The Art and Artillery of Artificial Muscles

By Jack Forman

Research Interests:

Morphing fabrics, Computational design of textiles, Fiber Synthesis, Smart Materials, Metamaterials

Bachelors

Carnegie Mellon University
Materials Science & Biomedical Engineering

Ph.D. & M.S.

MIT Media Lab
Tangible Media Group
Center for Bits and Atoms

Jack Forman
Graduate Research Assistant

Overview

- Passive Fiber Actuation
- Pneumatic Actuation
- Dielectric Fibers
- Thermal Actuation
  - Shape Memory Alloy
  - Twisted Then Coiled Polymer Muscles
  - LCE fibers

What is an artificial muscles?

“Artificial muscles, also known as muscle-like actuators, are materials or devices that mimic natural muscle and can change their stiffness, reversibly contract, expand, or rotate within one component due to an external stimulus (such as voltage, current, pressure or temperature).

The three basic actuation responses– contraction, expansion, and rotation can be combined within a single component to produce other types of motions (e.g. bending, by contracting one side of the material while expanding the other side). Conventional motors and pneumatic linear or rotary actuators do not qualify as artificial muscles, because there is more than one component involved in the actuation.” https://en.wikipedia.org/wiki/Artificial_muscle

Overview

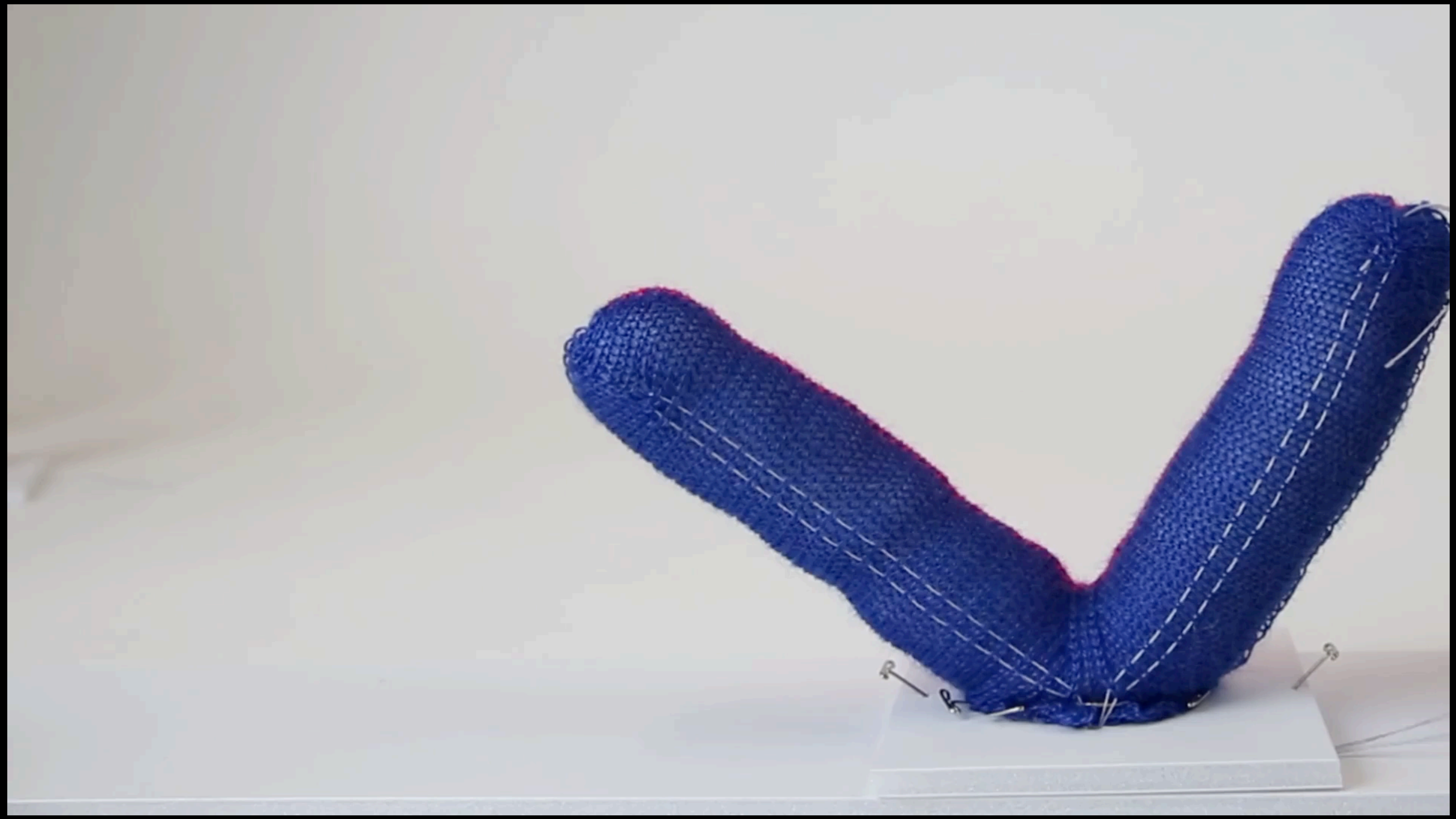
Ali Maziz et al. ,Knitting and weaving artificial muscles.Sci. Adv.3,e1600327(2017).DOI:10.1126/sciadv.1600327

https://tech.facebook.com/reality-labs/2021/11/inside-reality-labs-meet-the-team-thats-bringing-touch-to-the-digital-world/

Becker, Kaitlyn & Teeple, Clark & Charles, Nicholas & Jung, Yeonsu & Baum, Daniel & Weaver, James & Mahadevan, Lakshminarayanan & Wood, Robert. (2022). Active entanglement enables stochastic, topological grasping. Proceedings of the National Academy of Sciences of the United States of America. 119. e2209819119. 10.1073/pnas.2209819119.

Basic Tendon Actuation

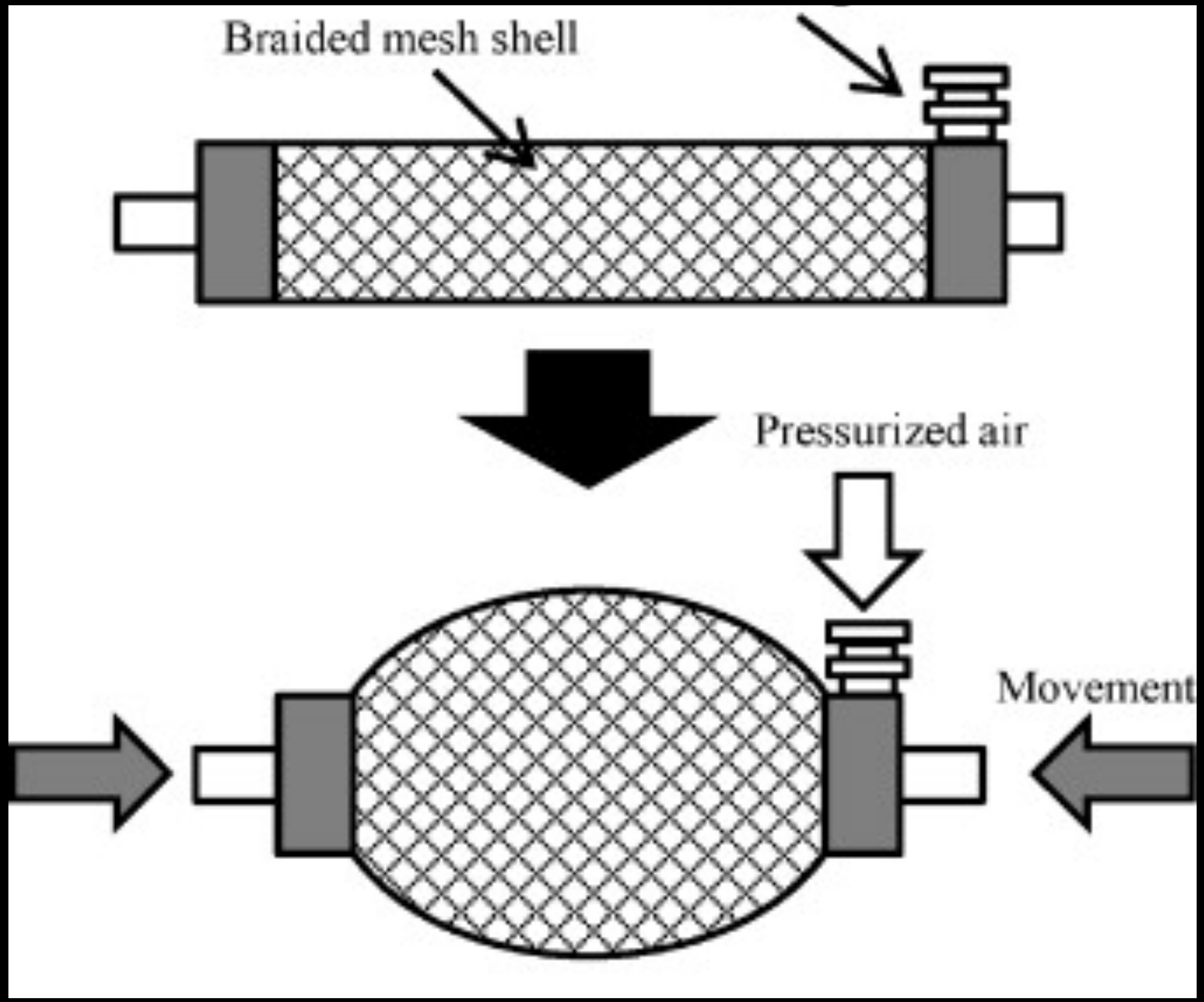
- Passive fiber pulled with a motor
- Pros
  - Extremely accessible
- Cons
  - External motors+electronics are bulky
  - Uneven actuation due to friction



Source: Albaugh, Lea, Scott Hudson, and Lining Yao. "Digital fabrication of soft actuated objects by machine knitting." *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019.

McKibben Actuator Background

- Composed of elastomeric tubing surrounded by a constraining braid
- Inflating the tubing causes the muscle to expand (or contract)
- Control of braiding angle and pattern can determine actuation displacement and behavior
- Hydraulic actuation fixes lag associated with pneumatic actuation



McKibben Muscle is composed of a inflatable bladder and a braided constraint

Source: Takashima, Kazuto, Jonathan Rossiter, and Toshiharu Mukai. "McKibben artificial muscle using shape-memory polymer." *Sensors and Actuators A: Physical* 164.1-2 (2010): 116-124.

McKibben Actuator Background

- Pros
  - Fast, powerful actuation
  - Cheap and accessible to produce
  - Hold actuated state unpowered
- Cons
  - Requires pump (noisy + bulky)

Pneumatic Textiles
Tokyo Institute of Technology

McKibben Actuator Applications

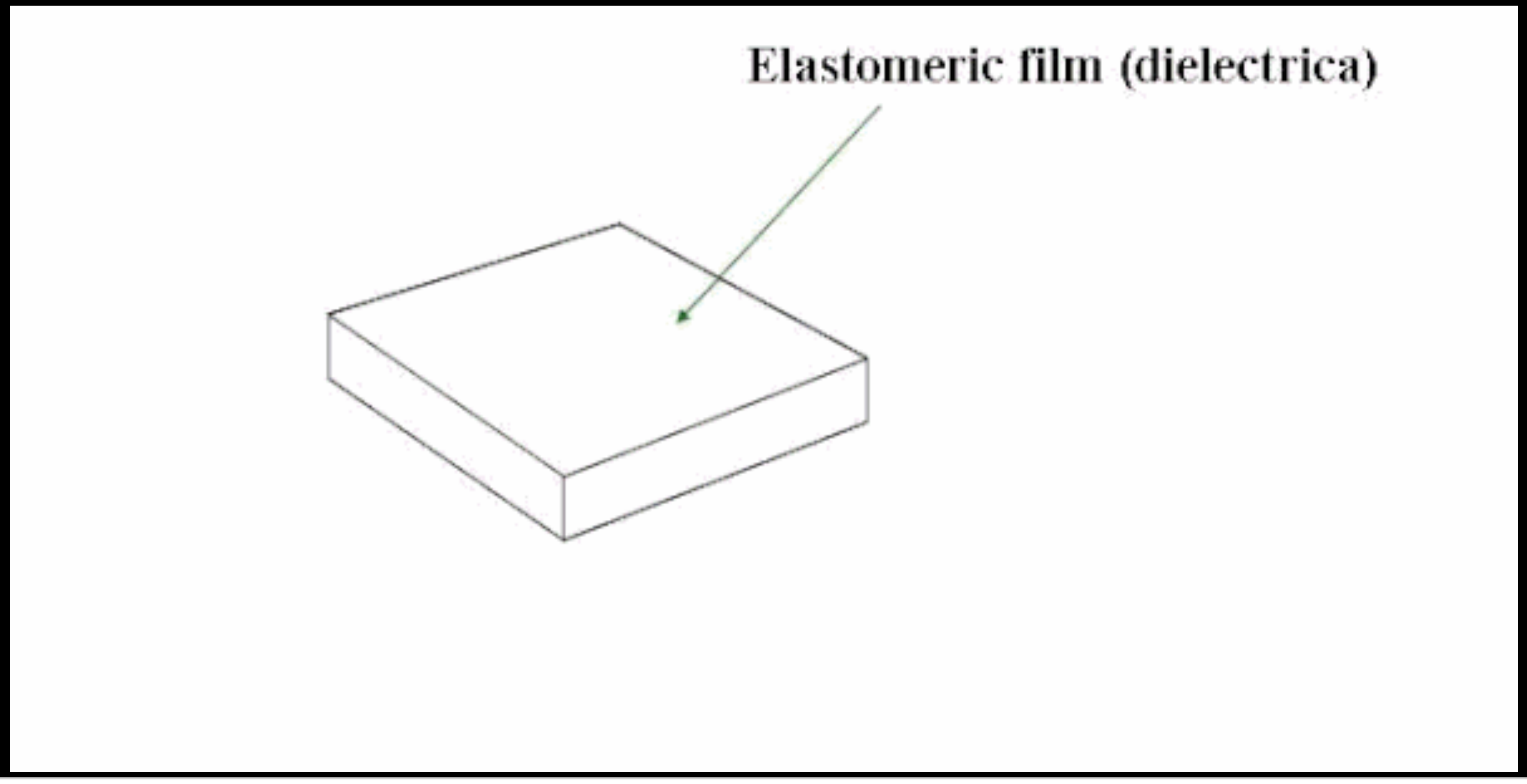
Source: Kilic Afsar, Ozgun, et al. "OmniFiber: Integrated Fluidic Fiber Actuators for Weaving Movement Based Interactions into the ‘Fabric of Everyday Life’." *The 34th Annual ACM Symposium on User Interface Software and Technology*. 2021.

Dielectric Elastomer Background

- Composed of a elastomer (often silicone) layer sandwich by two conductive electrodes (often carbon grease)

- Voltage-induced charge on plates cause attractive force

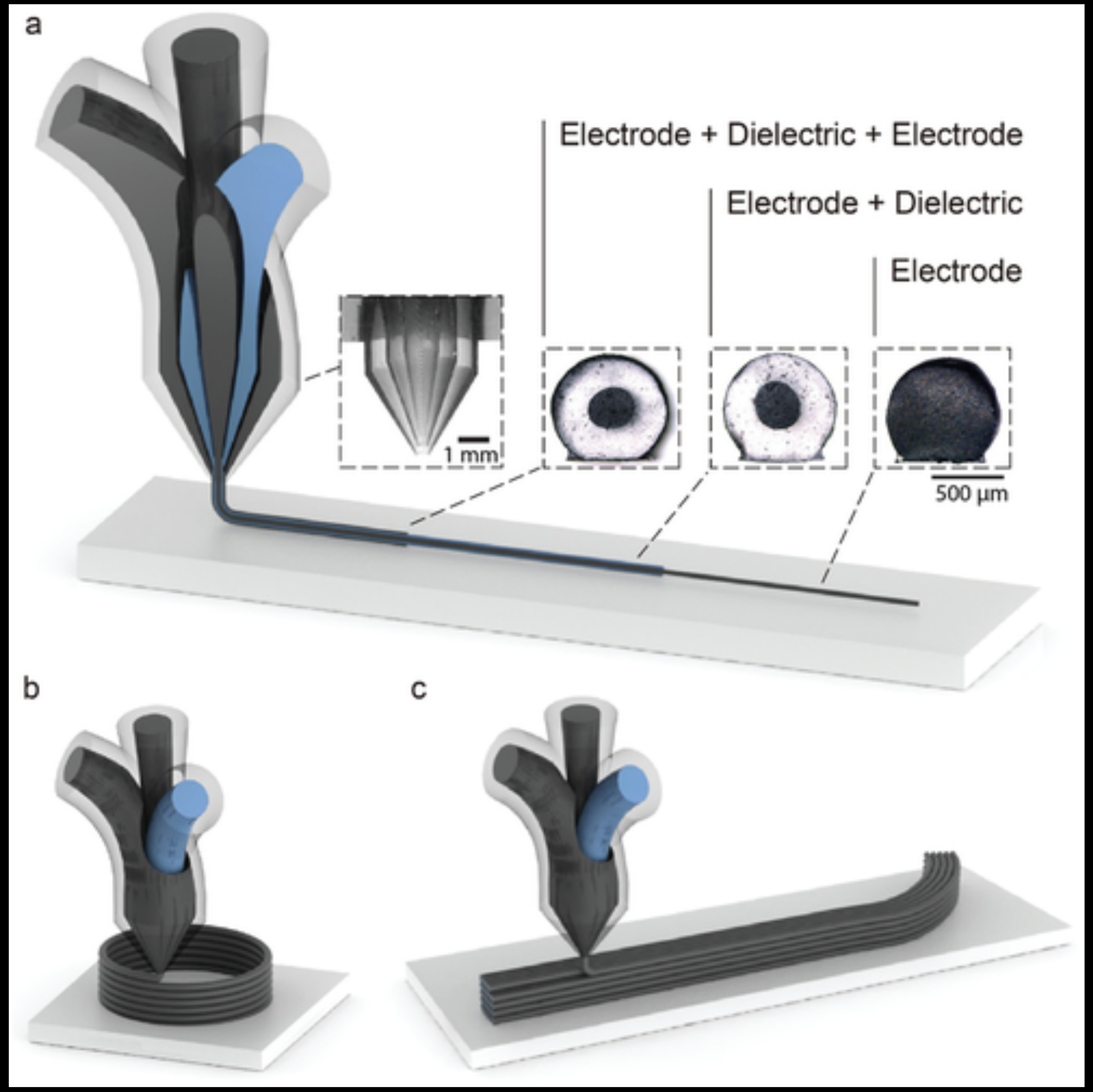
- Removing voltage removes attraction and allows elastomer to restore original shape



Principle mechanism behind Dielectric Elastomer Actuators (https://en.wikipedia.org/wiki/Dielectric_elastomers)

Dielectric Elastomers Background

- Pros
  - Fast actuation speed
  - Lightweight
  - Power efficient
- Cons
  - High voltages needed
  - Constant power needed to maintain actuation

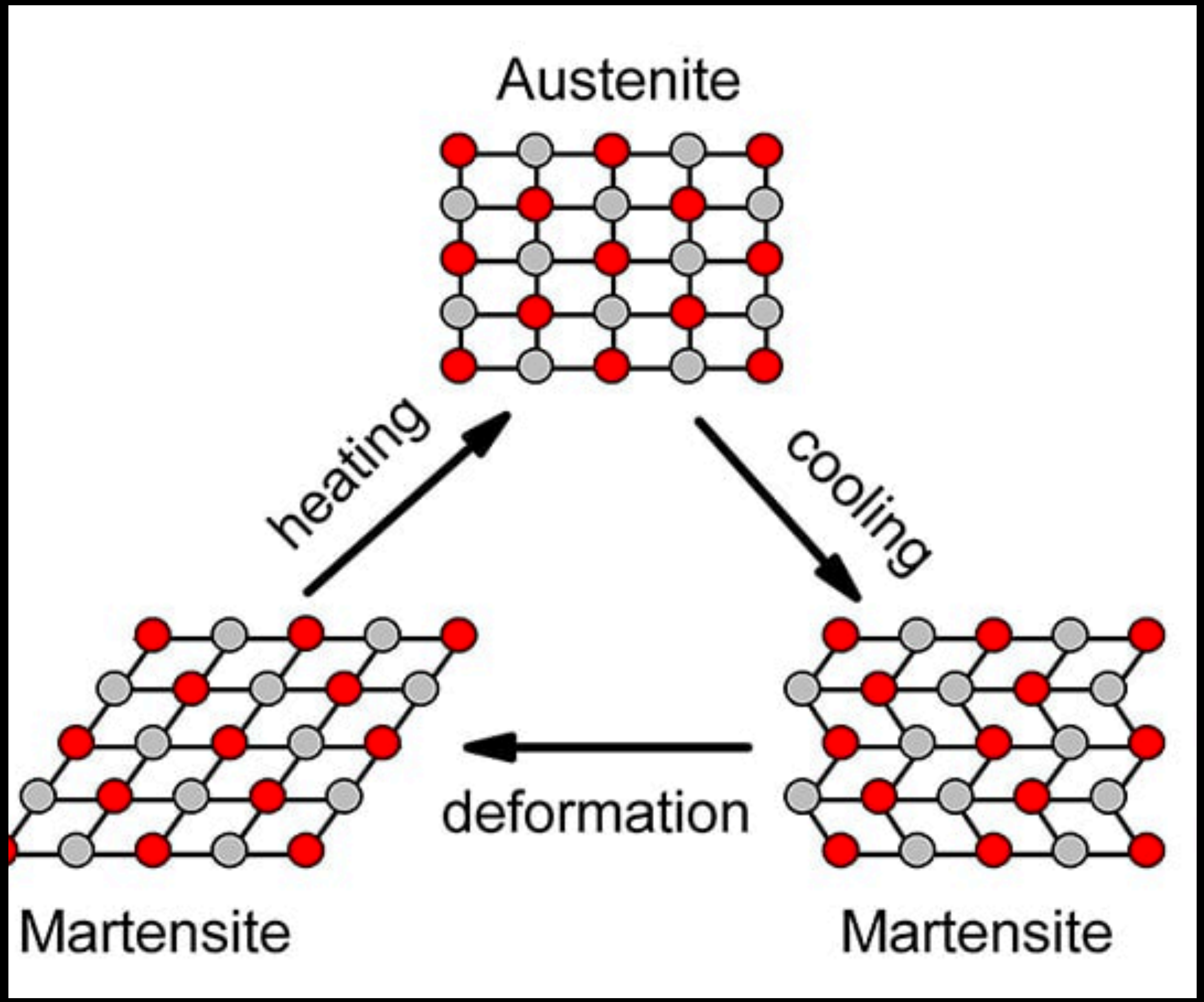


Rapid oscillation of 3D printed Dielectric fibers

Source: Chortos, Alex, et al. "Printing reconfigurable bundles of dielectric elastomer fibers." *Advanced Functional Materials* 31.22 (2021): 2010643.

Shape-Memory Alloy Actuator

- One of the most popular shape memory materials
  - Nickel Titanium Alloy
- A wire-like material that exhibits super elasticity at elevated temperatures



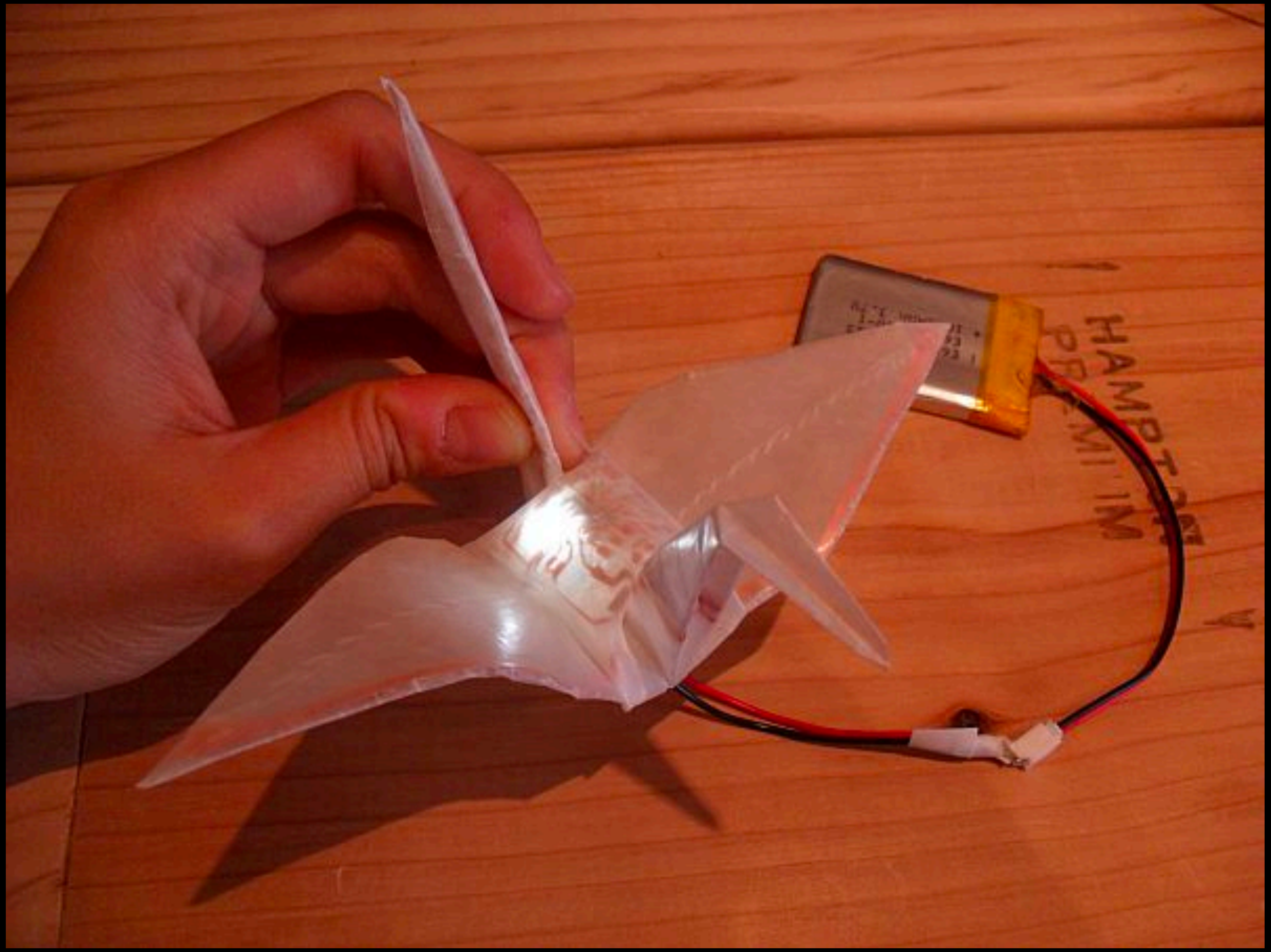
Phases of SMA in response to temperature and loading cycles

Source: https://www.skyfilabs.com/project-ideas/shape-memory-effect-intelligent-alloys

Jie Qi Self Flapping Crane

- https://fab.cba.mit.edu/classes/863.10/people/jie.qi/jieweek10.html

- https://www.youtube.com/watch?v=ARMepo5nY1Q&ab_channel=JieQi



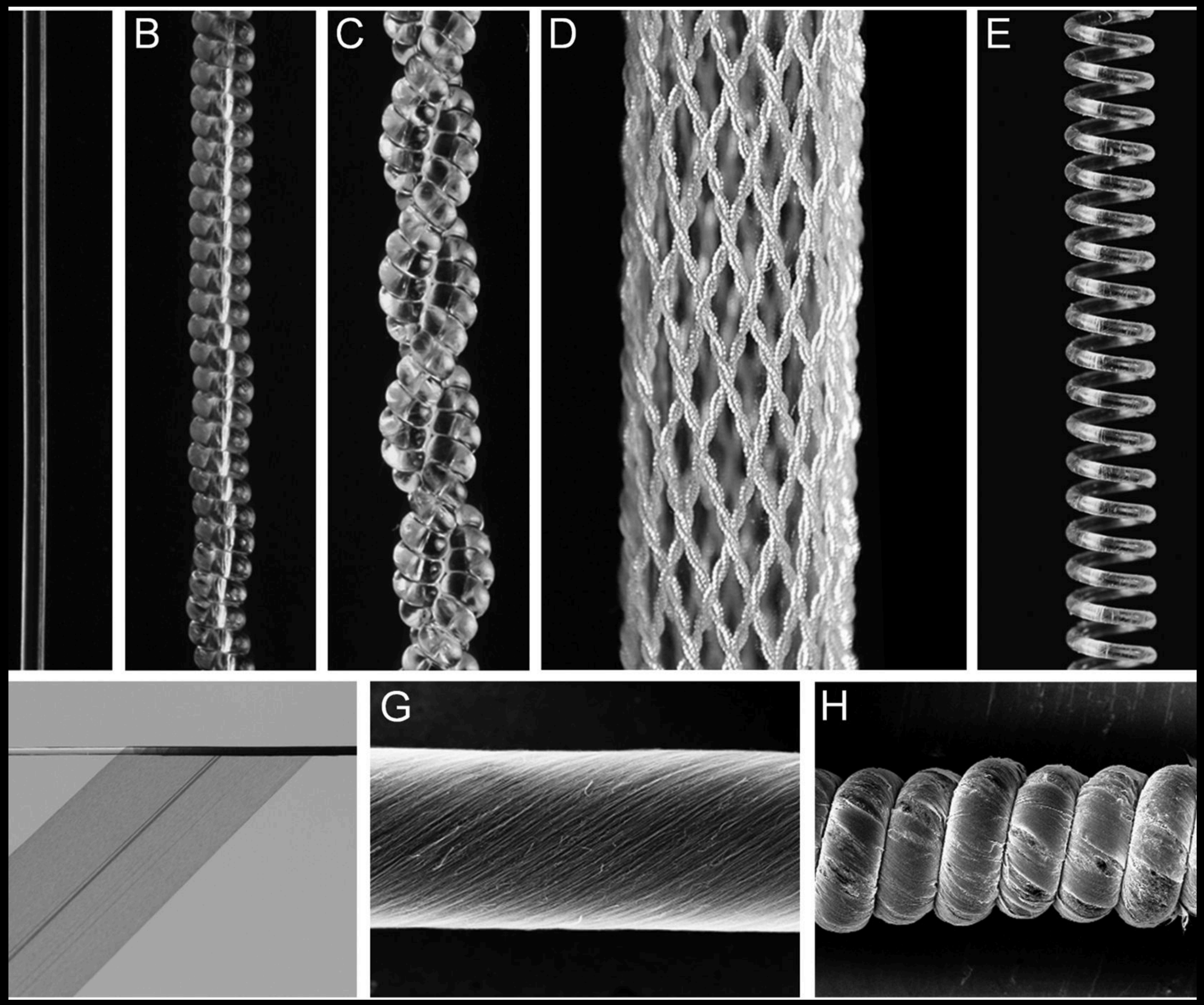
Shape-Memory Alloy Actuator

- Pros
  - Well-commercialized
  - Range of actuation temps and diameters
- Cons
  - Actuation displacement is small ~5% and not self-reversing
  - High hysteresis
  - Pain to work with and stiff

Kim, Jin Hee, et al. "KnitDermis: Fabricating tactile on-body interfaces through machine knitting." *Designing Interactive Systems Conference 2021*. 2021.

Fishing Line Actuators Background

- Hanes et. al found that over-twisting fishing line produced actuators 100x more powerful than human muscle



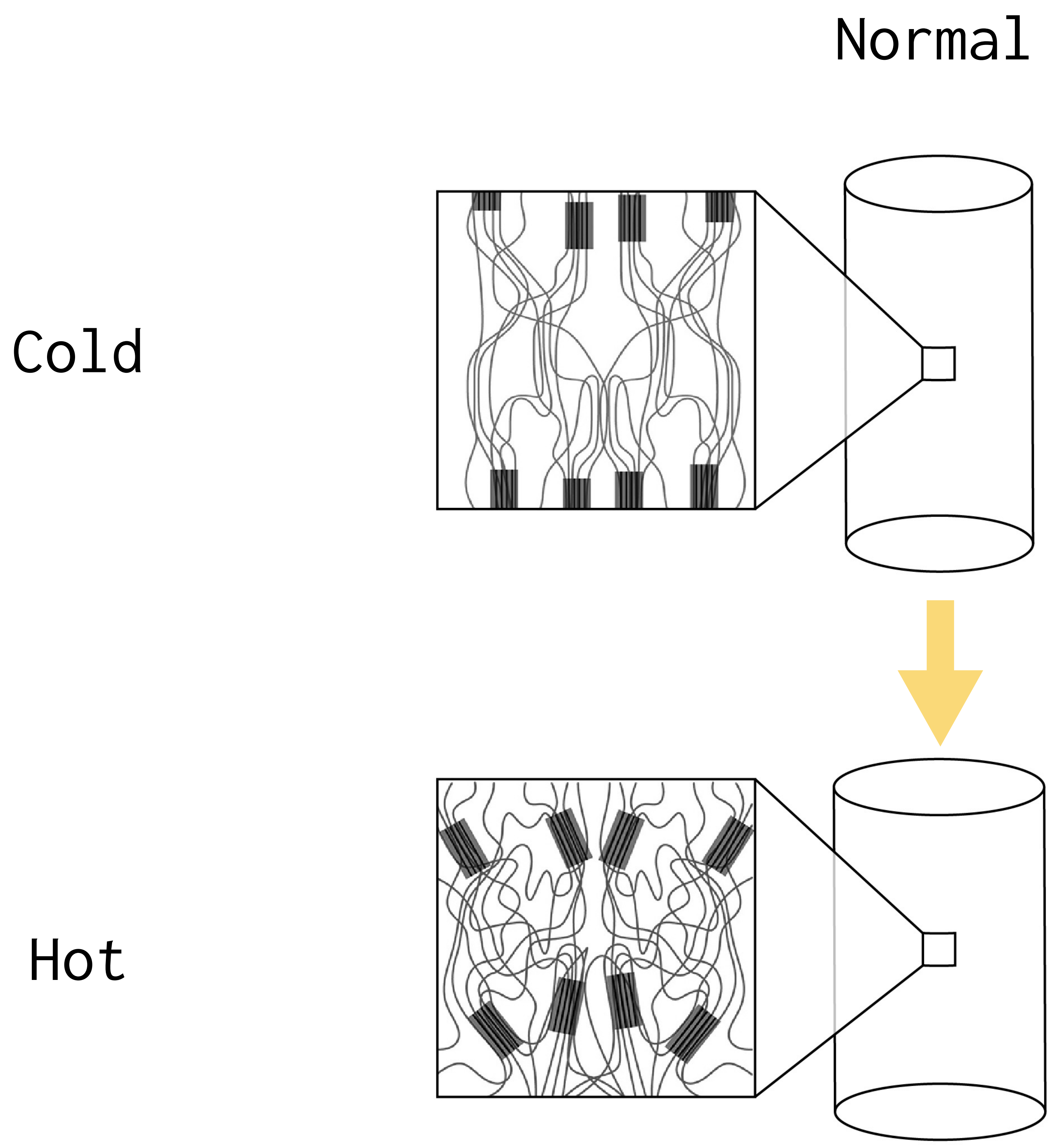
Overview of TCP muscles

Source: Haines, Carter S., et al. "Artificial muscles from fishing line and sewing thread." *science* 343.6173 (2014): 868-872.

APA

Material Mechanisms

Polymer Behavior



Fishing Line Actuators Background

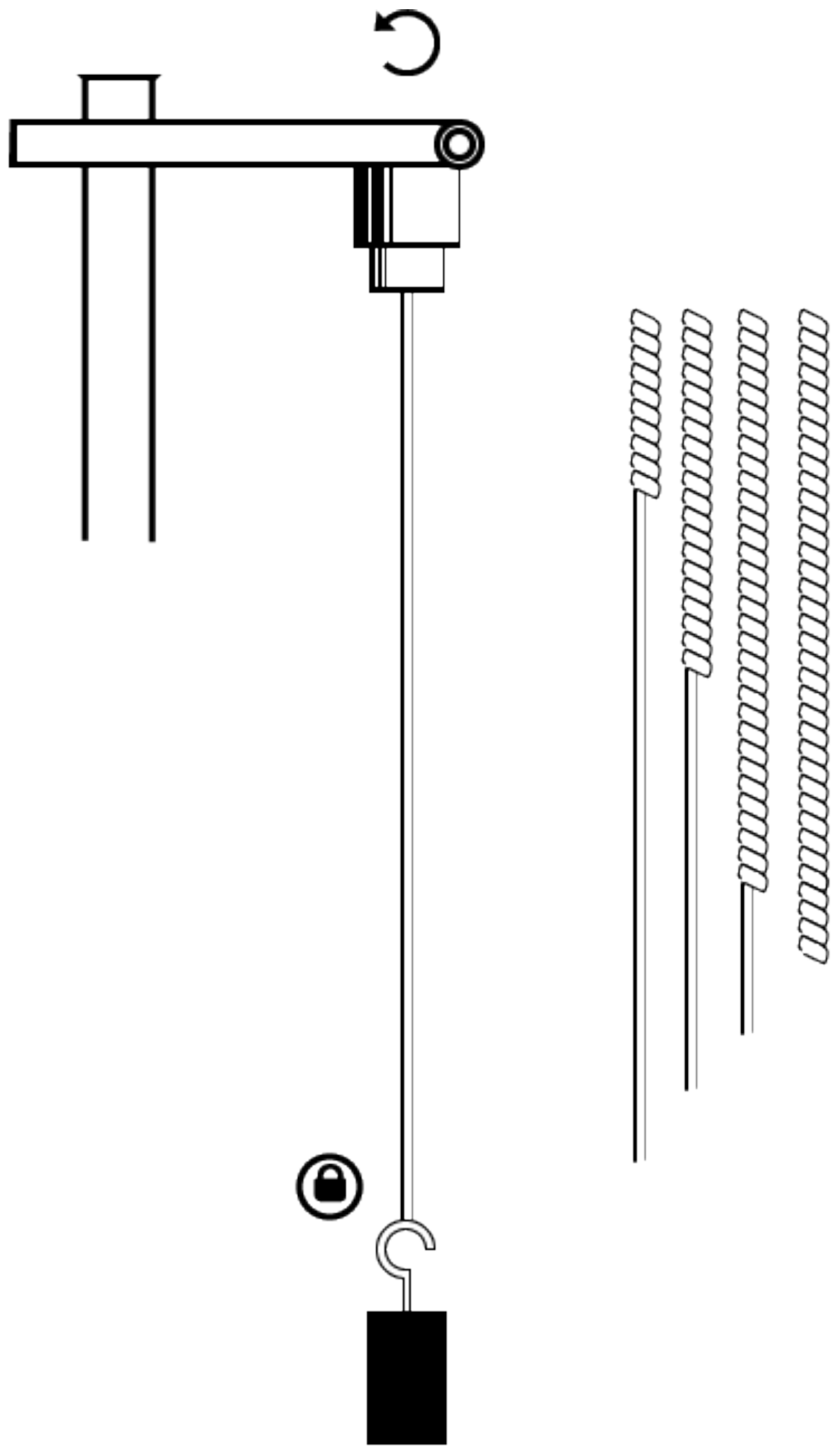
- Pros
  - Extremely accessible to fabricate with low cost masterial
  - Powerful actuators with no hysteresis (>1 million cycles)
- Cons
  - Constraining twist is challenging
  - Non-self reversing

Animation of muscle fabrication

Source: Intelligent Polymer Research Group

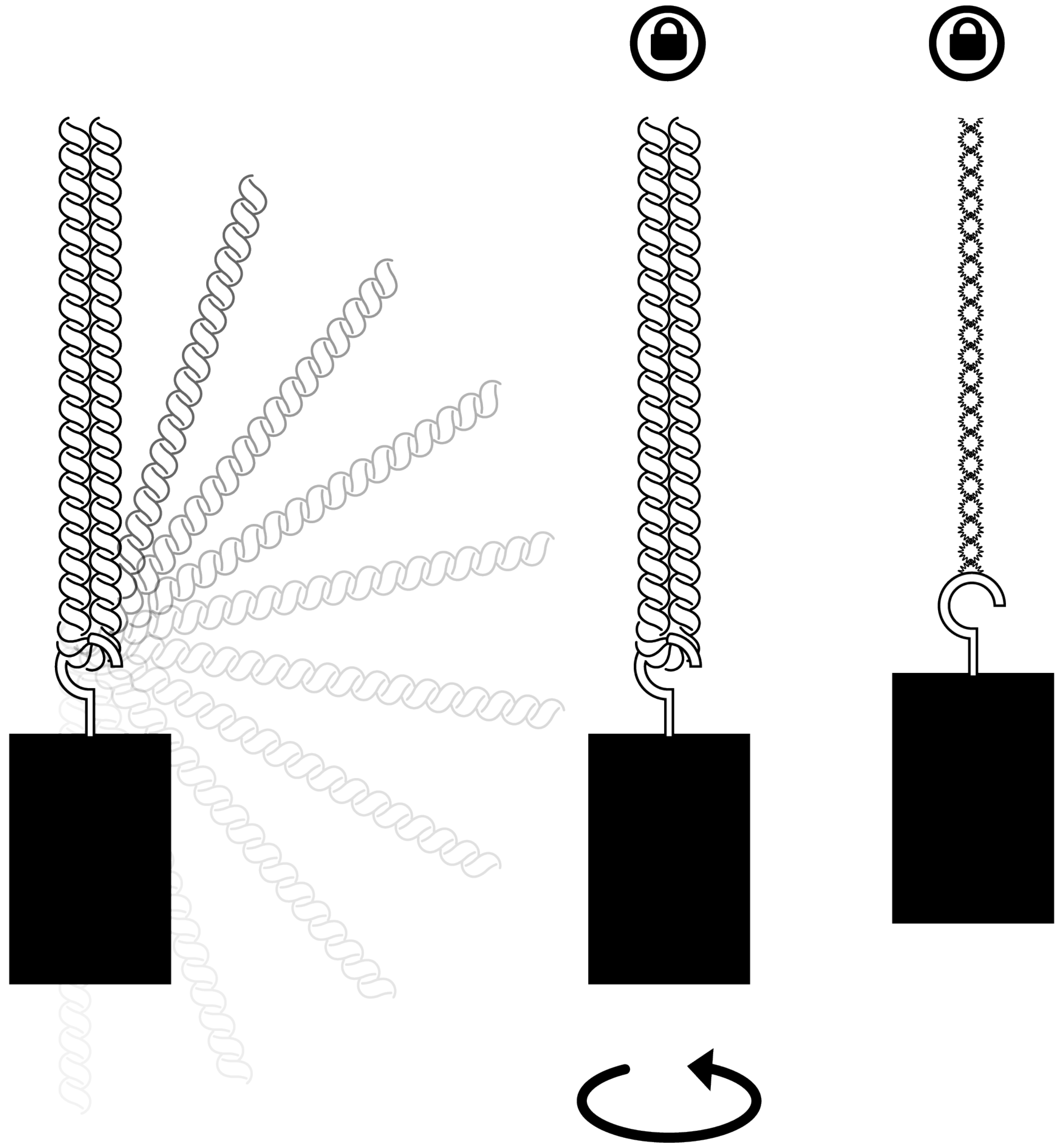
Fabrication

Step 1: Coiling



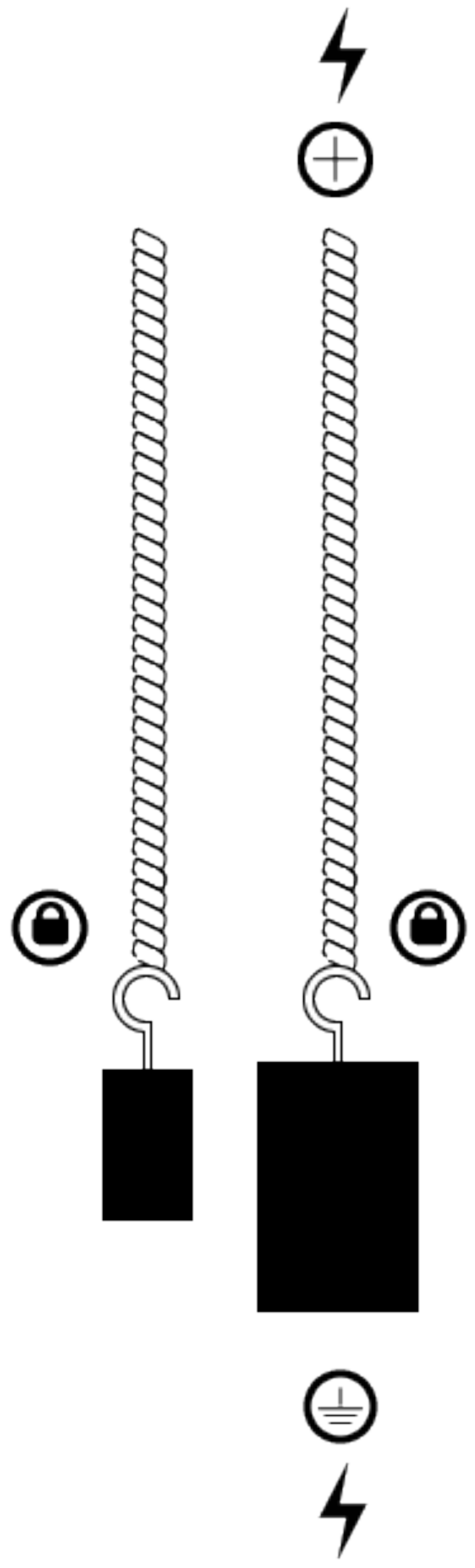
Fabrication

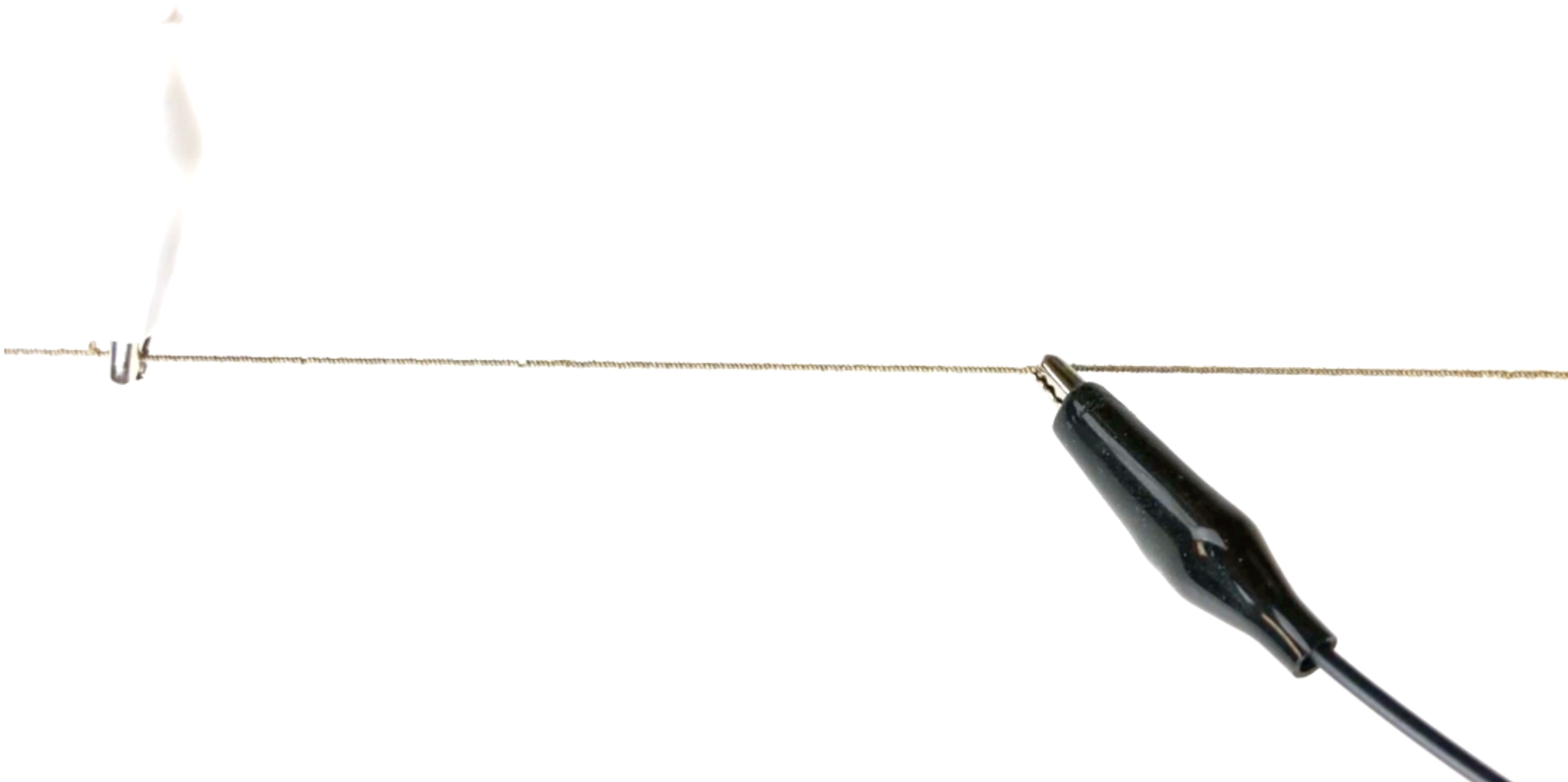
Step 2: Plying



Fabrication

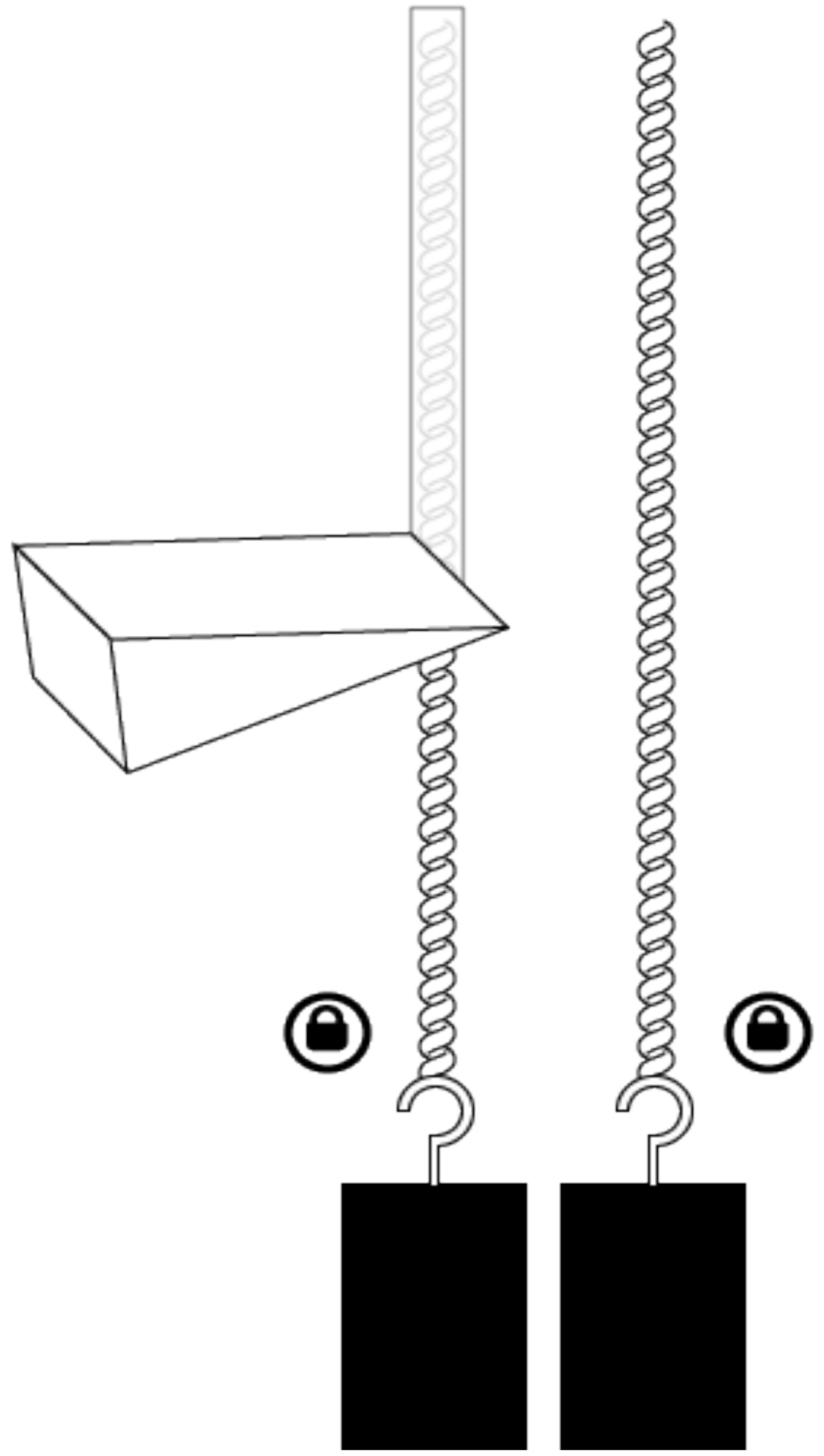
Step 3: Training



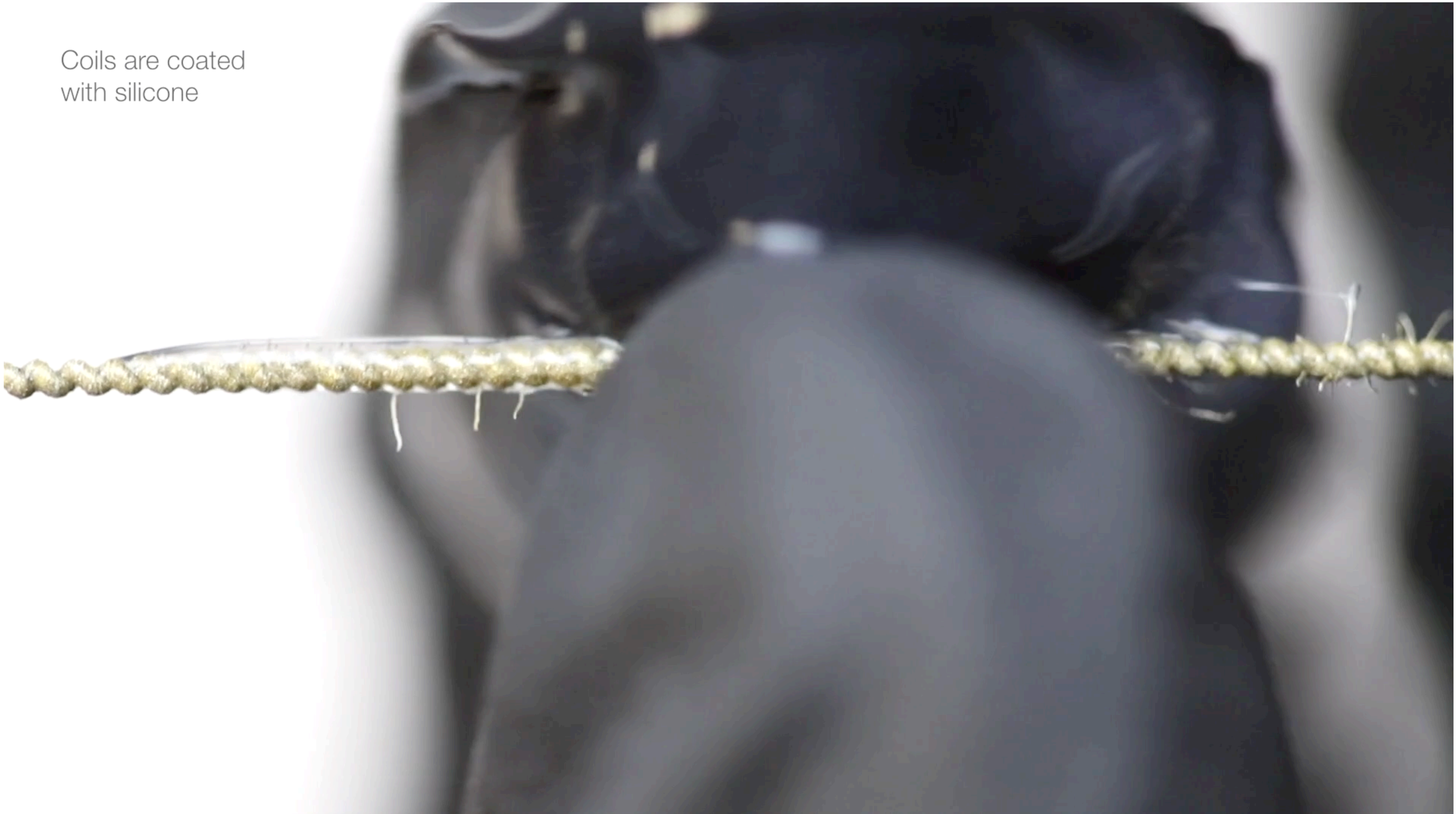


Fabrication

Step 4: Coating

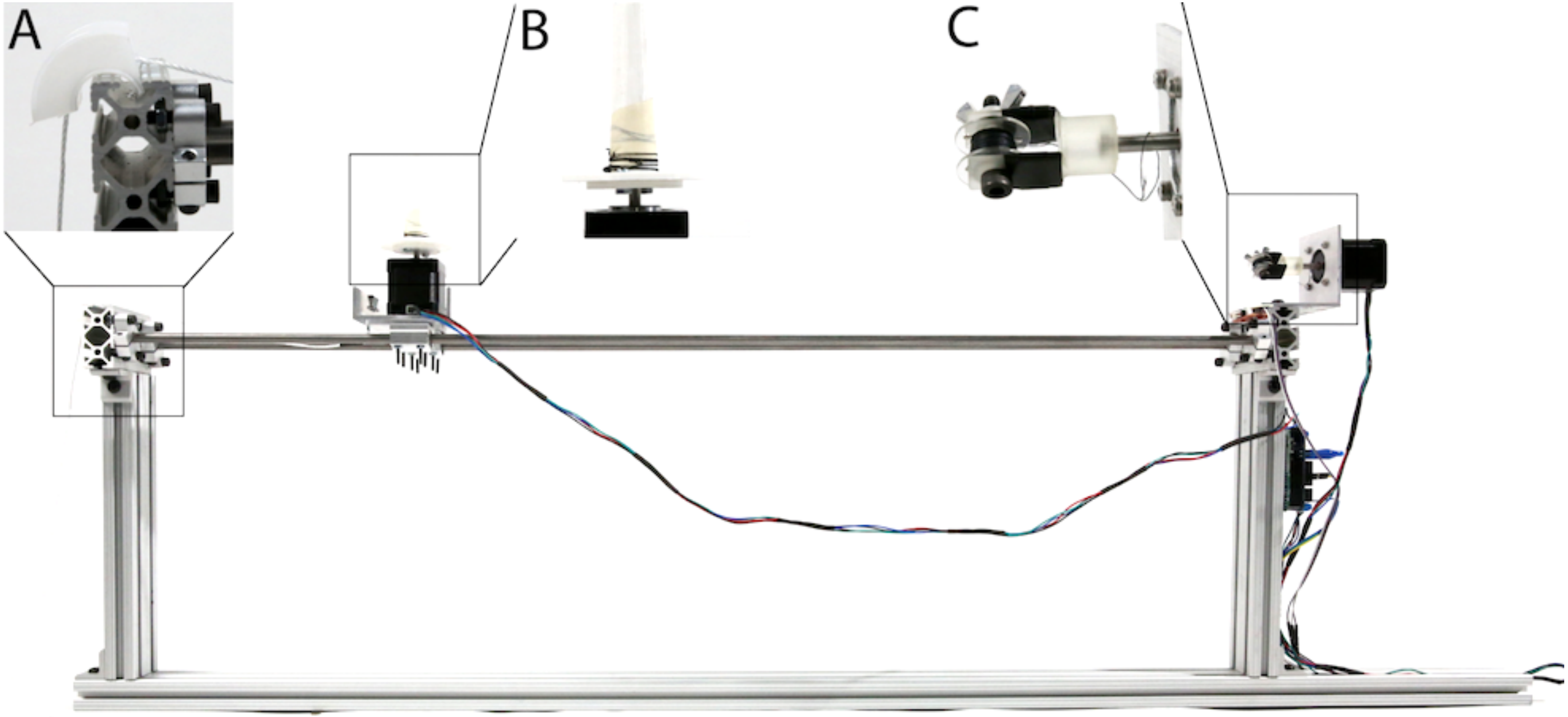


Coils are coated
with silicone



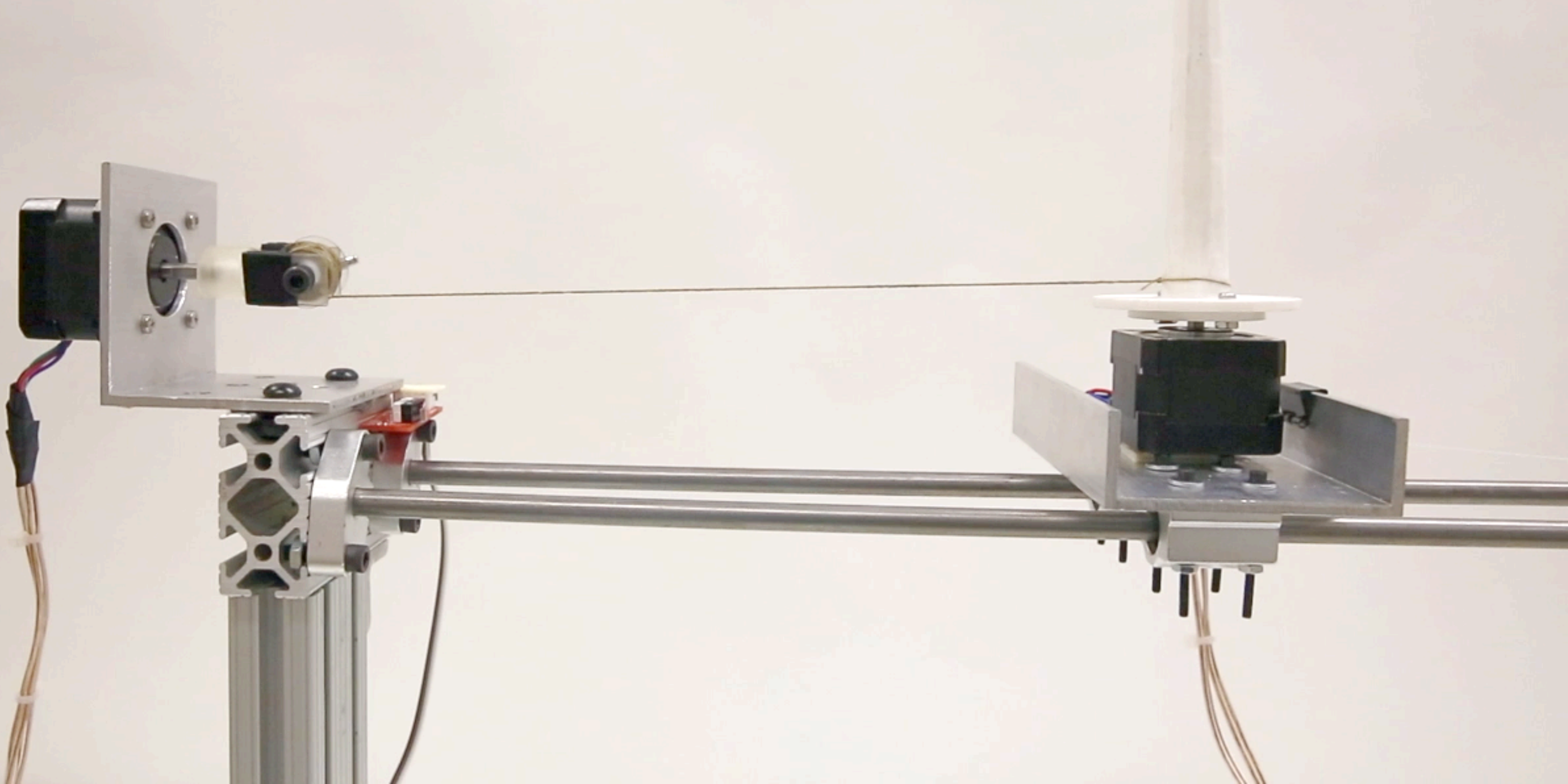
But what about much longer fibers?

Semiautomated Coiling



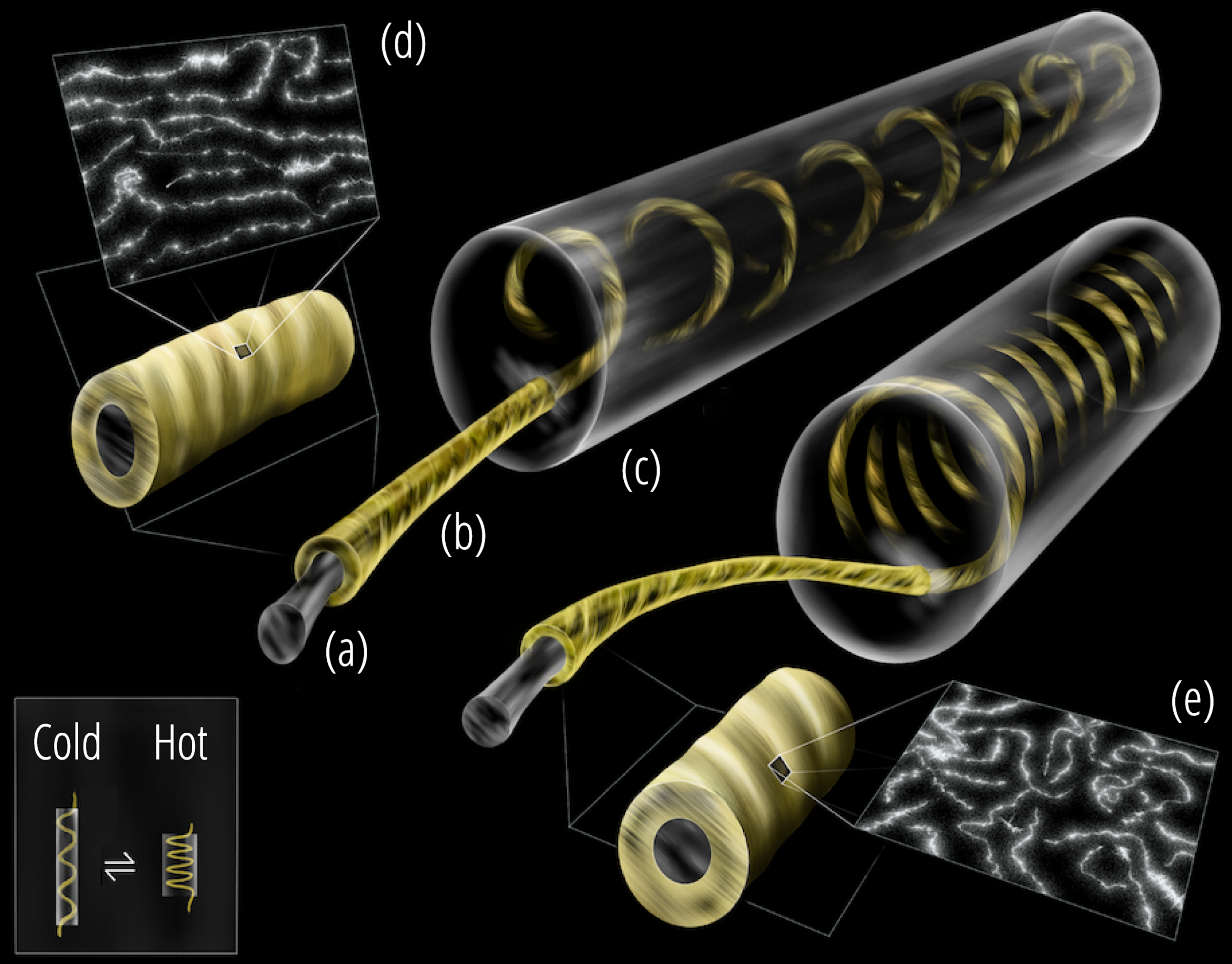
Fabrication

Semiautomated Coiling



ModiFiber

- TCP actuators coated in Silicone
- The compression of the silicone after actuation restores the
- By using silver-coated fishing line, the heating element is embedded and sensing is possible

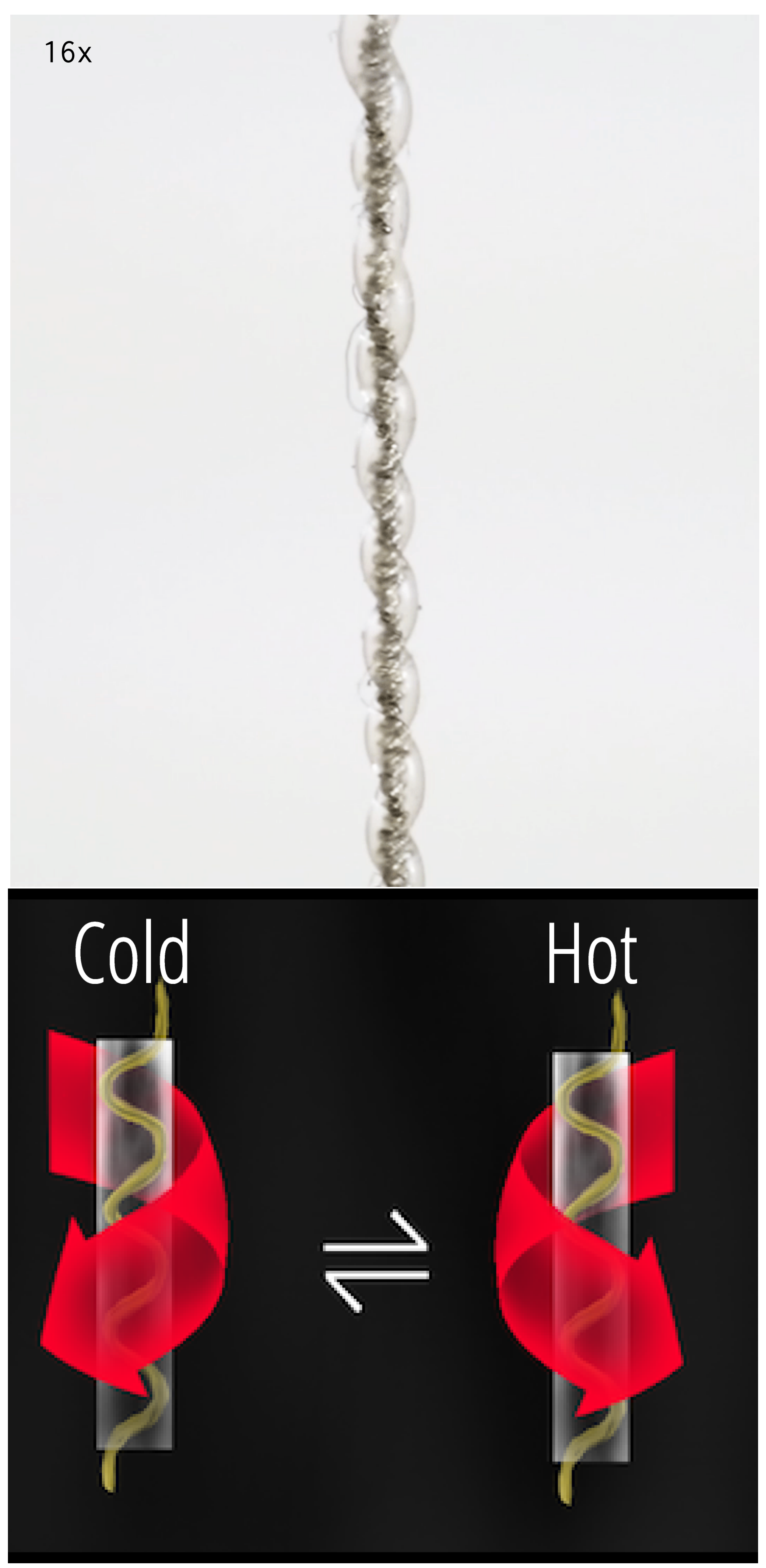


Source: Forman, Jack, et al. "Modifiber: Two-way morphing soft thread actuators for tangible interaction." *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019.

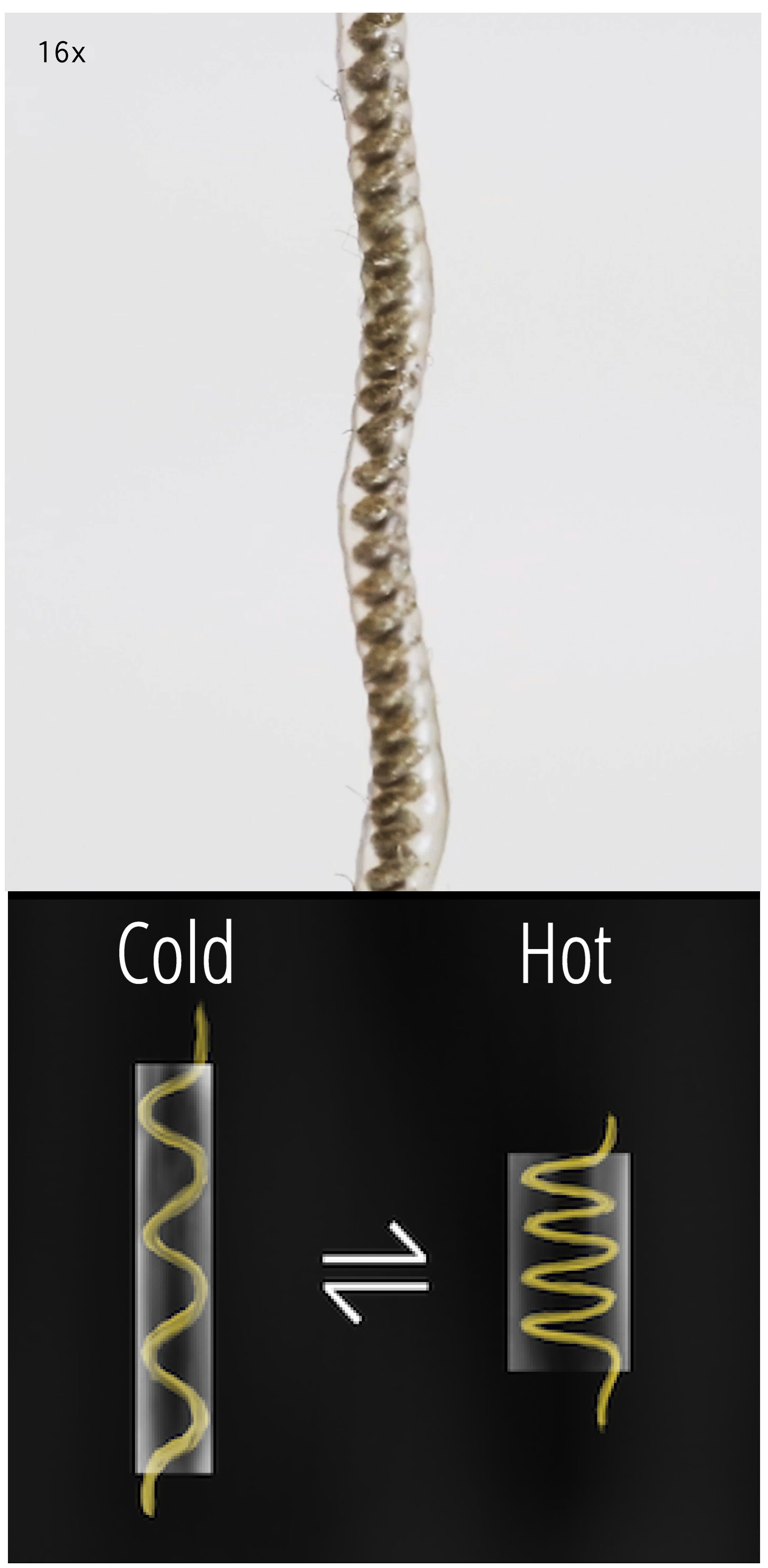
Actuation

Motion Types

(a) 1-Ply Twisting



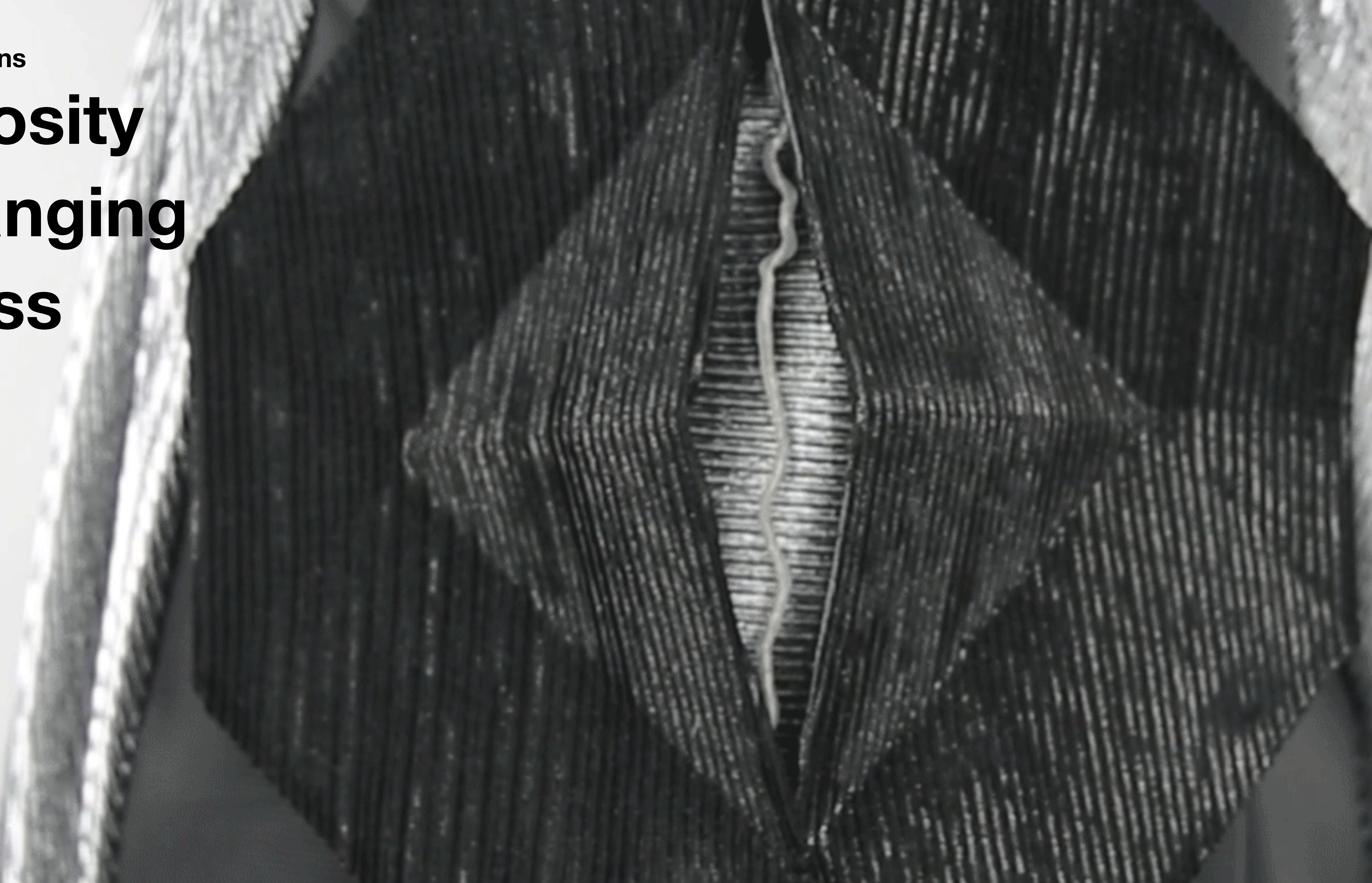
(b) 1-Ply Shrinking



(c) 2-Ply Shrinking

Applications

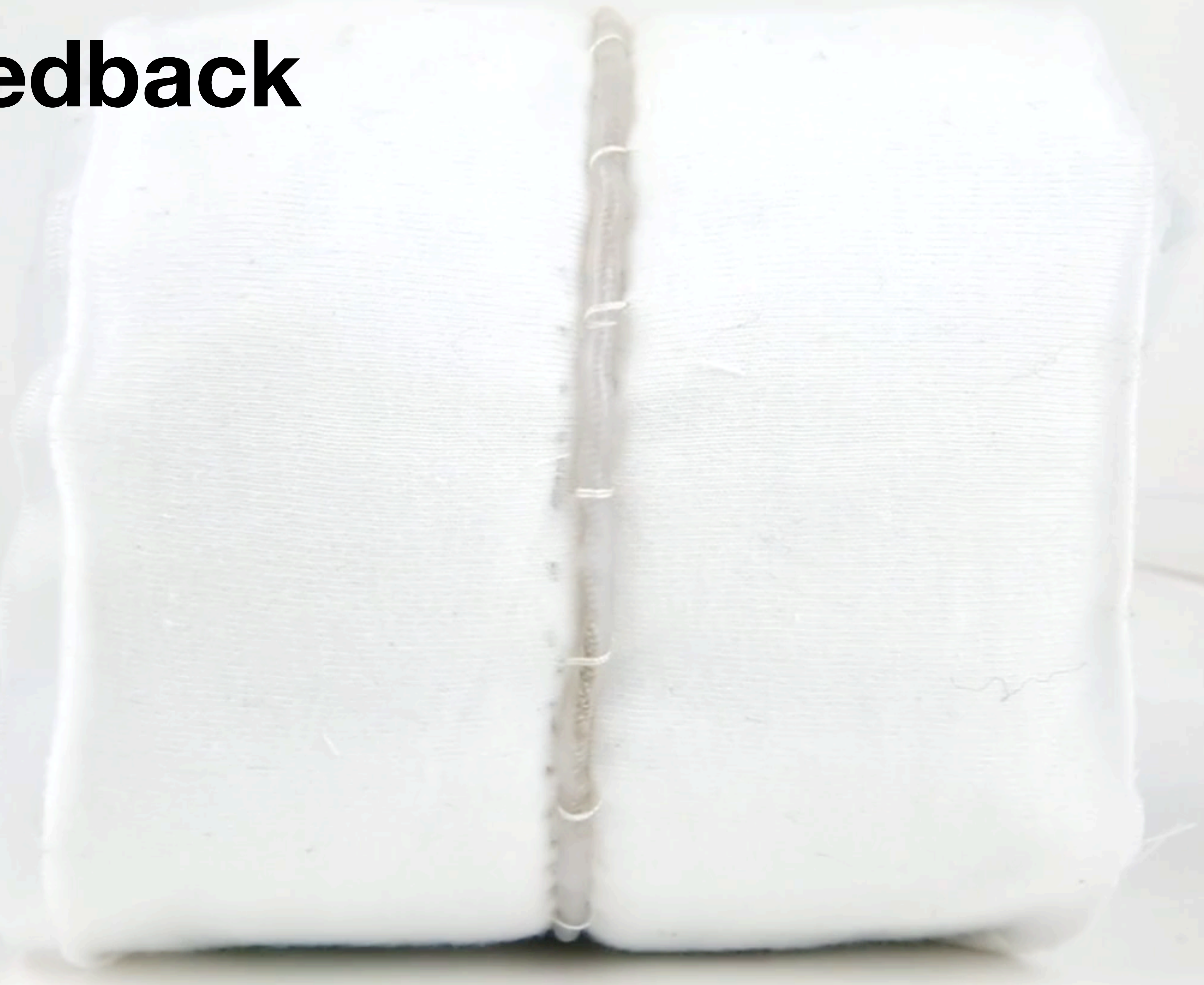
Porosity Changing Dress



Explorations

Fabric-Embedded Haptic Feedback

Constriction becomes noticible after 5 minutes



x30

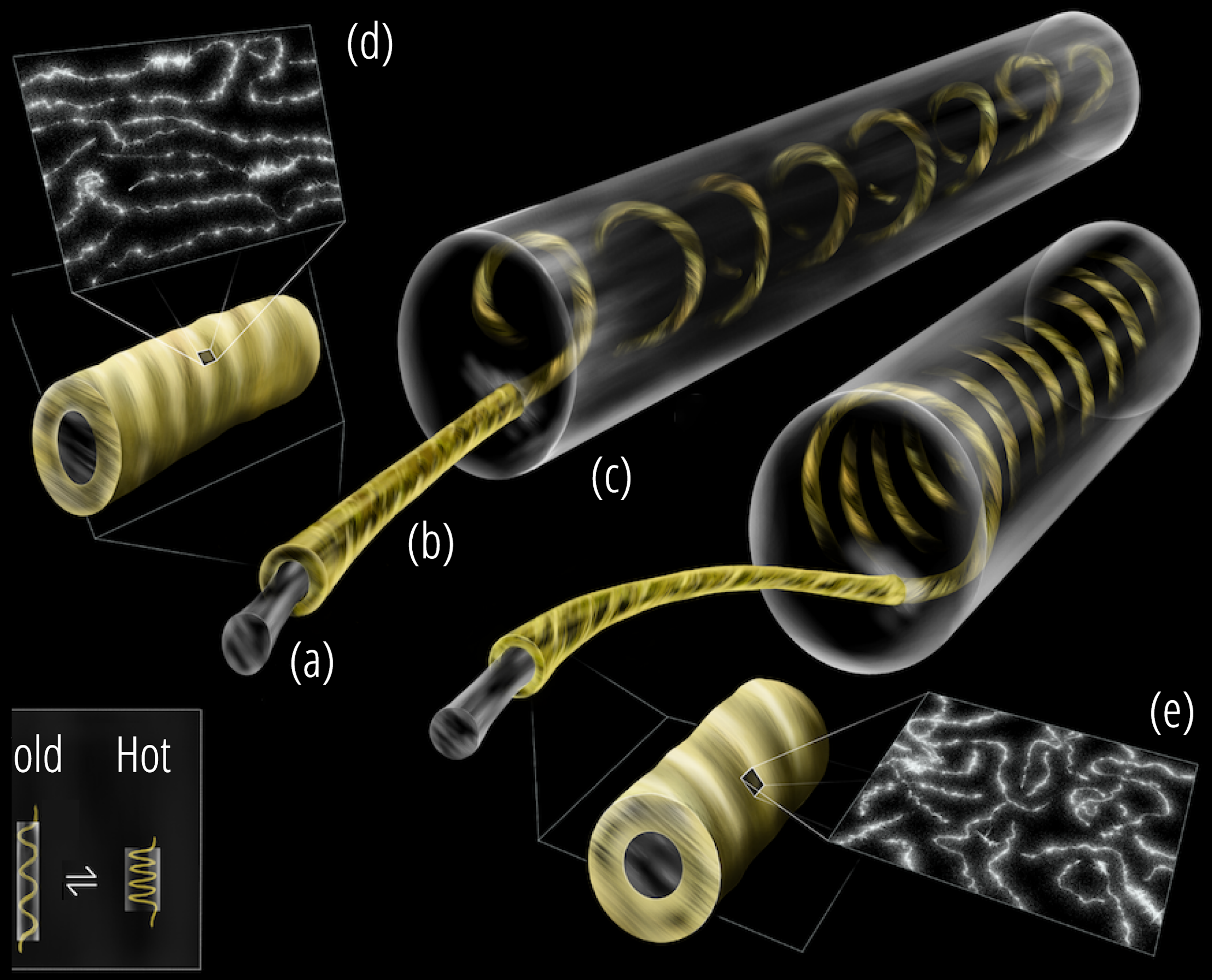
Application:
Non-invasive Haptics
2-Ply Shrinking Actuator

Functional Garment

Notification triggers
actuators embedded
in sleeve

ModiFiber

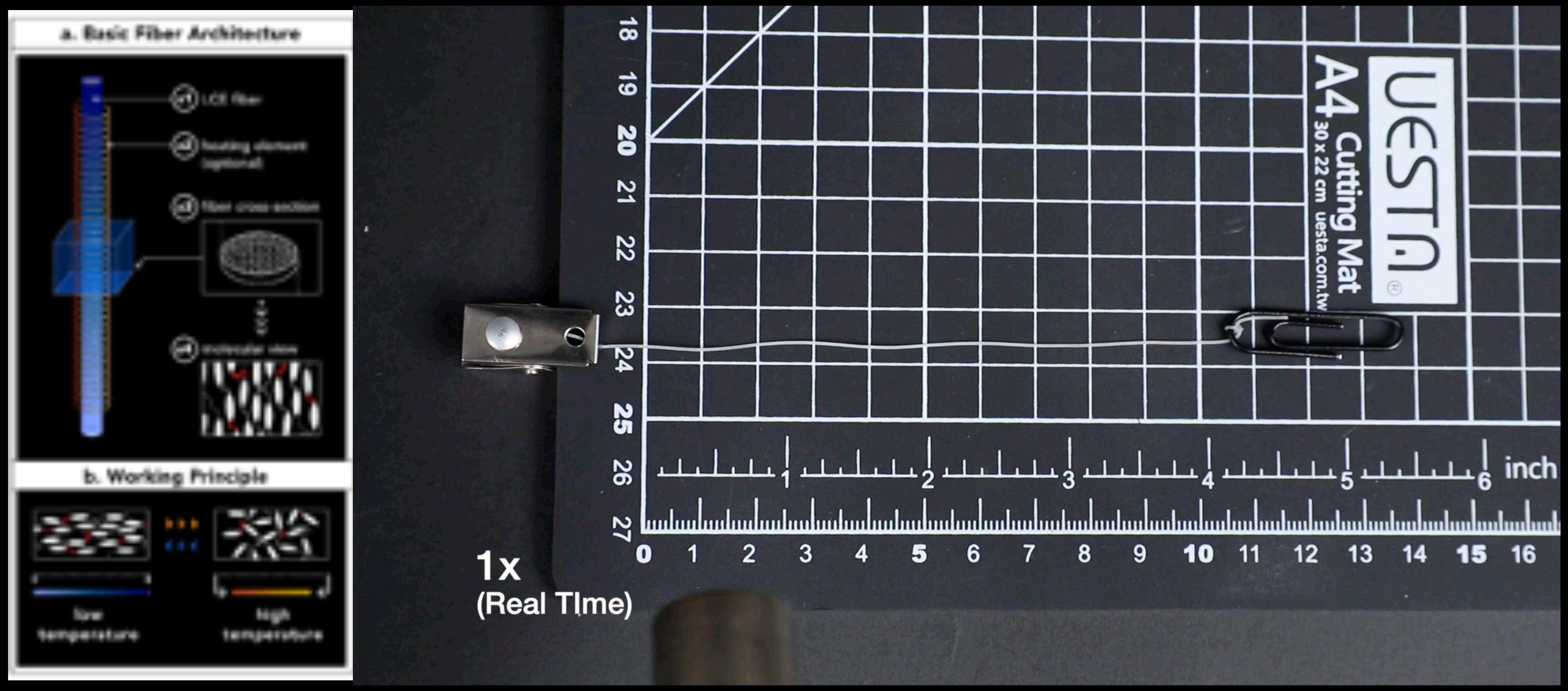
- Pros
  - Cheap to produce
  - Self-reversing
- Cons
  - Slow actuation speed (~5 minutes)
  - High temperatures needed



Forman, Jack, et al. "Modifiber: Two-way morphing soft thread actuators for tangible interaction." *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019.

Liquid Crystal Elastomer Fibers

- Soft rubbery material
- Massive strains of 40-60%
- Self-reversing
- 1 Hz actuation speed
- Actuation temperatures from 15-60°C



Liquid Crystal Fiber Overview

Source: Forman, J., Kilic Afsar, O., Lin, R., Nicita, S., Yang, L., Kothakonda, A., Gordon, Z., Honnet, C., Dorsey, K., Gershenfeld, N., and Ishii, H. 2023

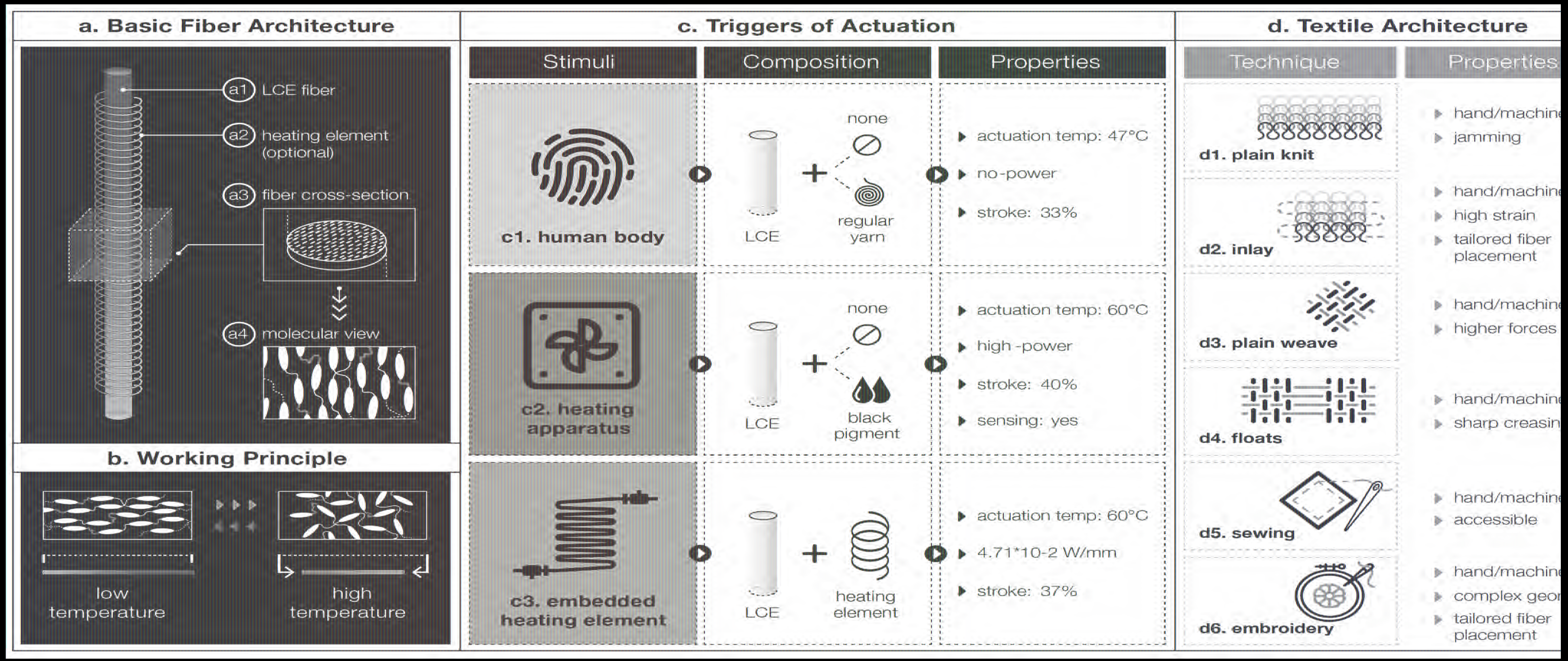
FibeRobo:

Fabricating 4D Fiber Interfaces by Continuous Drawing of Temperature Tunable Liquid Crystal Elastomers

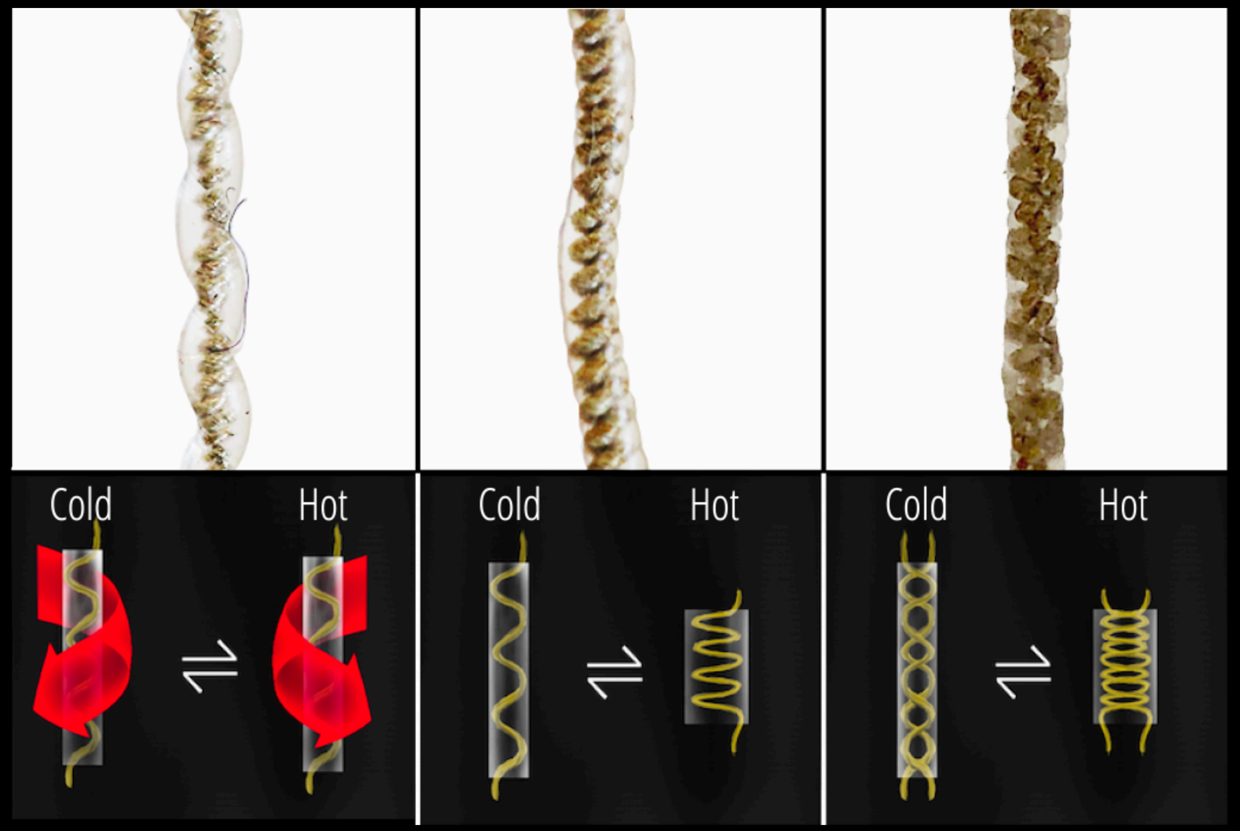
Jack Forman, Ozgun Kilic Afsar, Sarah Nicita, Rosalie Lin, Liu Yang, Megan Hofmann, Akshay Kothakonda, Zachary Gordon, Cedric Honnet, Kristen Dorsey, Neil Gershenfeld, Hiroshi Ishii

Overview

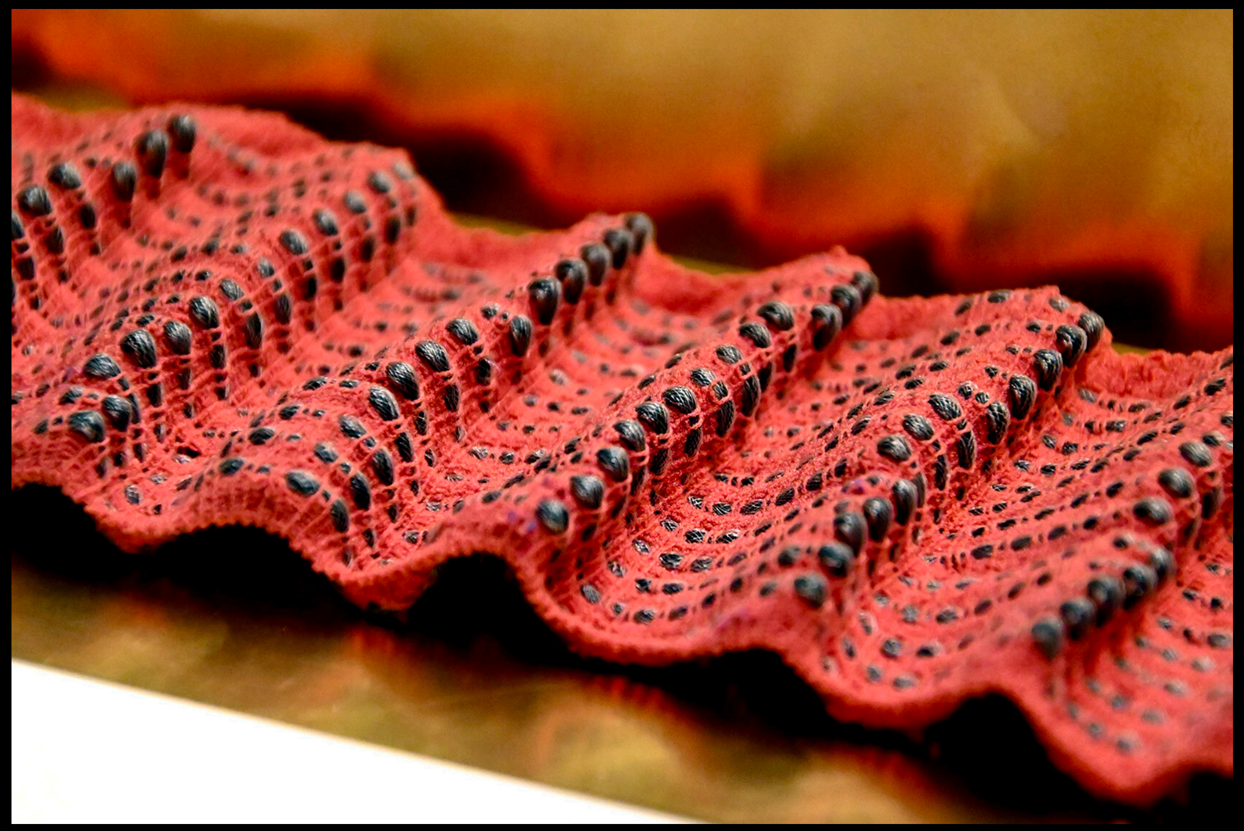
- Why Fabricate FibeRobo
- Fabricating FibeRobo
- Fabricating with FibeRobo
  - Knitting
  - Weaving
  - Embroidery



Related Work: Shape Shifting Fabric Interfaces



Forman et al. ModiFiber: Two-Way Morphing Soft Thread Actuators for Tangible Interaction. CHI 2019



Afsar et al. OmniFiber: Integrated Fluidic Fiber Actuators for Weaving Movement based Interactions into the 'Fabric of Everyday Life' UIST 2021

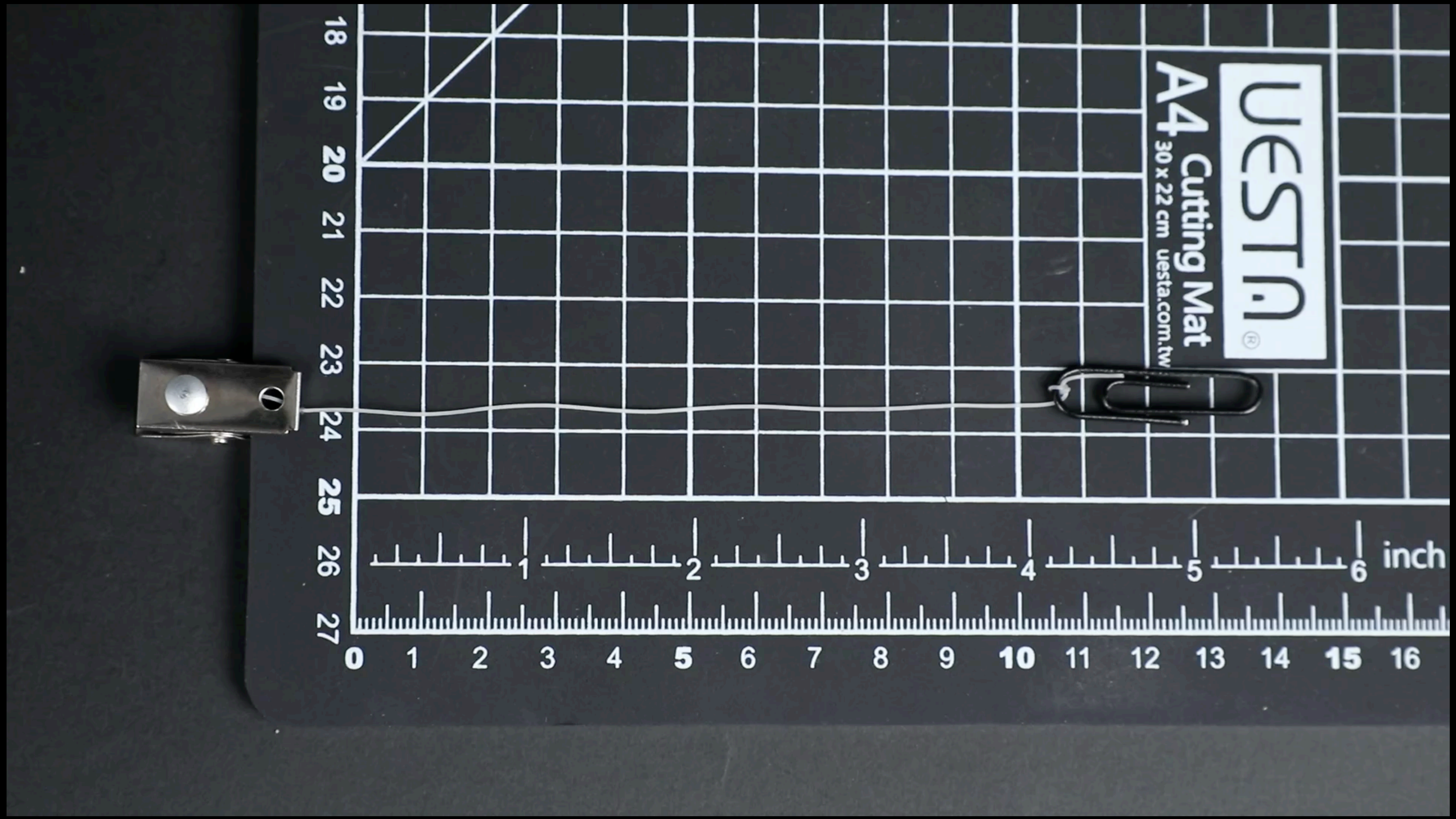
Kim et al. KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting. DIS 2021

Guiding Principles

- **Process Compatibility**
  - Work with, not against, standard textile machinery
- **Modifiable Materiality**
  - Enable fiber tunability for a specific application
- **Integrated Interactivity**
  - Embed dynamic digital interaction within a fabric form factor

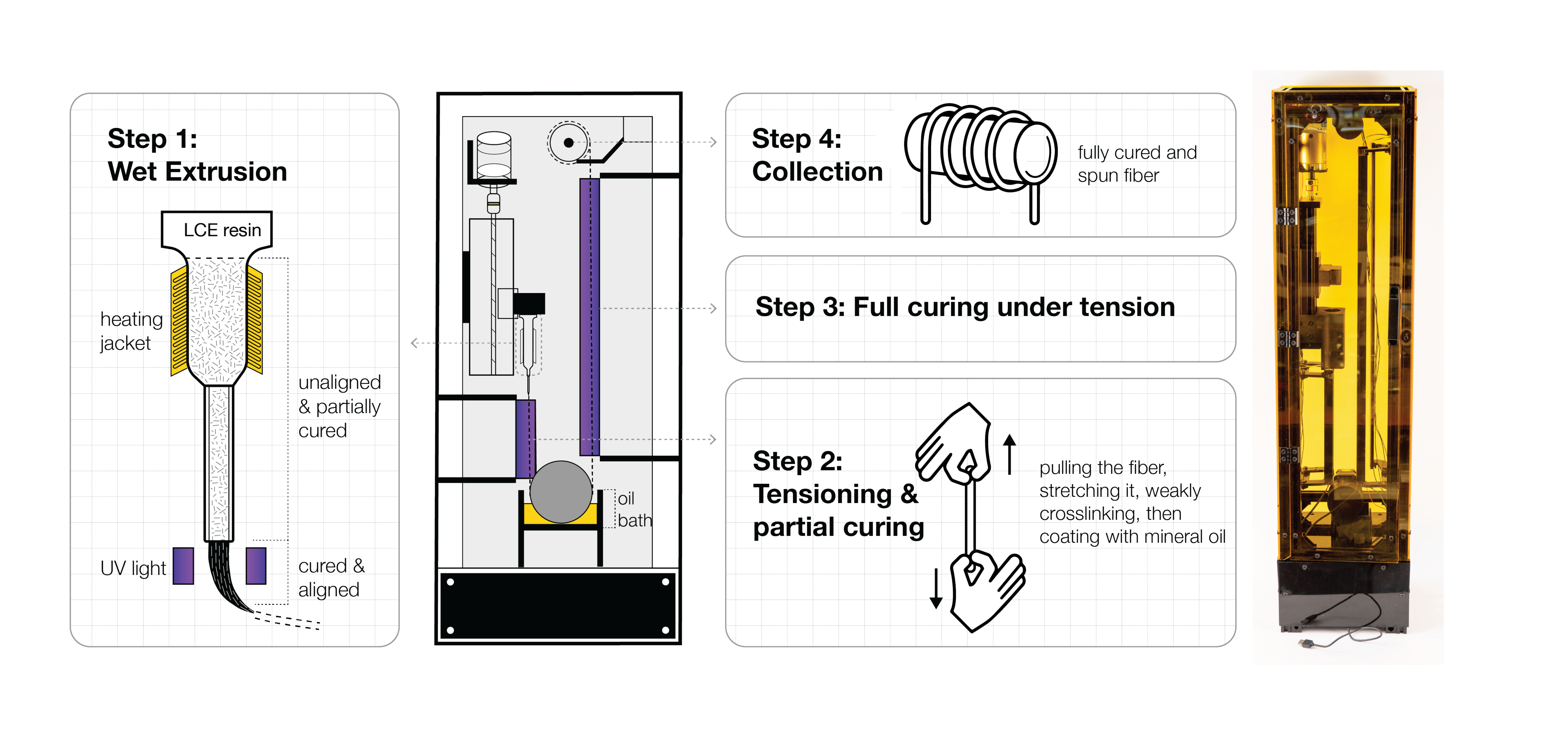
Key Features

- 42% contraction at ~60°C
- Self-reversing without hysteresis
- Can be triggered by heat or electricity
- Soft and safe to the touch
- Compatible with industrial knitting, weaving, sewing, etc.
- 30-60X cheaper to produce than purchasing SMA, with 10x more stroke



Actuation of fiber sample with heat gun
(real time)

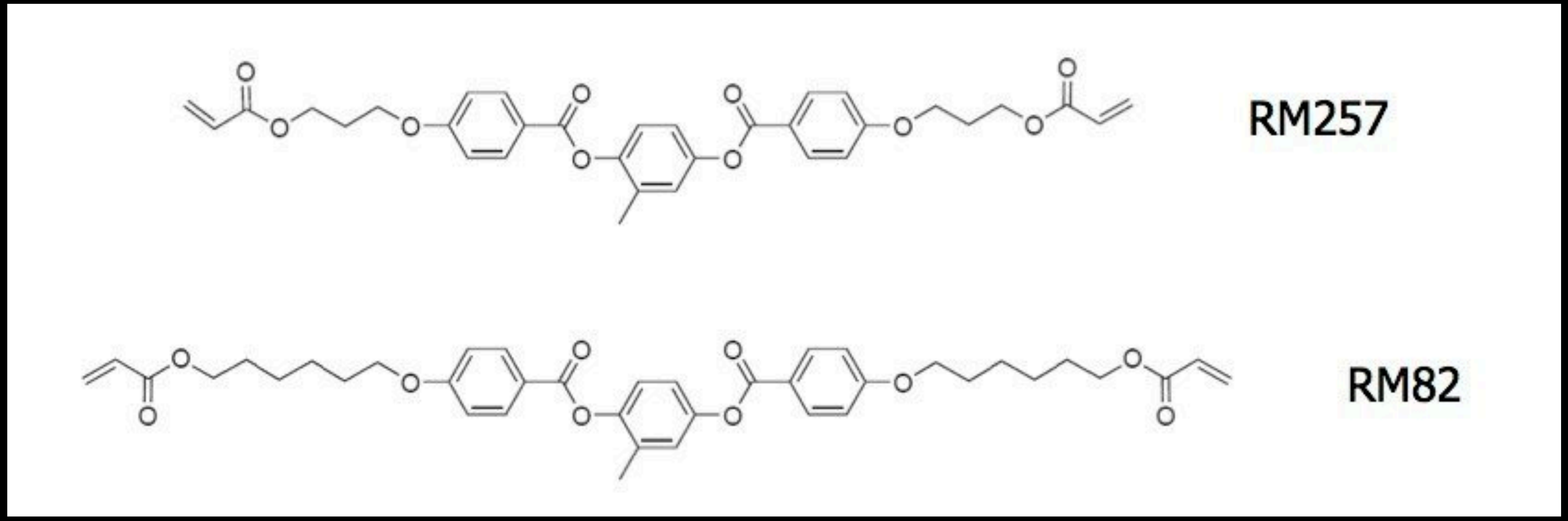
Fabrication Overview

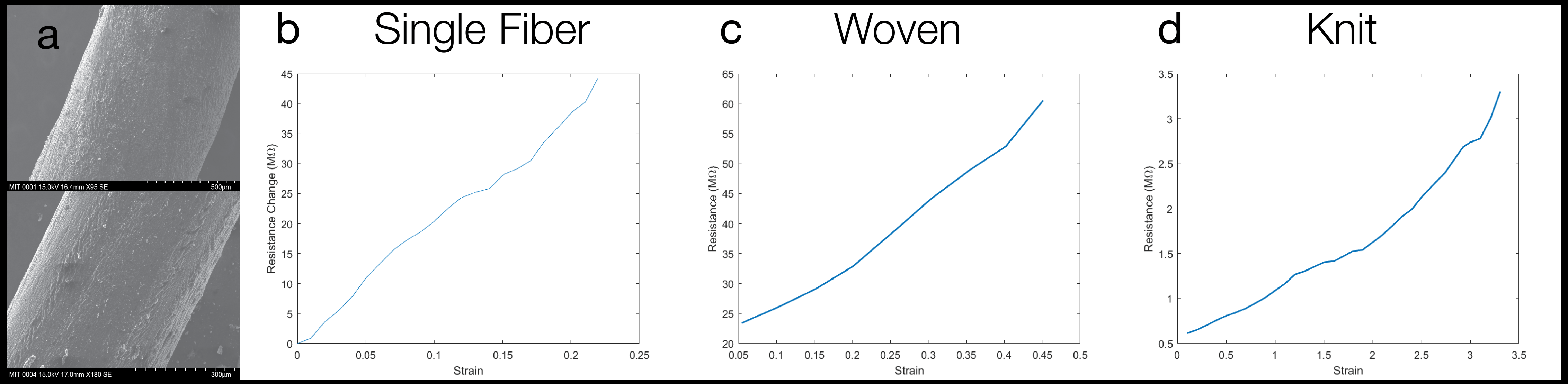


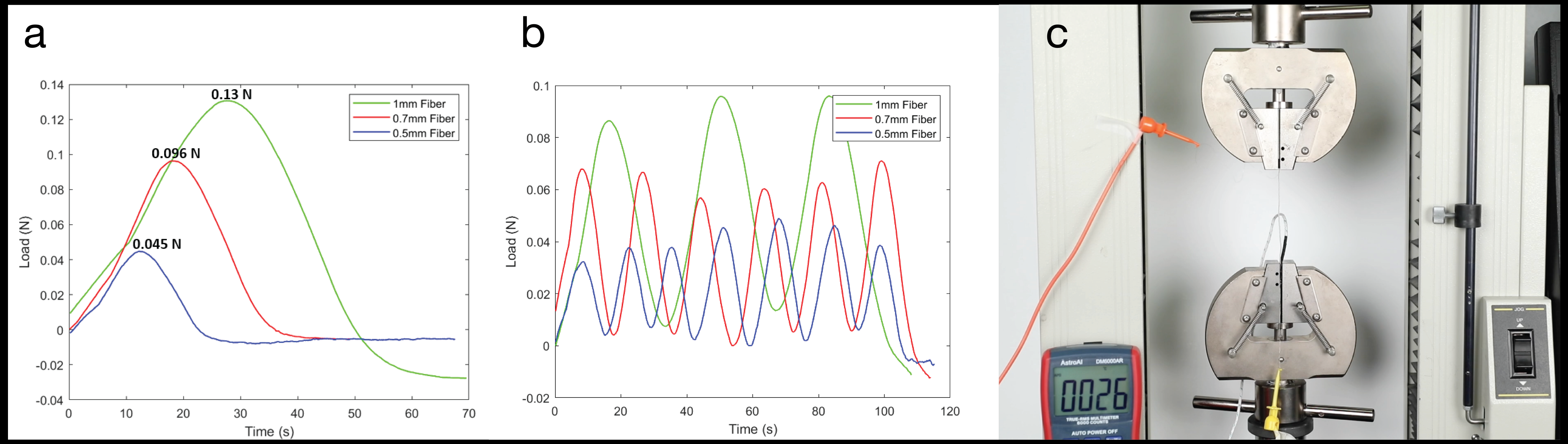
UV fiber spinning using
custom desktop setup

Fabrication Overview

- Actuation temperature changes with LC mesogen
- Carbon Black dyeing affords resistive sensing
- Thicker fibers generate more force but slower actuation

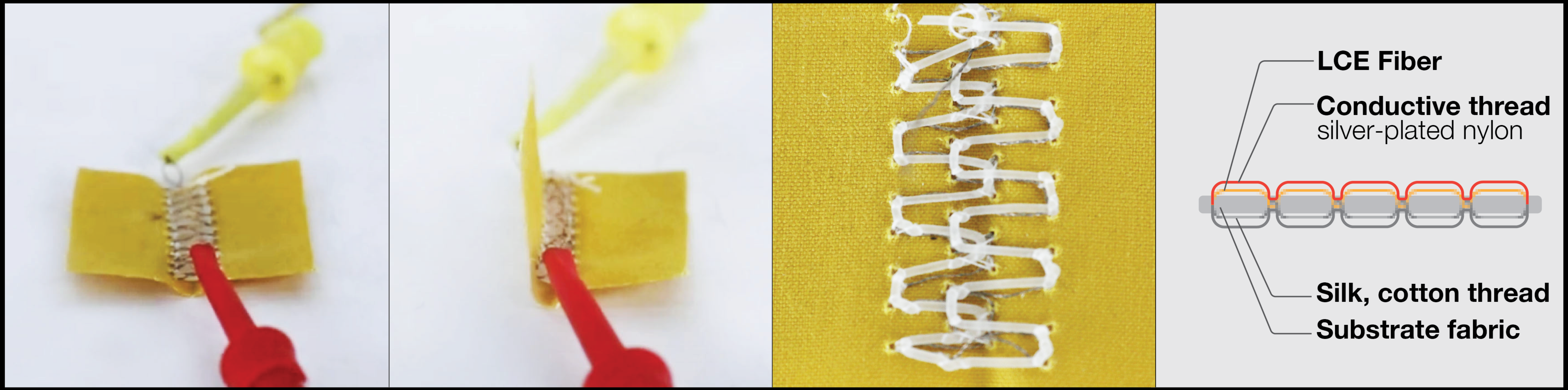


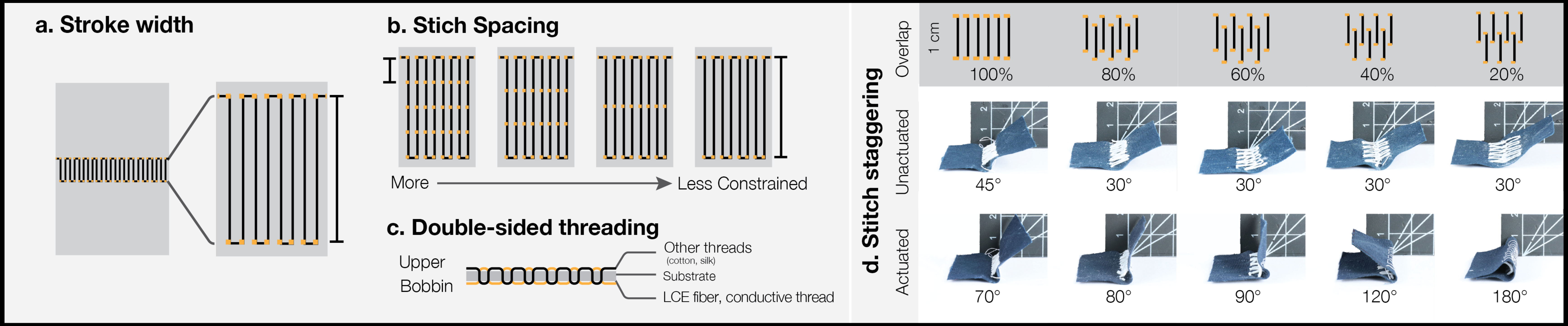





Braiding with litz wire enables
integrated heating

Embroidery

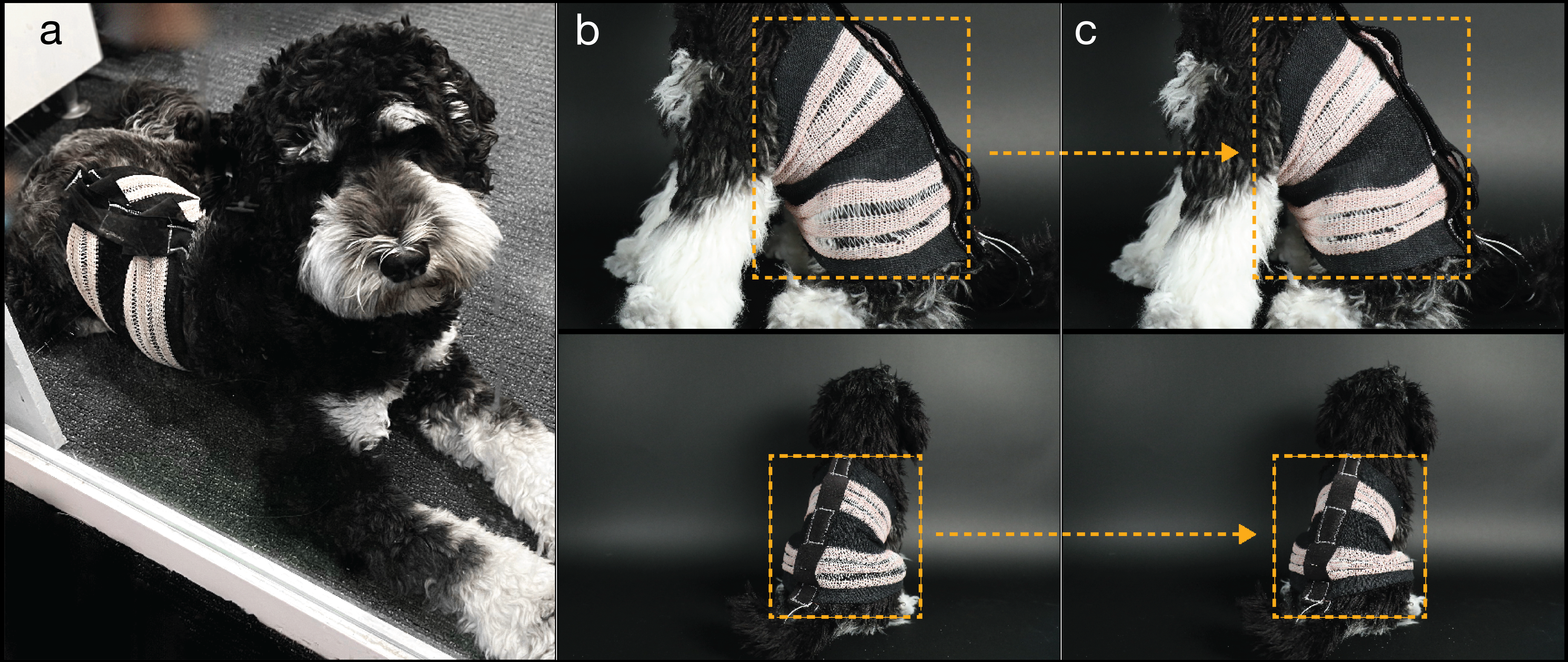

LCE Fiber
Conductive thread
silver-plated nylon
Silk, cotton thread
Substrate fabric


a. Stroke width
b. Stich Spacing
More
Less Constrained
c. Double-sided threading
Upper
Bobbin
Other threads
(cotton, silk)
Substrate
LCE fiber, conductive thread
d. Stitch staggering
Overlap
Unactuated
Actuated
1 cm
100%
80%
60%
40%
20%
45°
30°
30°
30°
30°
70°
80°
90°
120°
180°


Embroidered
blooming lampshade
20x

EiheRoho Knitting

FurbeRobo



Future Works

- Fabricating complex textile closed loop interfaces with weaving and knitting machines
- Reformulation of resin to make recyclable or compostable
- Making fibers even more accessible
- Understanding needs of textile designers and craftspeople

Jack Forman

Ozgun Kilic-Afsar

Sarah Nicita

Rosalie Hsin-Ju Lin

Liu Yang

Prof. Megan Hofmann

Akshay Kothakonda

Zachary Gordon

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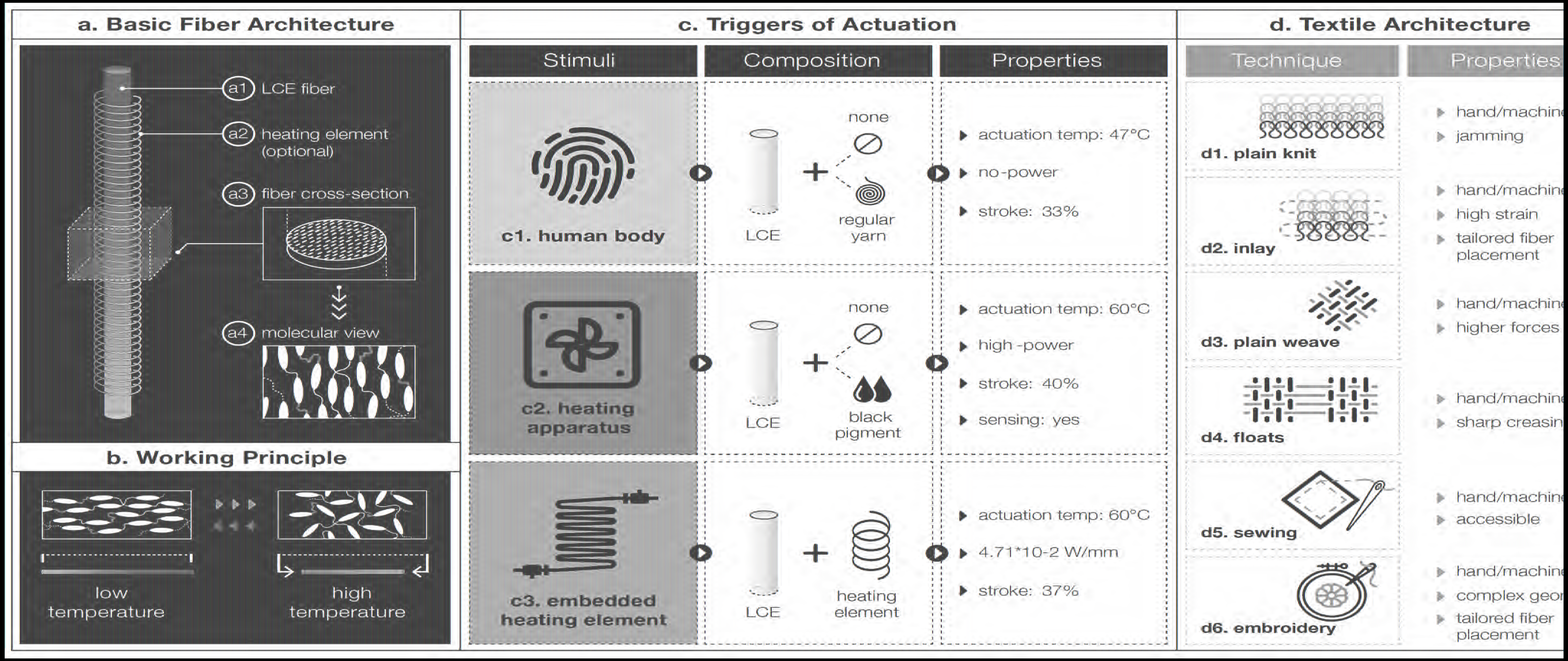

Overview

	Stimuli	Actuation Strain	Max Cycle Speed	Hysteresis	Self Reversing	Accesibility	Notes
McKibben	Pneumatic/ Hydraulic	~66%	40 Hz	Neglible	Yes	Commercially Available	Bulky/Noisy pump required
Dielectric Elastomer	Voltage (kV)	~10%	700 Hz	Neglible	Yes	Early Laboratory Material	Extremely high voltages needed
Shape-Memory Alloy	Thermal	~5%		Significant	No	Commercially Available	Stiff, hard to work with, stops working
Fishing Line Actuators	Thermal	~10-30%	~2 Hz	Neglible	No	Easy and Cheap to produce	Requires external bias force, difficult to prevent twisting during actuation
Liquid Crystal Elastomers	Thermal	~40-60%	~1 Hz	Neglible	Yes	Early Laboratory Material	Easiest to work with!` n

Wildcard Week?!

Thank you! Any Questions?

Wanna work on artificial muscles? Reach out!

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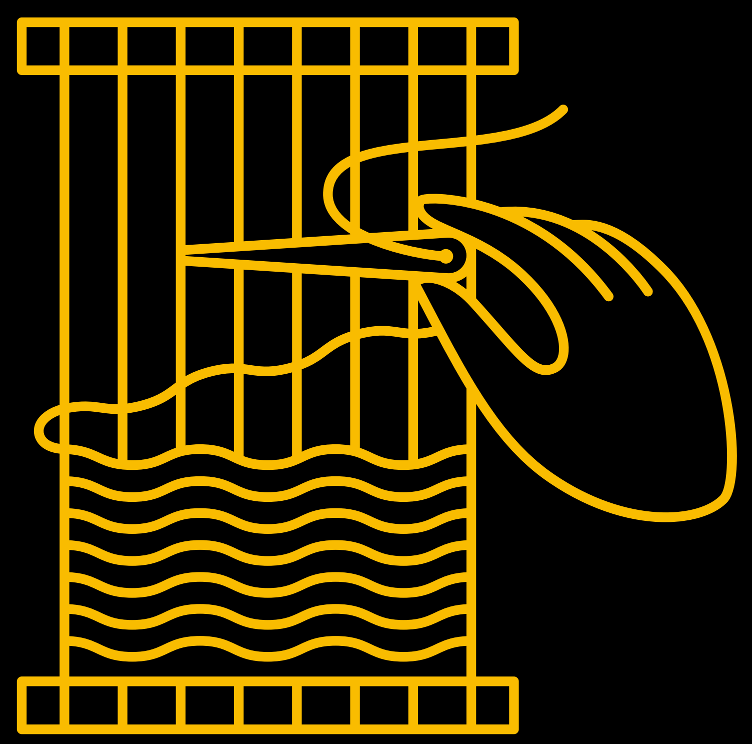
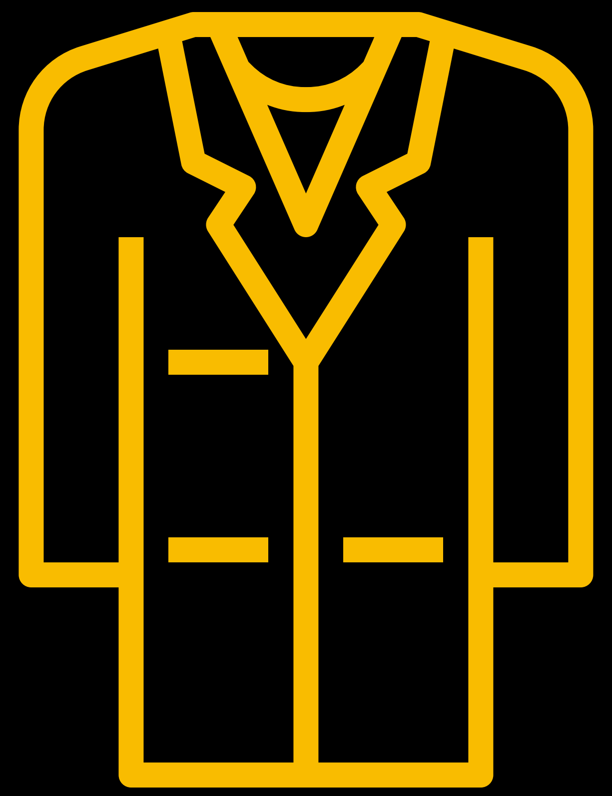
Forman’s Four F’s of Fabric Formation

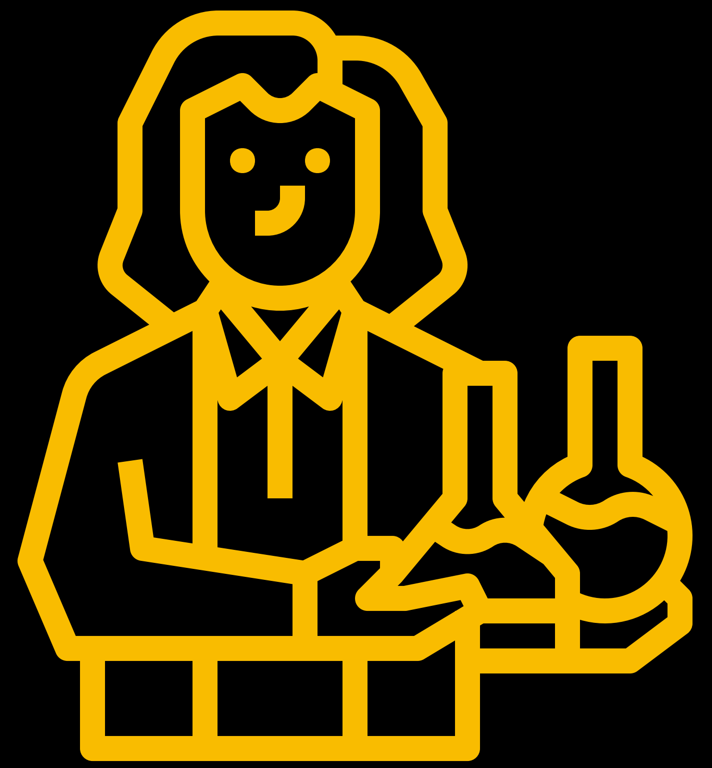
Fiber



Fabrication



Form



Function