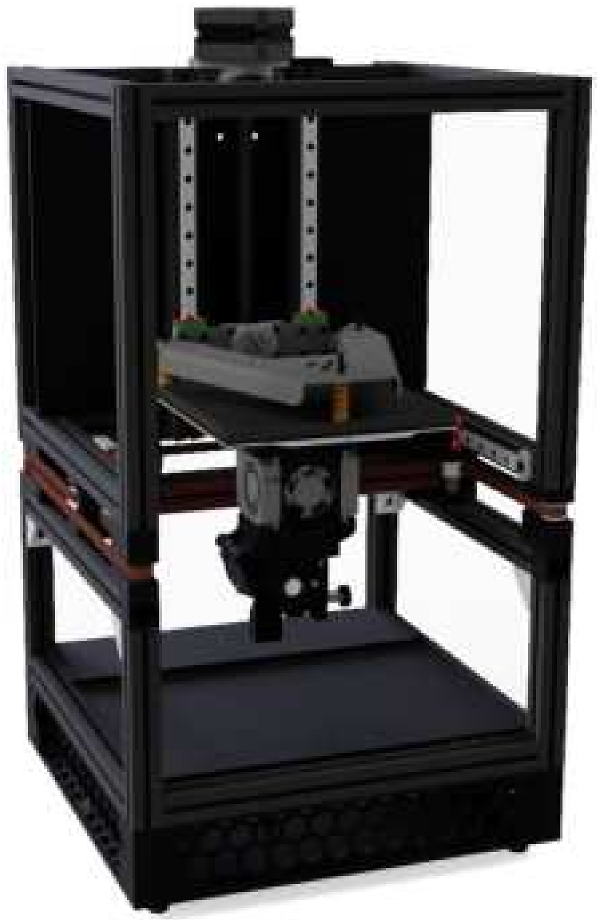
Bioinspired Engineering

Gepner et al. (2025) Device 0(0) 100800


Soft Systems Group
Bioinspired Engineering
The robot is printed in a single run.
Total time: 8h 52 min

Upside-down printing

- Open-source platform
- Utilizes gravity for flex material printing
- 2.85 mm Ø filament reduces buckling



Flex Printer:
- Open-source platform.
- Costs <$500.
- Fits on any desktop.
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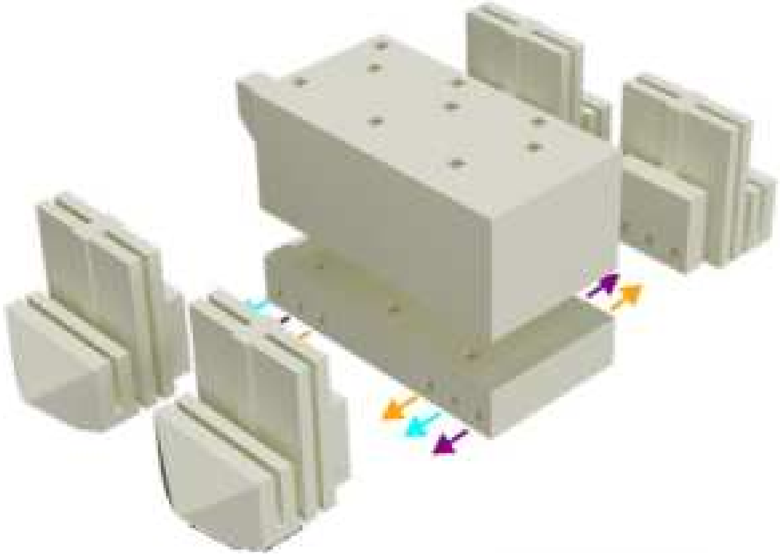
Rapid iteration in only a few hours:
New idea → Robot walking off the printbed.



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Upside-down printing

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Gepner et al. (2023) Device 0(0) 100800

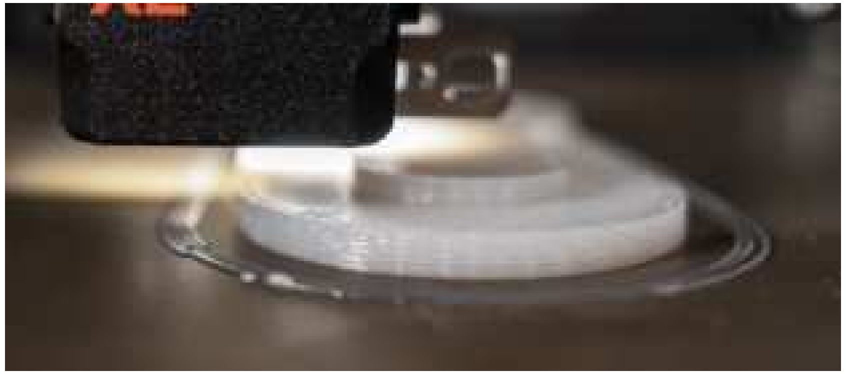
The Bestiary of Fluidic Machines

Fluidic Machine Bestiary:
- Open-source library of ready-to-print fluidic component blocks.
- Ready to assemble into new bio-inspired designs.
- Accessible to anyone.

Soft Systems Group
Bioinspired Engineering

Multi-material printing with the Prusa XL

No photos/
No videos

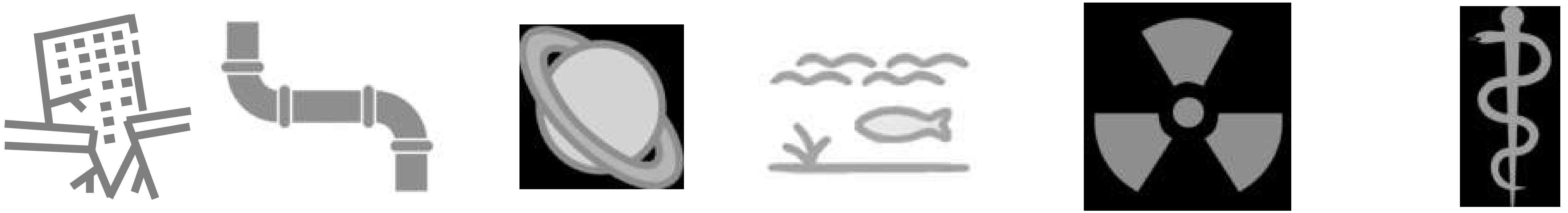


prusa3d.com/product/original-prusa-xl-silicone-printing-toolhead/

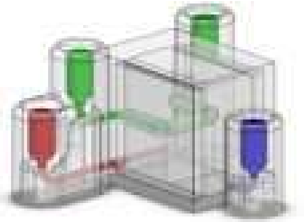
Multi-material electronic free robots

- Multi-material enables complex systems
- Load bearing through combination of stiff and soft materials in one print
- Sensors and connectors with conductive TPU
- On board power supply?

Possible applications for soft robots…



Search & Rescue | Pipeline Inspection | Space Exploration | Underwater Monitoring | Radioactive Environments | Medicine & Healthcare



Key take aways

3D printing of soft robots speeds up developmental phase and enables fully flexible systems.

During design phase keep the production in mind.

Dry your flexible filament for easy printing.

Novel multi-material printing enables fully integrated soft robots.

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