# Week 06: Magnetoelastic Microrobots

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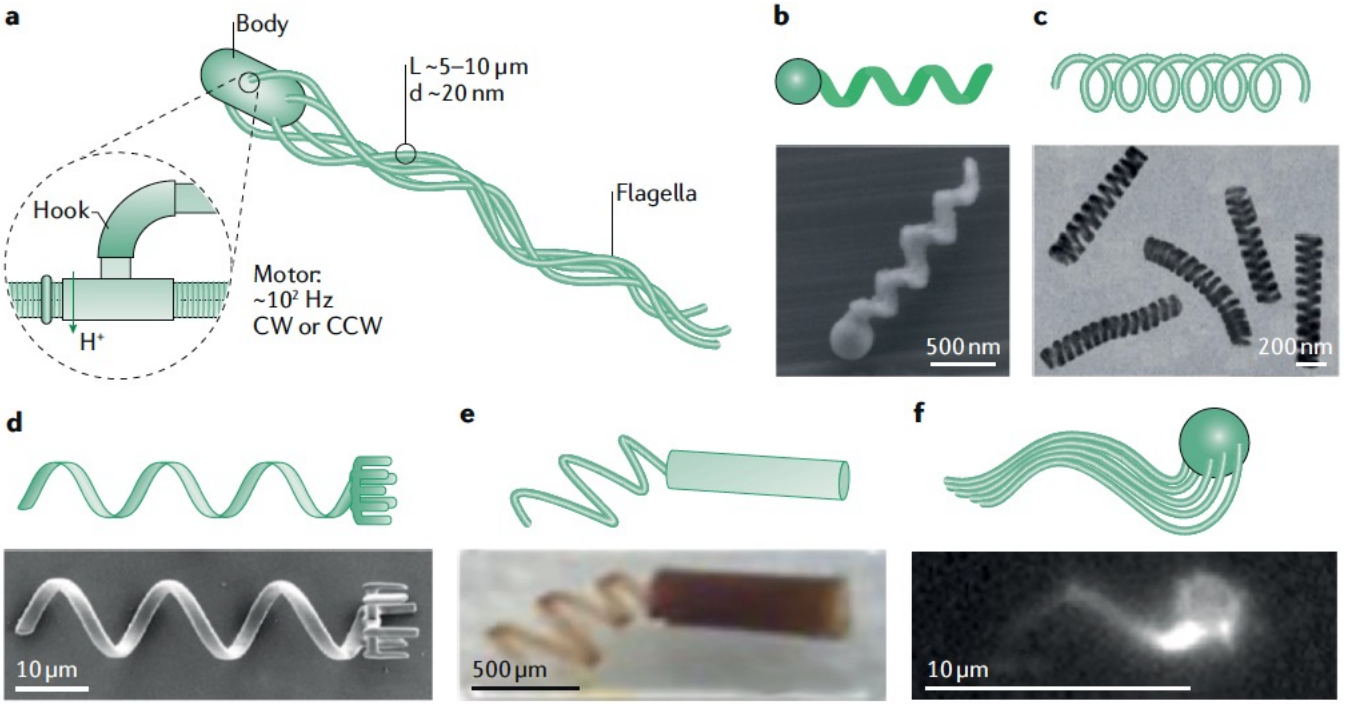
# Lecture Overview

- Bioinspired swimming strategies
- Magnetoelastic microrobots
- Medical instruments

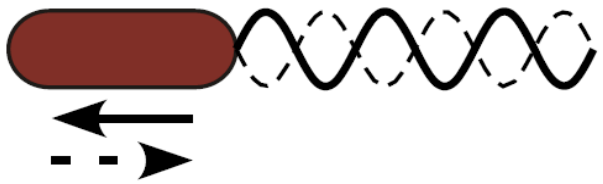
# Swimming at Low Reynolds Number

- How to elude the scallop theorem (Aristotelian fluid regime)
  - Rotate a chiral arm
  - Wave an elastic arm

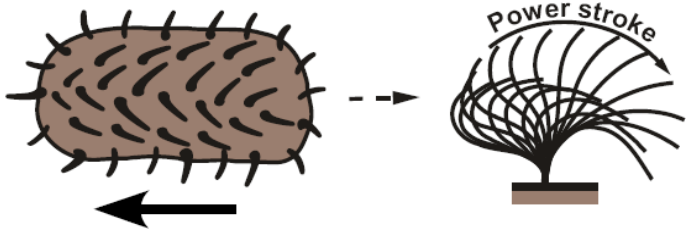


# Eukaryotic Flagella and Cilia

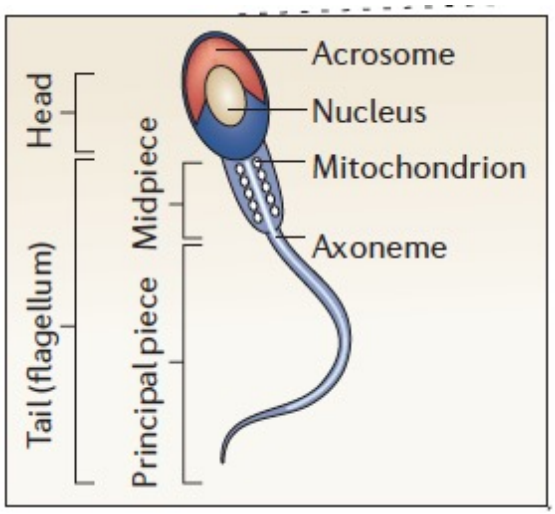
- **Eukaryotic flagella**
  - Active organelles which create traveling waves
  - Swimming direction can be reversed by reversing the direction of the wave
    - Head-to-tail: moving forward
    - Tail-to-head: moving backwards

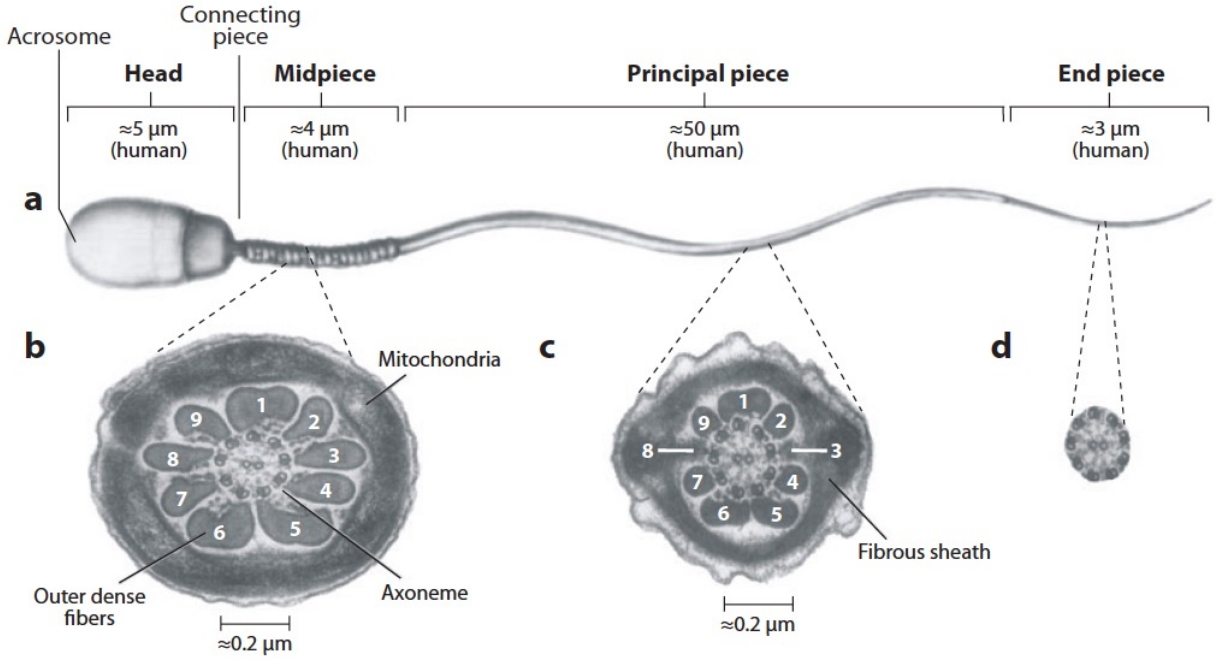


- **Cilia**
  - Active organelles
  - Held perpendicular during the power stroke
  - Parallel during recovery stroke



# Sperm Flagella



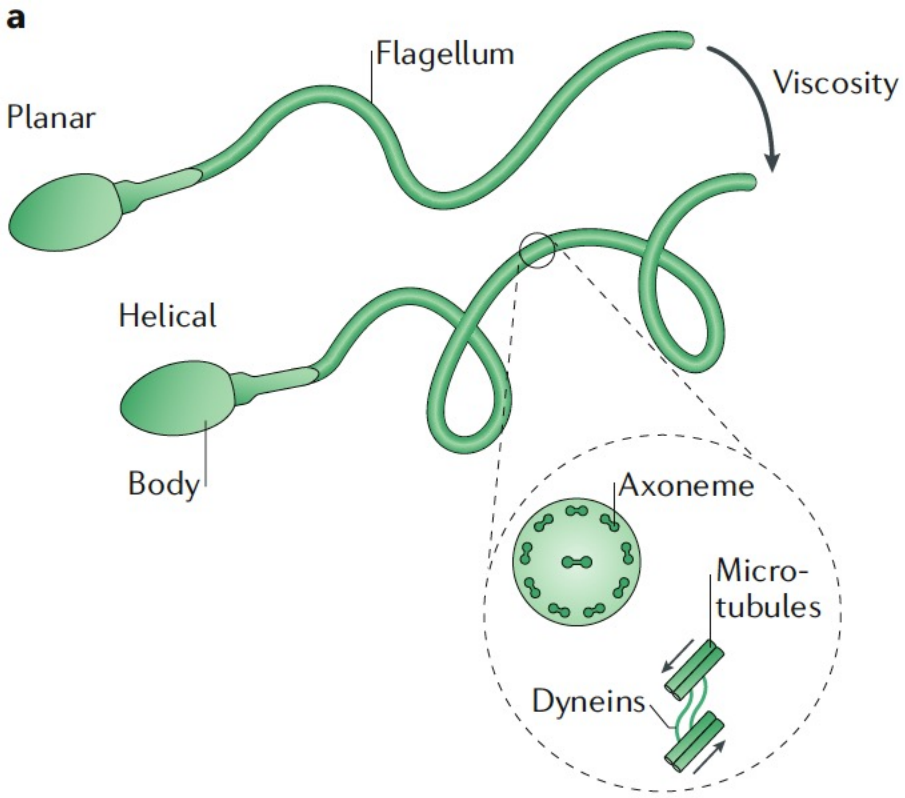

- Elastic connecting piece
- Active force arises from the action of dynein motors
- Bending wave propagating from head to the tail
- Beating frequency and waveform is modulated by calcium signaling

# Eukaryotic Flagellum

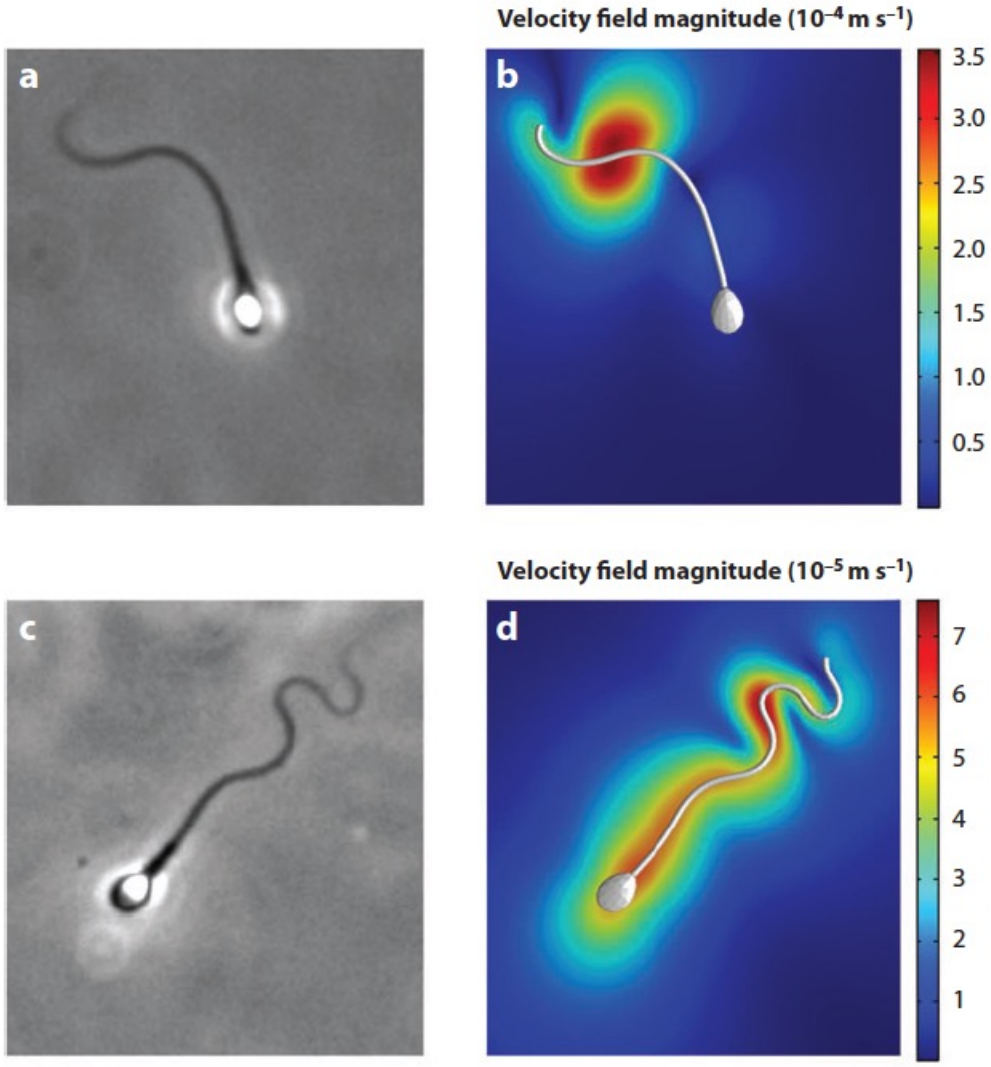
- Sperm cells swim owing to bending waves that propagate along their long, flexible flagellum

- The whole tail is actuated
  - Bending is powered by dynein motor proteins that cause sliding of microtubule doublets in the axoneme
- The waveform depends on the viscosity of the surrounding fluid: planar or helical

- Long and thin flagellum
  - Guarantees asymmetry in the resistance to forward and sideways motion

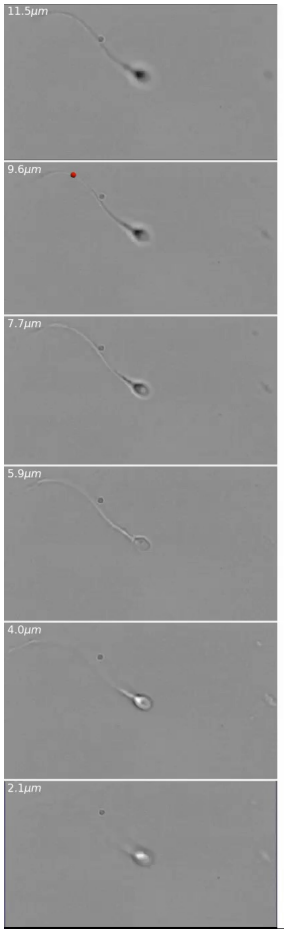


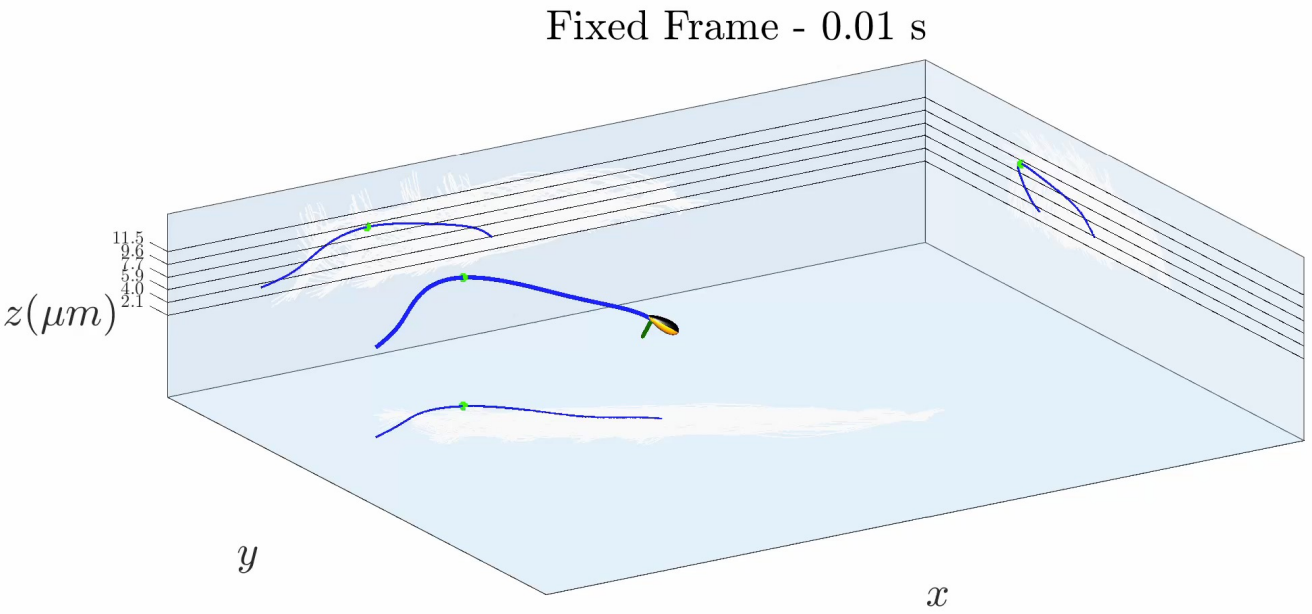
# Sperm Motility (video)




- Human sperm migrating in low and high viscosity fluids
- Boundary element method/Slender-body theory for fluid mechanics calculations
- Flow-field disturbance is an order of magnitude greater in low viscosity medium

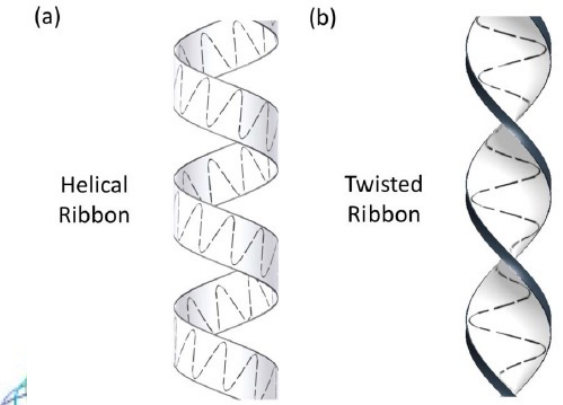
# Sperm Motility

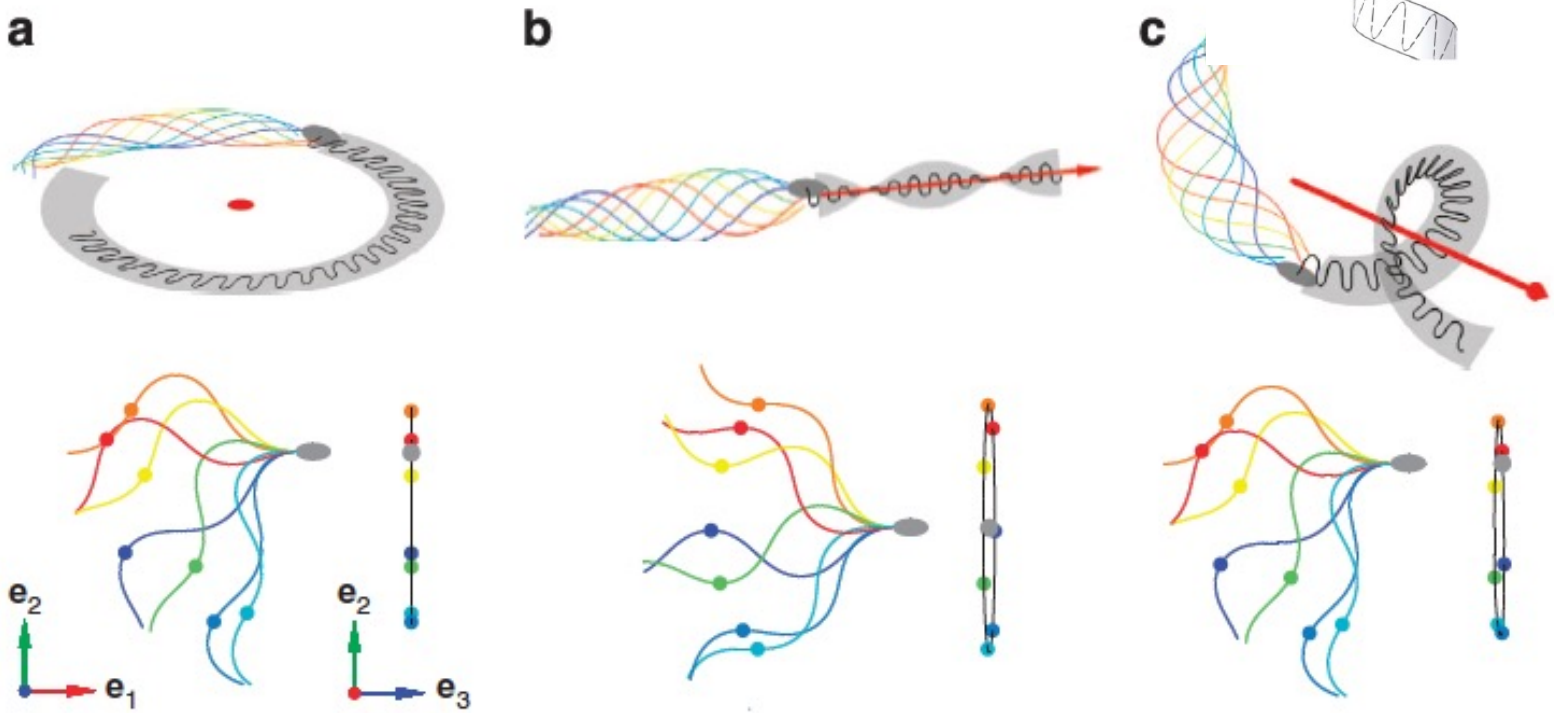


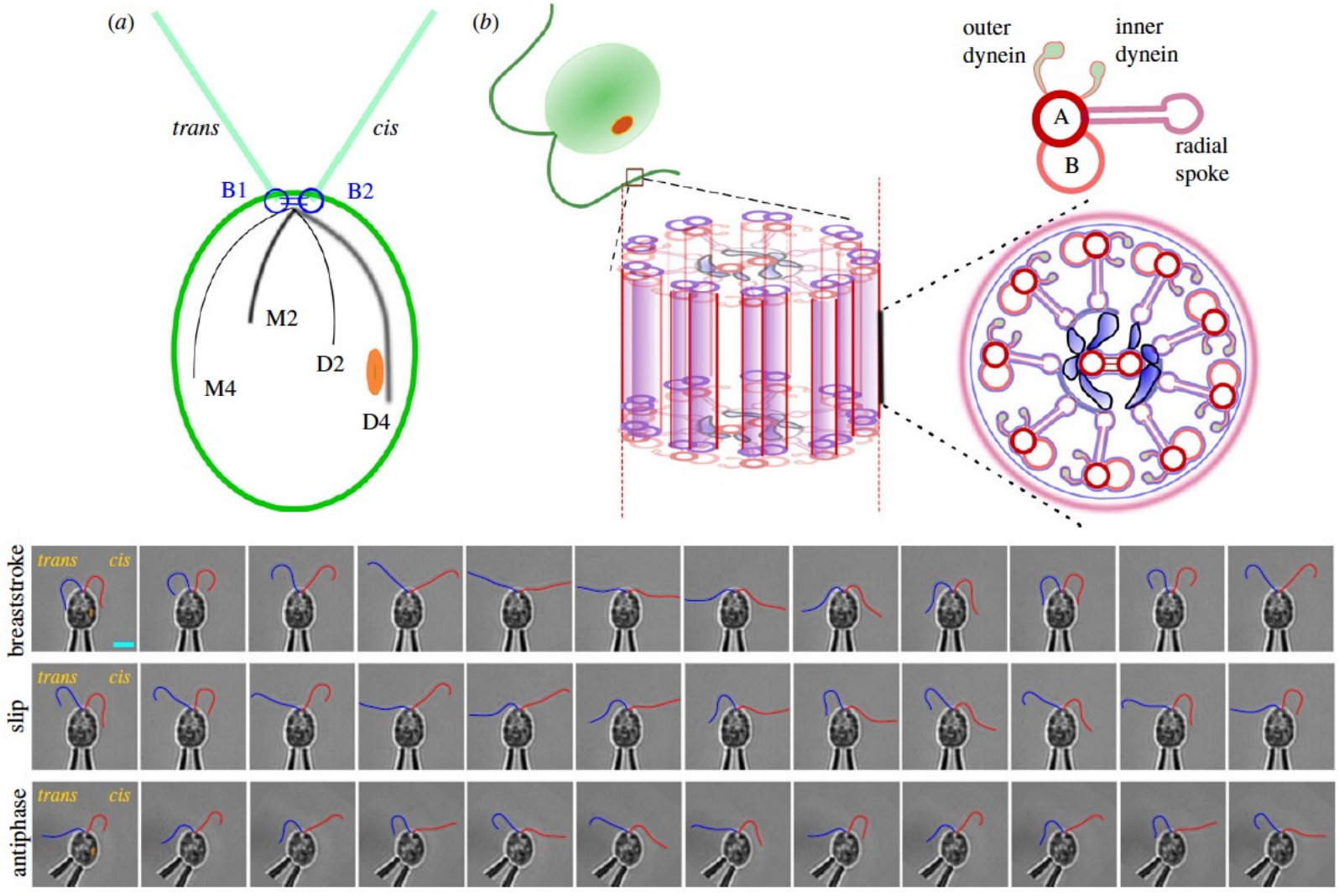
# Sperm Motility

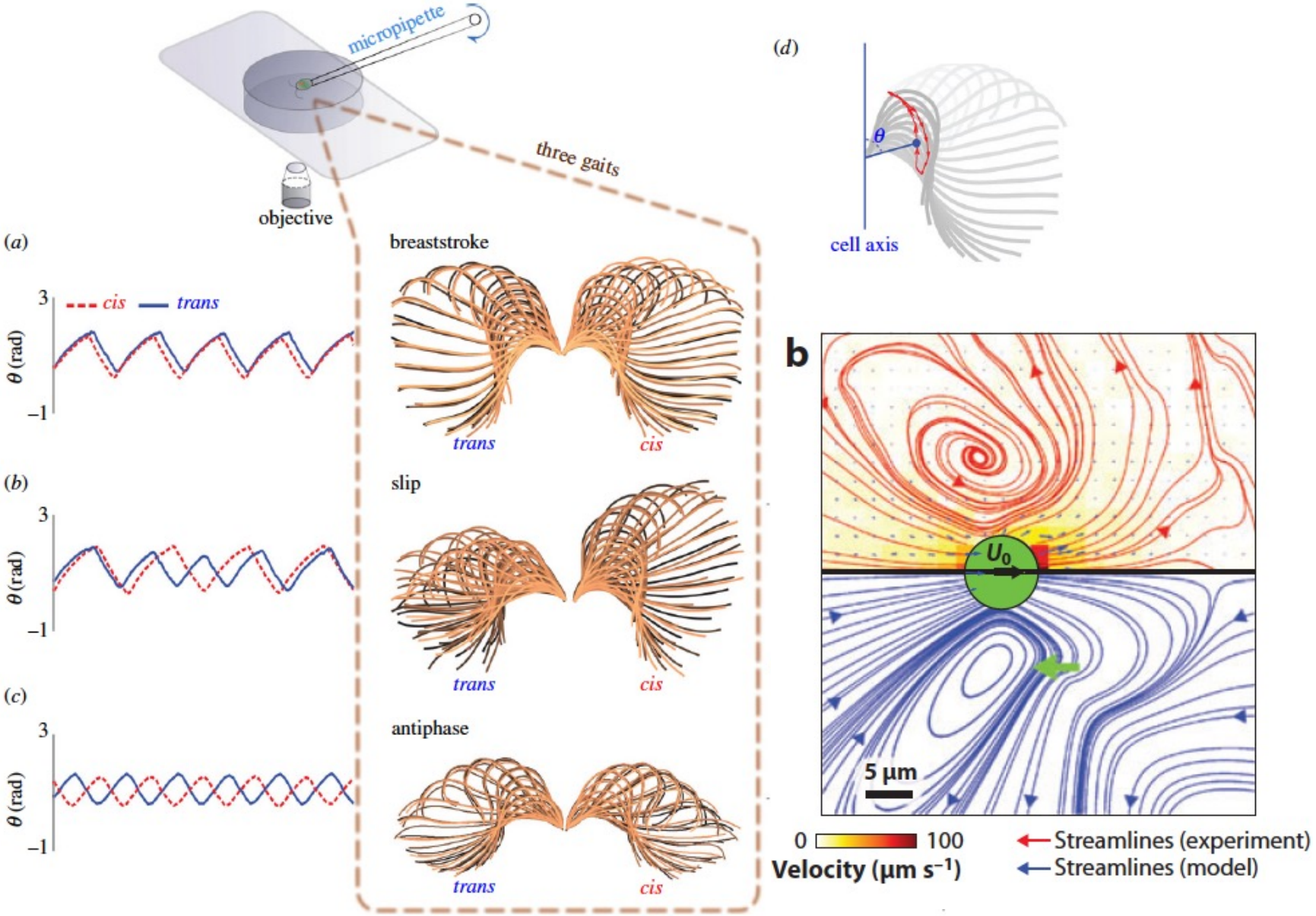
- 3D swimming pattern following helical ribbons
- Planar and asymmetric beating (a)
- Non-planar symmetric beating (b)
- Non-planar asymmetric beating (c)



# Biflagellate Alga *Chlamydomonas* (video)



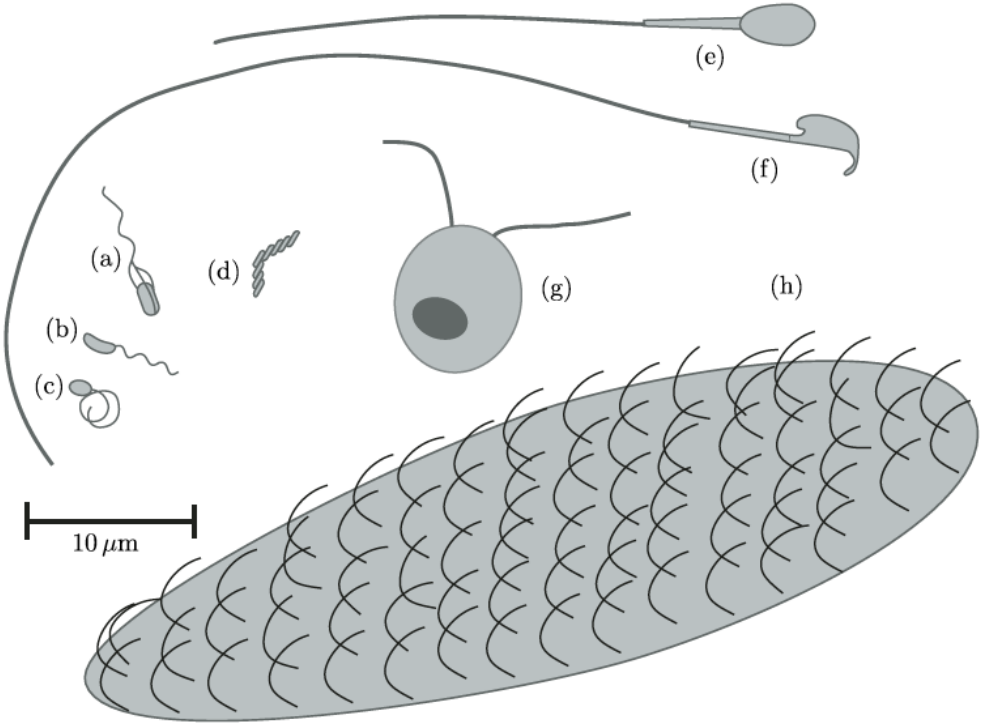

micropipette
objective
three gaits
(a)
(b)
(c)
3
θ (rad)
−1
cis
trans
breaststroke
slip
antiphase
trans
cis
(d)
θ
cell axis
b
$U_0$
5 μm
0
100
Velocity (μm s⁻¹)
Streamlines (experiment)
Streamlines (model)

# Scaling of Appendage Size

- Eukaryotic flagella are at least ten times larger (diameter and length) than bacterial flagella
  - Typical diameter: 20nm vs 200nm

- Cilia: thousands of small appendages that beat in coordinated manner
  - Propelling the cell at speeds of 500 um/s

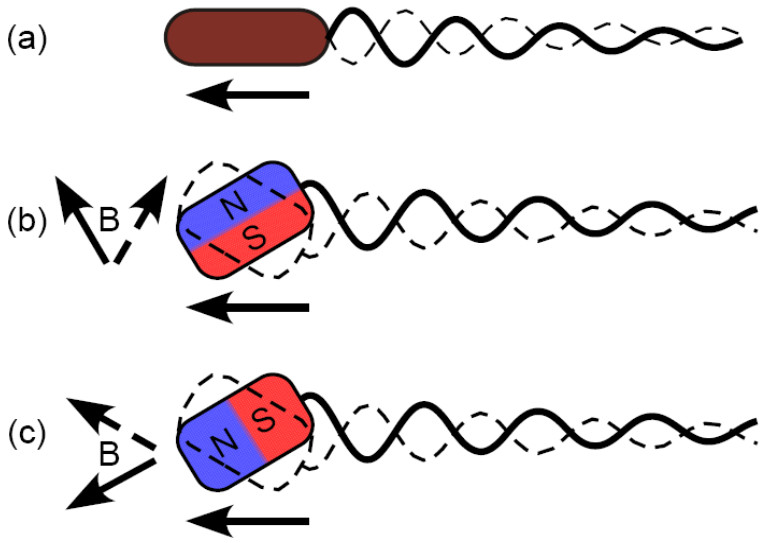
- With increasing size, we see a transition from flagellum to cilia



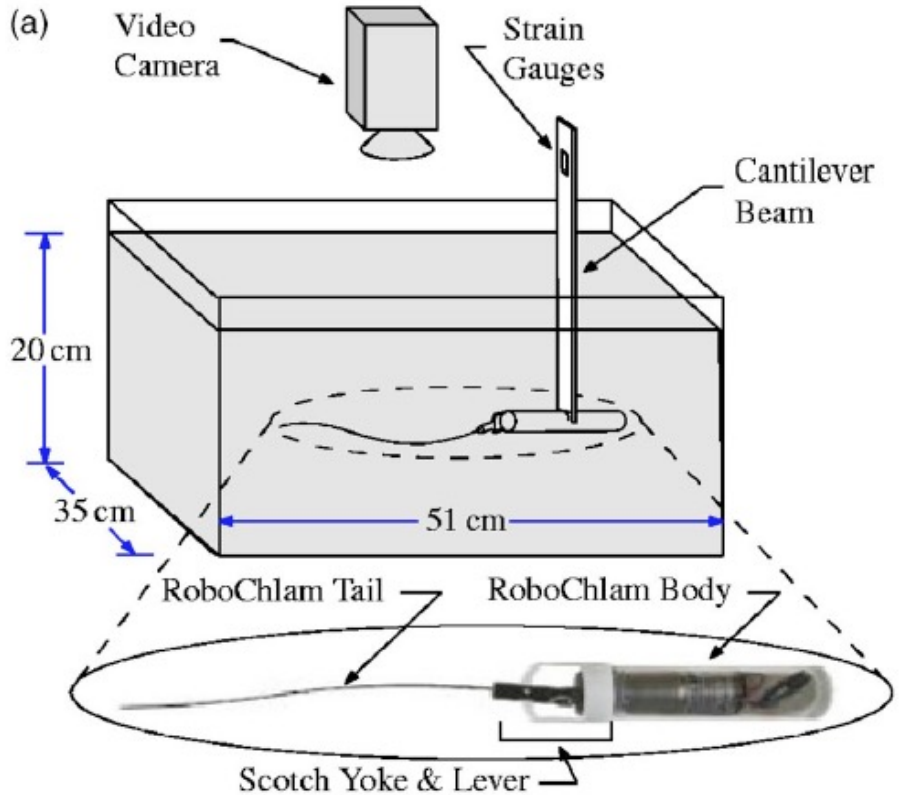
# Bioinspired Swimming: Elastic Oar

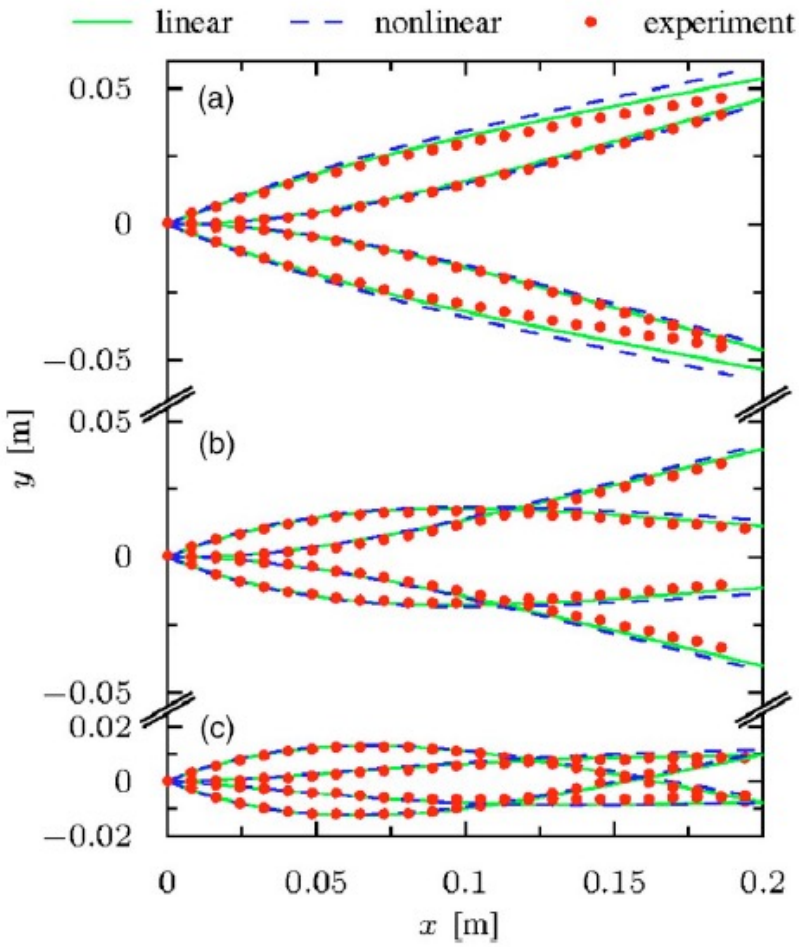
- One-sided actuation
  - There exists an optimum in tail elasticity and length
    - Too short & rigid
      - "Scallop theorem"
    - Too long & elastic
      - Increased drag

- Use of varying magnetic fields
  - Magnetic field creates a torque on a magnet
  - By varying the field, the torque is a function of time
  - Induces a waving motion to the following tail

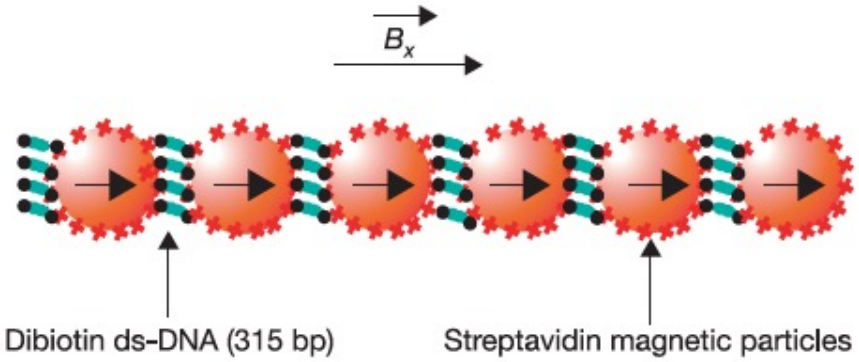


# Flexible Oar Swimmer



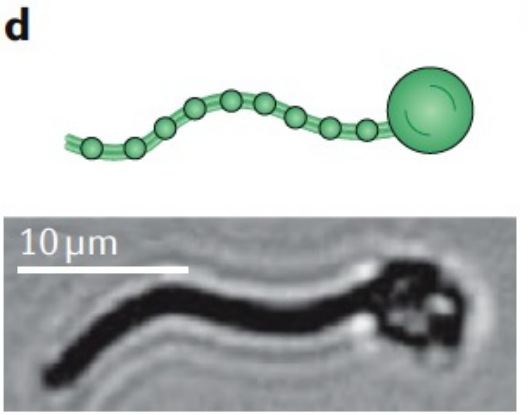



# Artificial Eukaryotic Flagellum

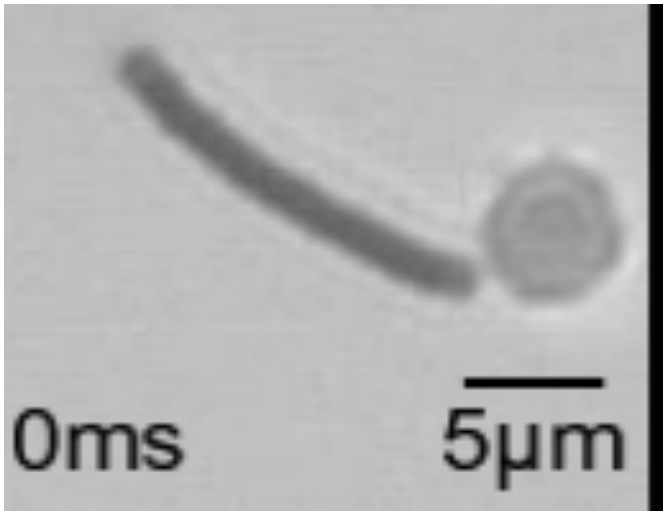



$$\mathbf{B}_x = B_x$$

$$\mathbf{B}_y = B_y \sin(2\pi ft)$$

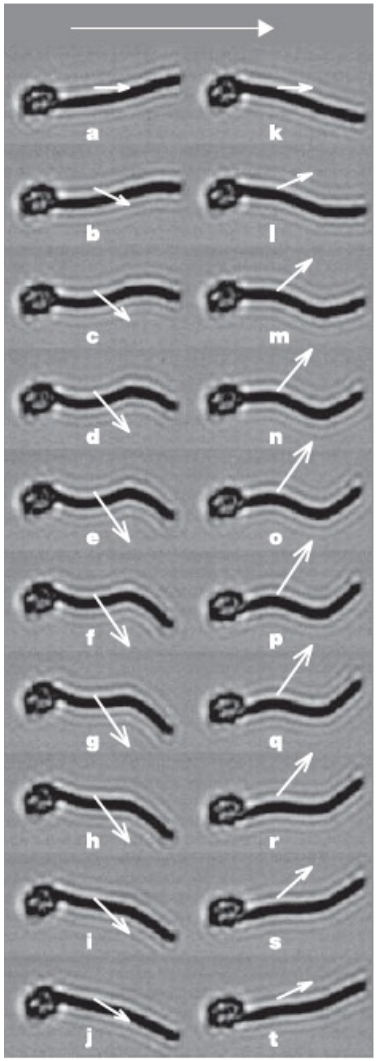



- Magnetic microbeads
  - Each bead has an easy axis
  - They are linked with DNA
  - The beads tend to align with an oscillating external magnetic field



# Artificial Eukaryotic Flagellum

- An undulation that propagates toward the attachment point from the tip of the tail
- Remember that in sperm cells bending wave propagates from head to tail

# Sperm Number

- A dimensionless number that represents the relative importance of viscous to elastic stresses on a filament

$$S_p = \frac{L}{\sqrt[4]{\left(\frac{\kappa}{\xi_\perp \omega}\right)}}$$

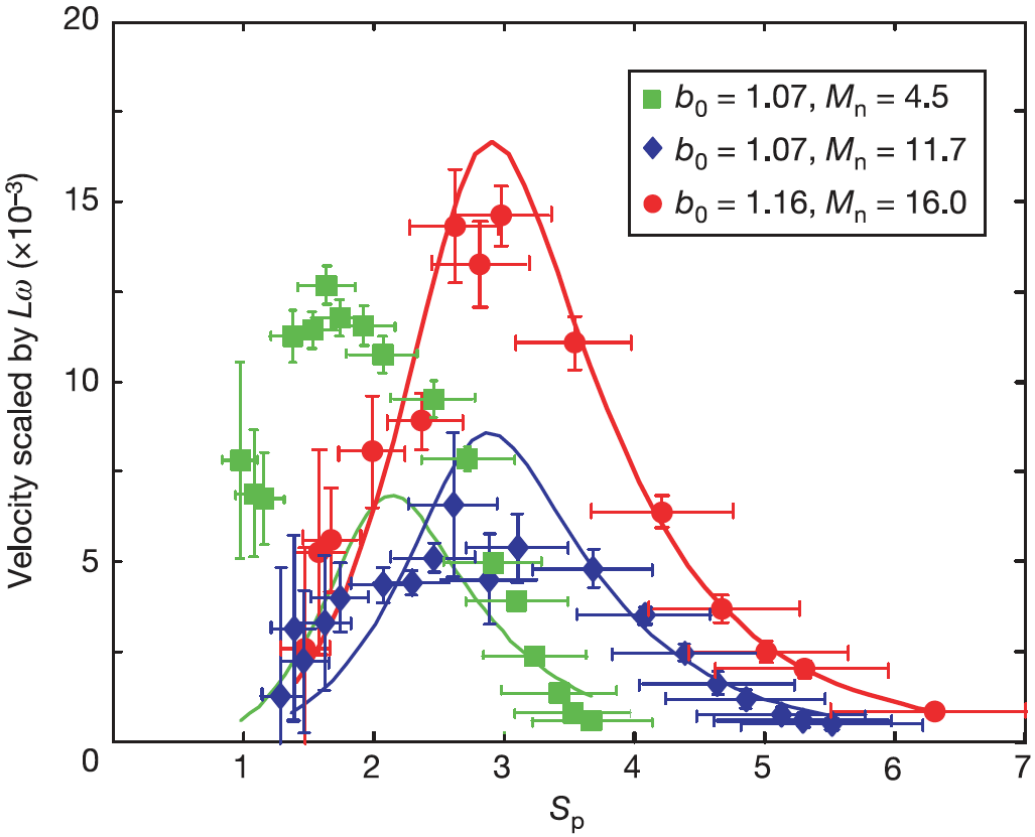
L: length of the filament
$\kappa$: bending rigidity
$\omega$: angular driving frequency
$\xi_\perp$: perpendicular viscous coefficient

- For a one-armed swimmer, two extreme regimes emerge
  - At low $S_p$, internal elasticity dominates
  - At high $S_p$, viscous friction dominates
- Maximum normalized swimming speed ($V/L\omega$) is attained for $S_p$ of the order unity (for sperm cells $S_p$ = 7)

# Magnetoelastic Number and Velocity Profile

$$M_n = \frac{2\pi(aB_xL)^2}{3\mu_0\kappa}\left(\frac{\chi_\parallel - \chi_\perp + \chi_\parallel\chi_\perp/4}{(1-\chi_\parallel/6)(1+\chi_\perp/12)}\right)$$

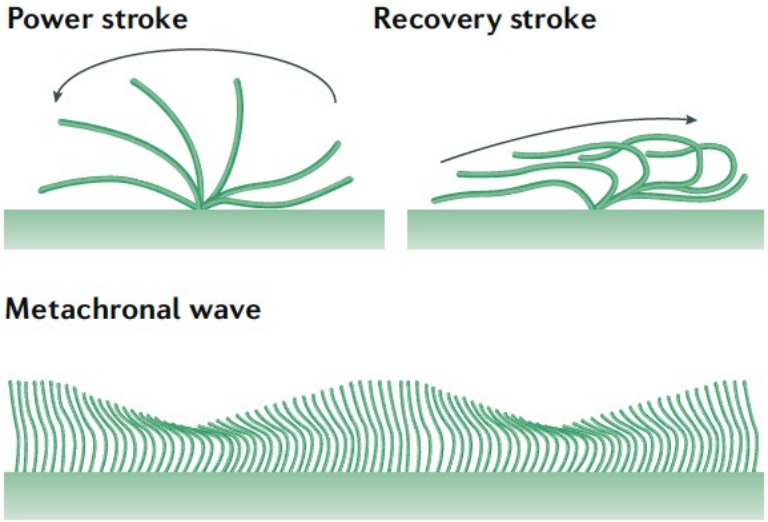
$\chi$: magnetic susceptibility
$\mu$: magnetic permeability
$a$: radius of the particles




$$b_0 = B_y/B_x$$

# Cilia

- Found in many tissues and unicellular organisms
- Coordinated action of thousands of cilia as an effective waving surface
- **Metachronal Waves**
  - Self-organized
  - Hydrodynamic interactions
  - Not complete synchrony or randomness
  - 10-fold higher efficiency compared to cilia all beating in phase



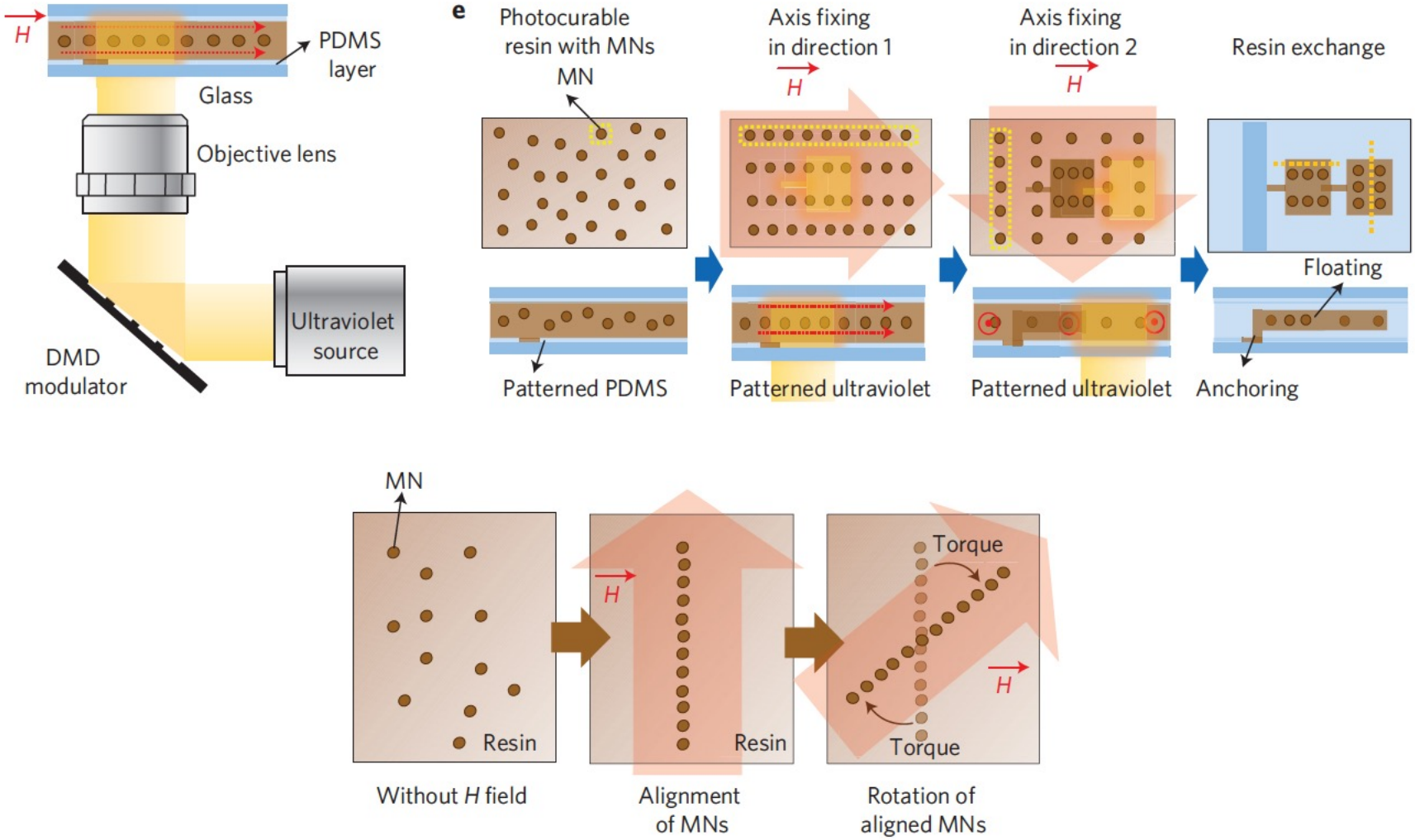
# Flexible Magnetic Composites

- Magnetoreactive soft materials such as magnetorheological elastomers and ferrogels
- Under the influence of magnetic fields, the embedded particles interact with one another and with the polymer matrix
- Vibration absorbers, sensing devices, engine mounts

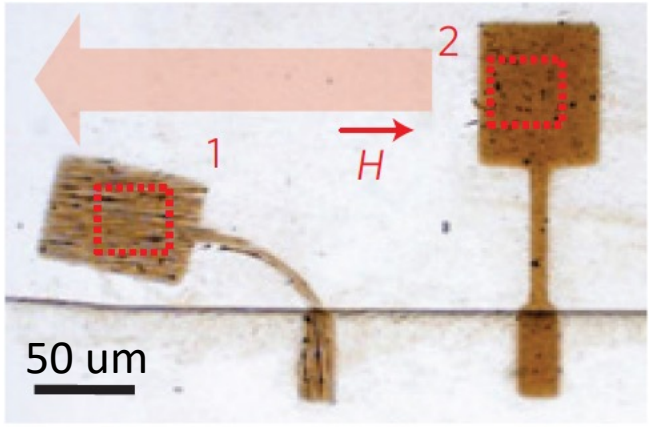
# Soft Magnetic Composites

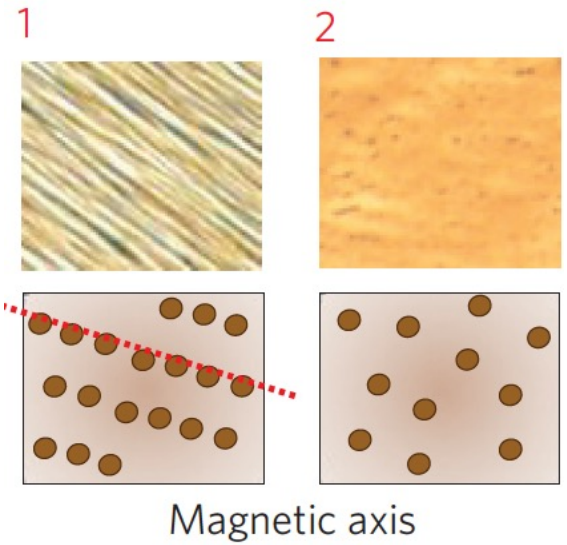
- Embedding particles of low-coercivity ferromagnetic materials in hydrogels
  - Soft magnetic materials
  - Iron and iron oxides
- Soft magnetic materials develop strong magnetization along the applied magnetic field
- They do not retain the strong magnetism once the external field is removed
- Deformation is limited to elongation or compression under magnetic field gradients

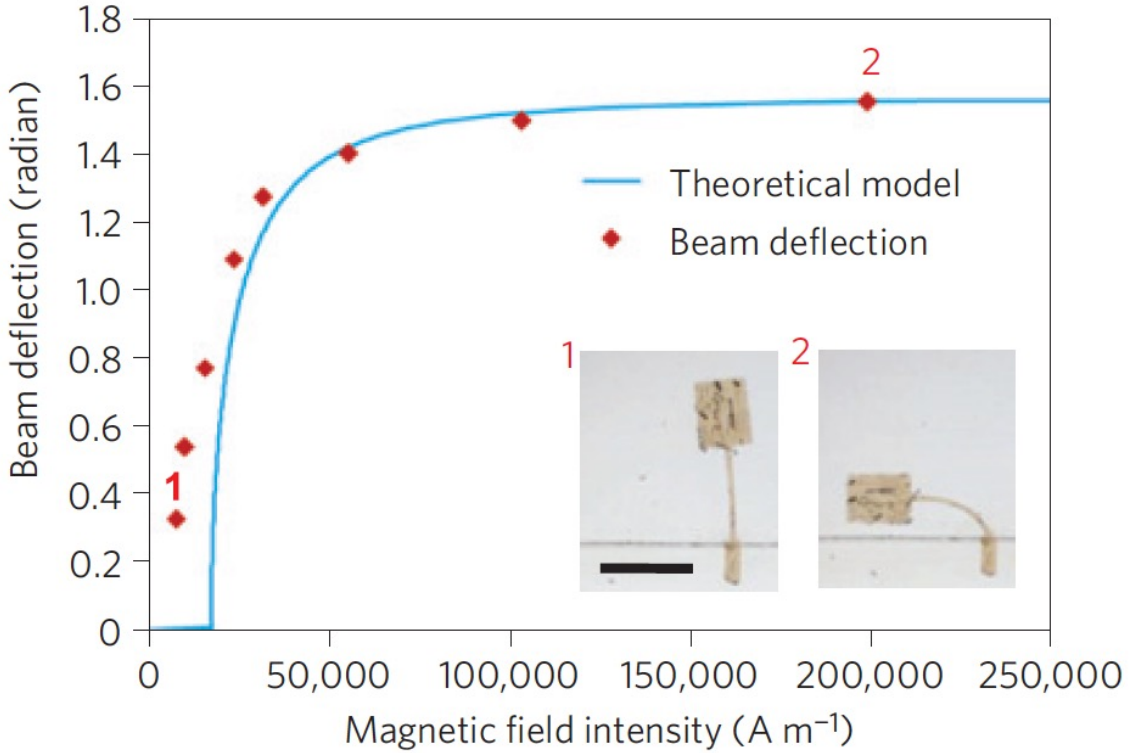
# Programming magnetic anisotropy



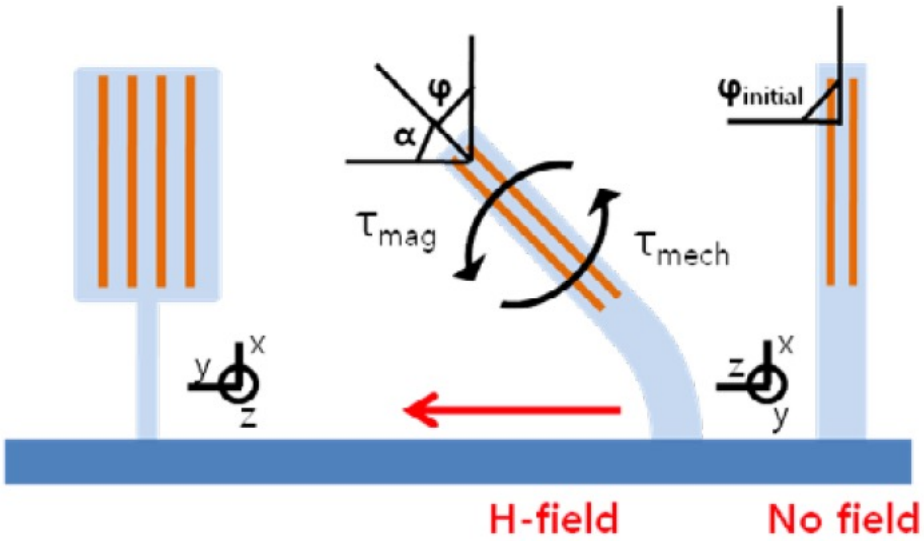
# Programming magnetic anisotropy



# Programming magnetic anisotropy

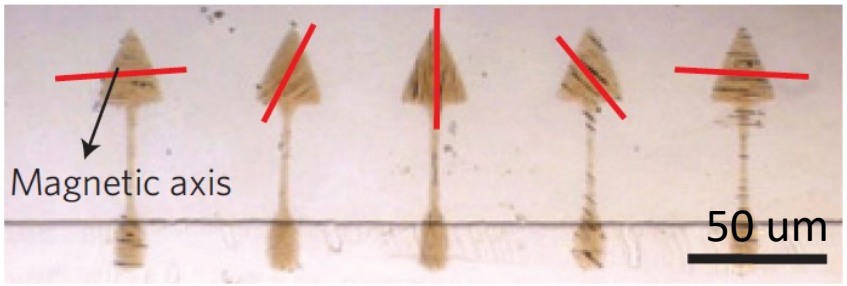


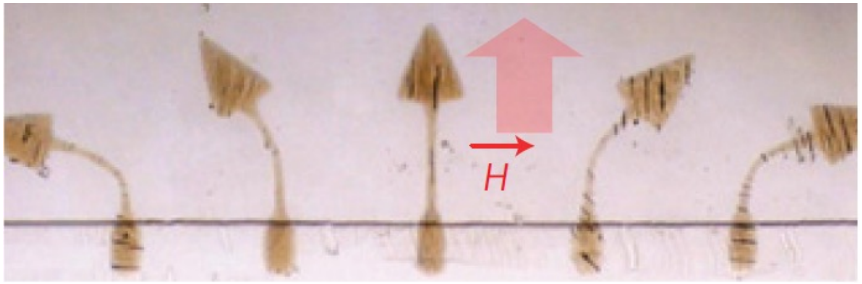

$$\tau_{mechanical} = -k_{\varphi}\varphi$$

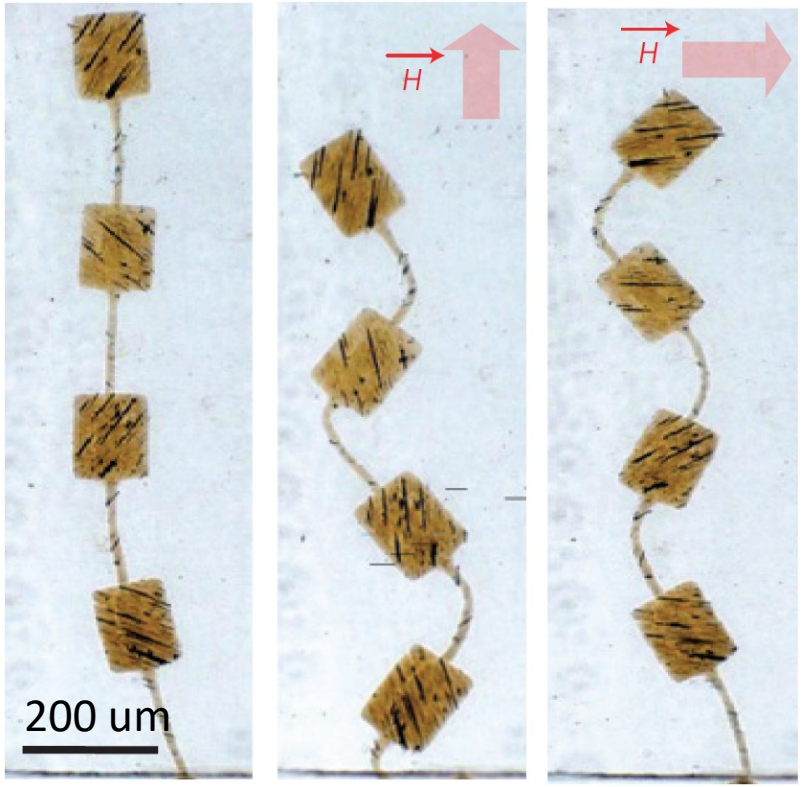
$$k_{\varphi} = \frac{E_y}{I}\frac{wD^3}{12}$$

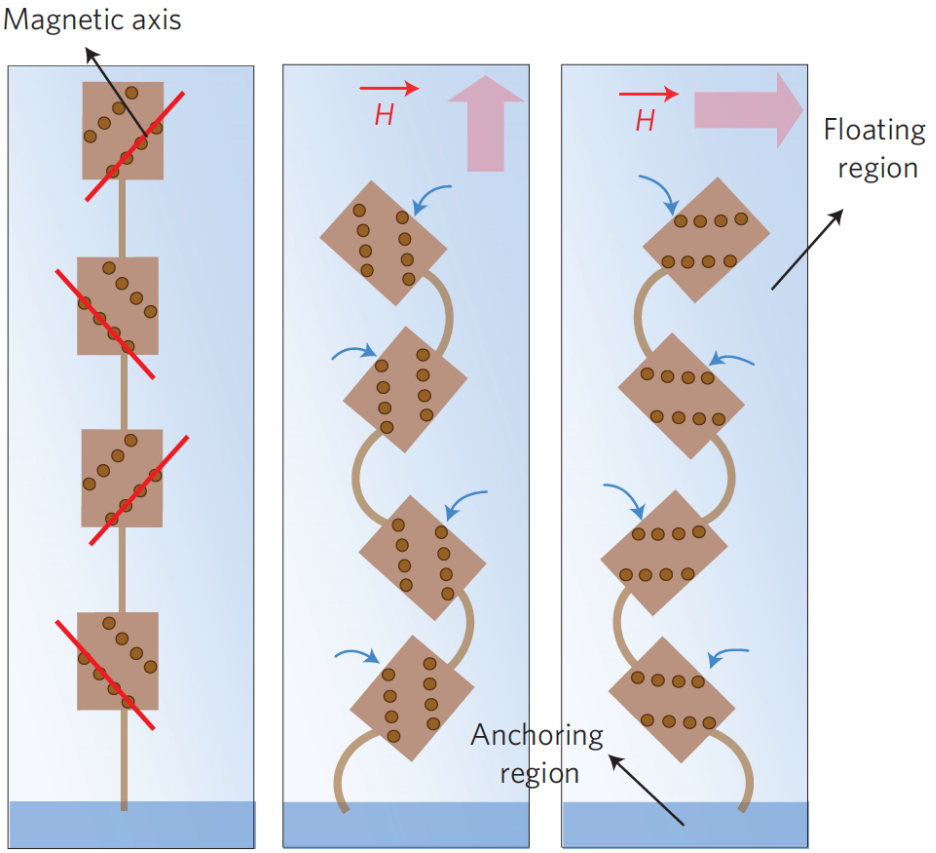
$$\tau_{magnetic} = N\frac{3\mu_0 m^2}{4\pi}sin(2\alpha)\frac{n^2}{d^3} = N\frac{3\mu_0 n^2\chi^2 R^6\pi}{4\pi}H^2 sin(2\alpha)$$

# Programming magnetic anisotropy

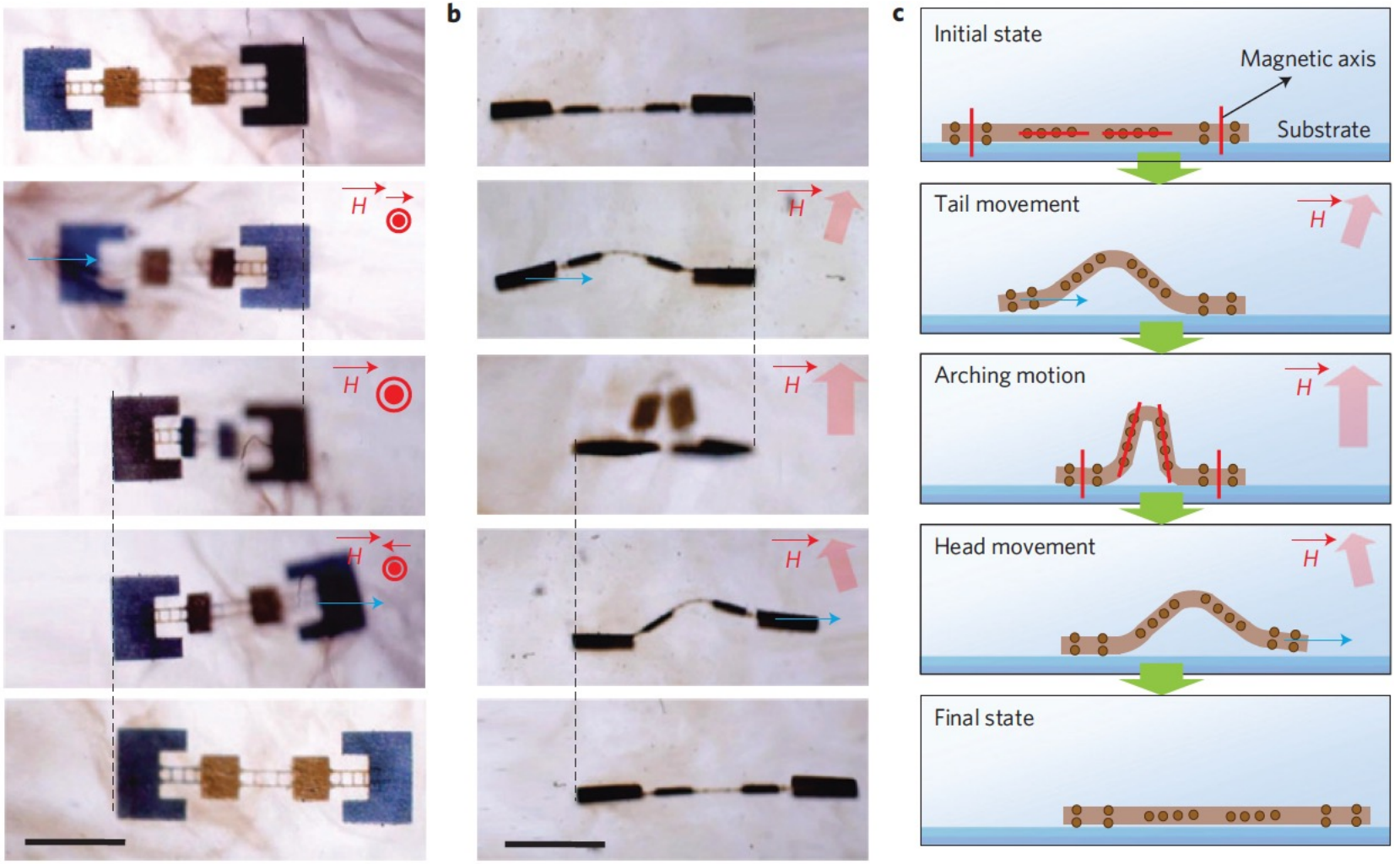


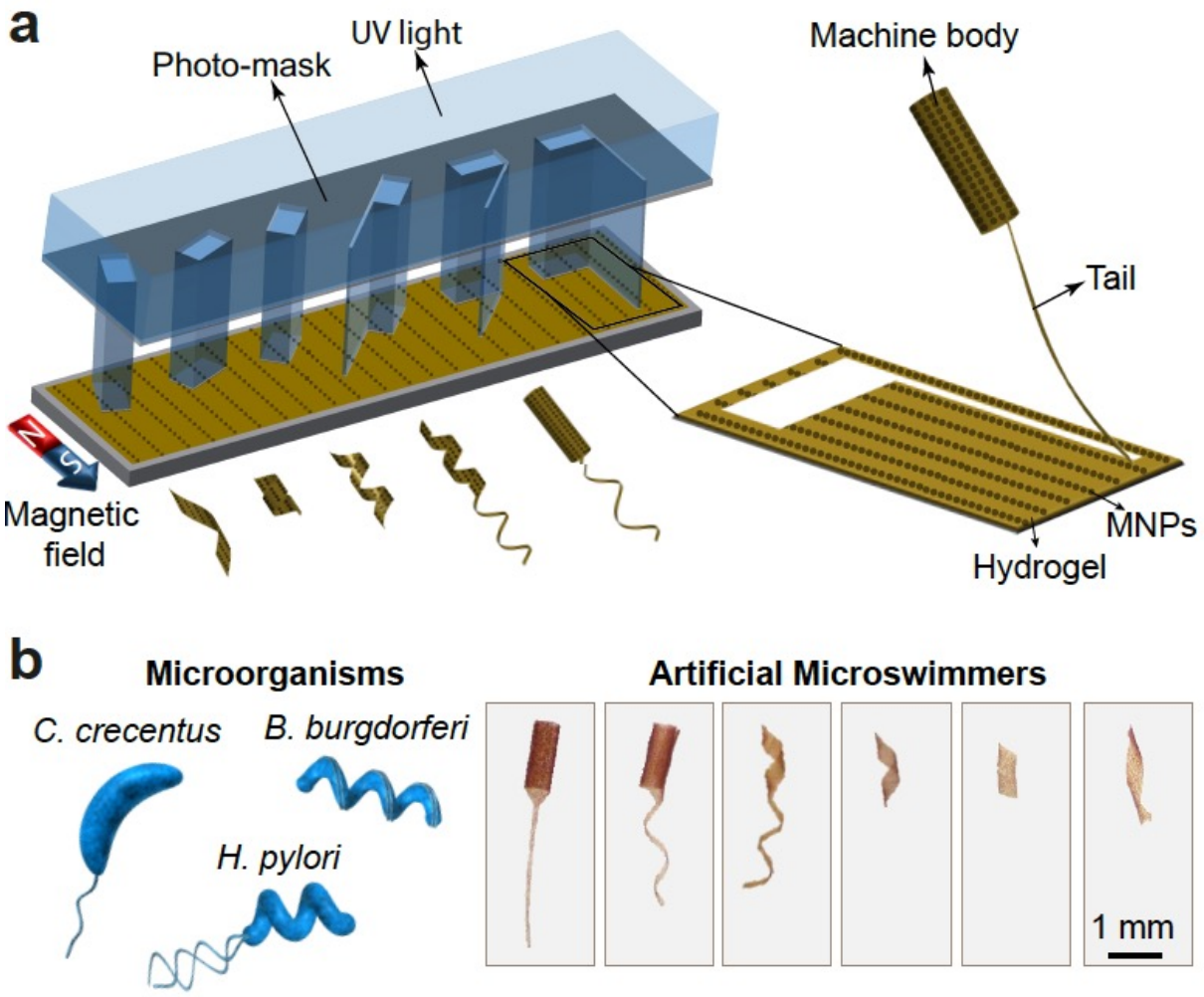



# Programming magnetic anisotropy

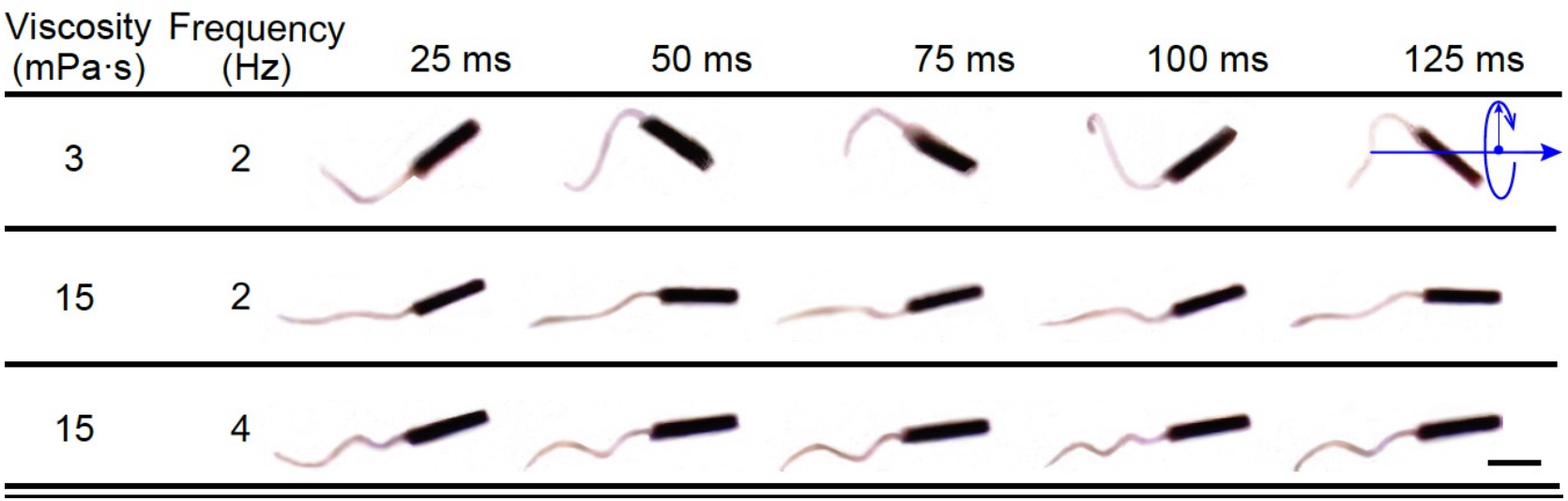


# Programmable self-folding

- Differential Swelling via Particle Gradients



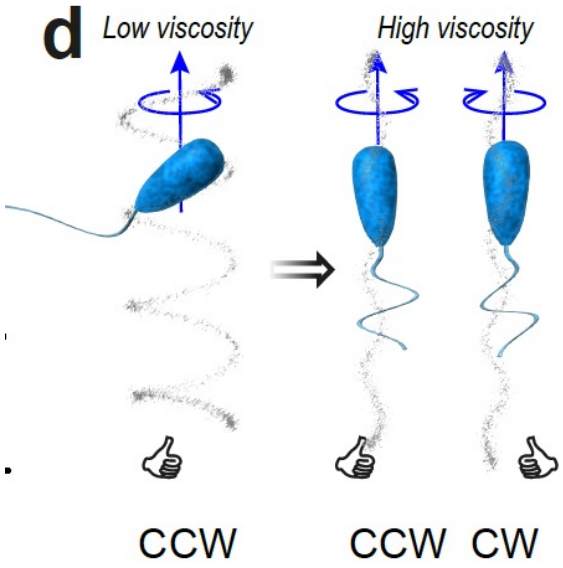
# Elastohydrodynamic Coupling




**Sperm Number**

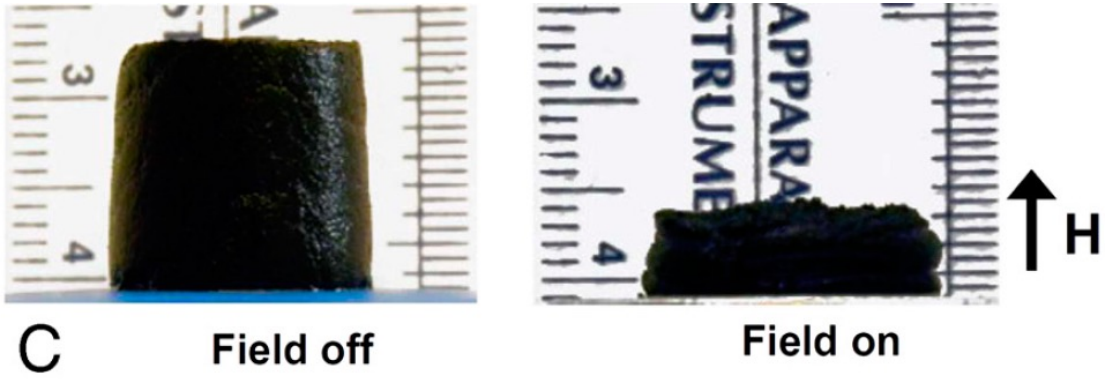
$$S_p = L/\left(\frac{\kappa}{\zeta_\perp \omega}\right)^{1/4}$$

Bending rigidity vs viscous drag



# Ferrogels

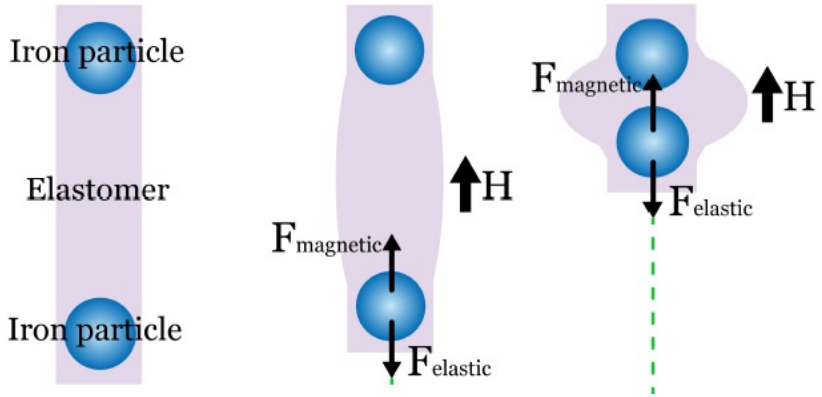
- Reduce elastic rigidity by creating macroscale pores inside the gel
- Reversible deformation with compressive strain over 80% before fracture
- Deformation under nonuniform magnetic fields
  - Body force proportional to the gradient of the applied field

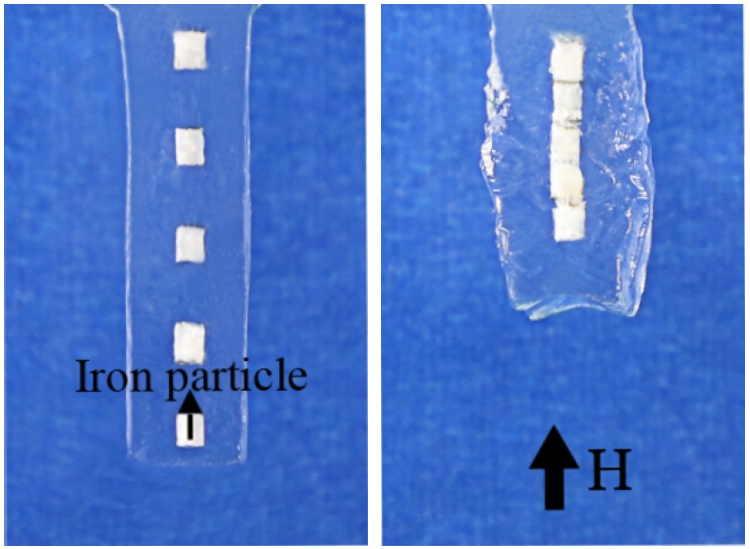



$$\mathbf{F} = \upsilon ( \mathbf{M} \cdot \nabla ) \mathbf{B}$$

# Magnetoelastic Effect

- Magnetic pull-in instability




**Magnetic Force**

$$F_m \approx 3\mu_0 m^2/(2\pi l^4)$$

$$m = V\chi_m H$$

**Elastic Force (neo-Hookean)**

$$F_e = A\gamma[l/l_0 - (l/l_0)^{-2}]$$

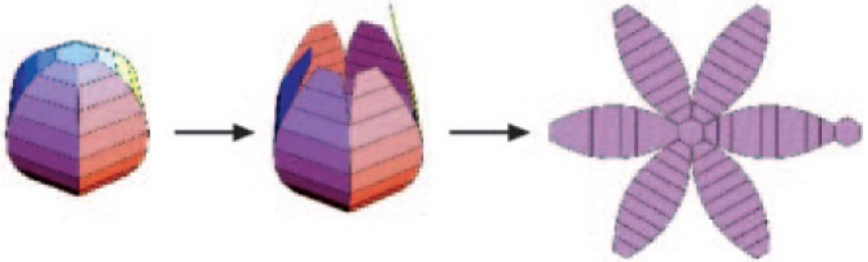
- Shear modulus of the matrix vs the magnetic Maxwell stress
- Placement of magnetic particles is the key

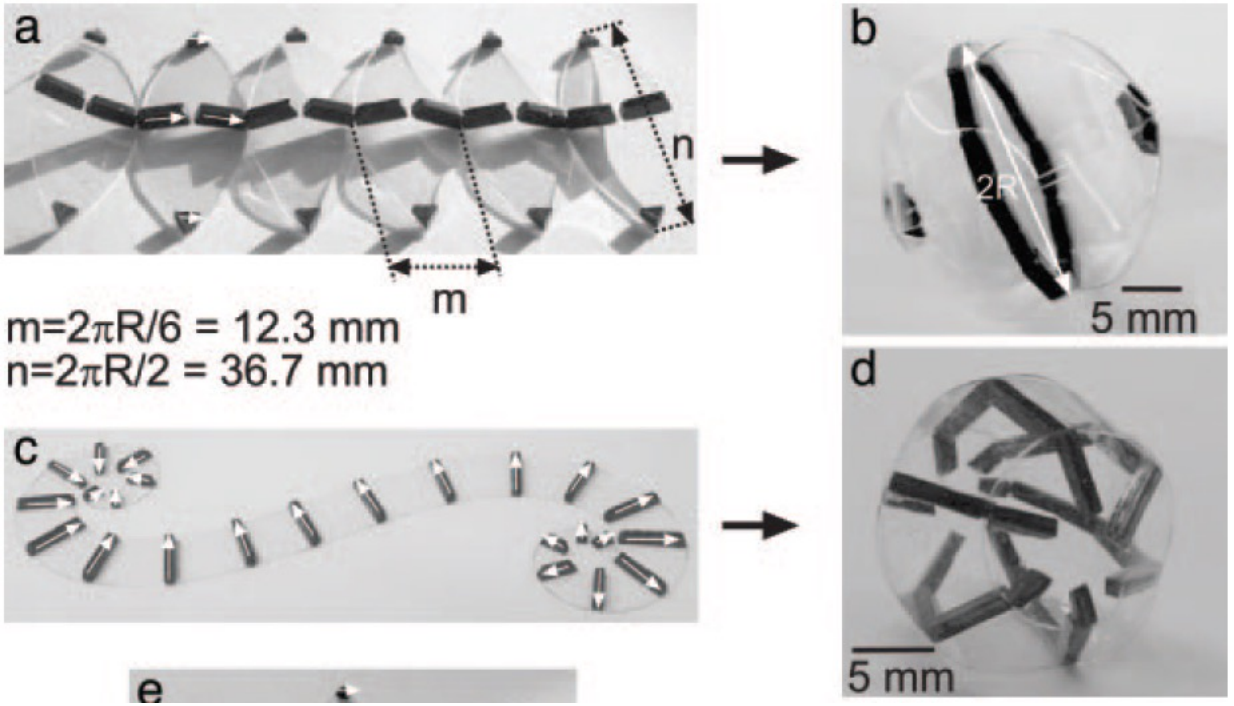
# Hard Magnetic Composites

- Particles of high-coercivity ferromagnetic materials
  - Hard magnetic materials
  - such as NdFeB
- High remnant characteristics allow them to retain high residual magnetic flux density even in the absence of magnetic fields after saturation (high magnetization at low field)
- High coercivity helps them sustain high residual magnetic flux density over a wide range of applied magnetic fields below the coercive field strength (hard to demagnetize or re-magnetize)

# Magnetic self-assembly

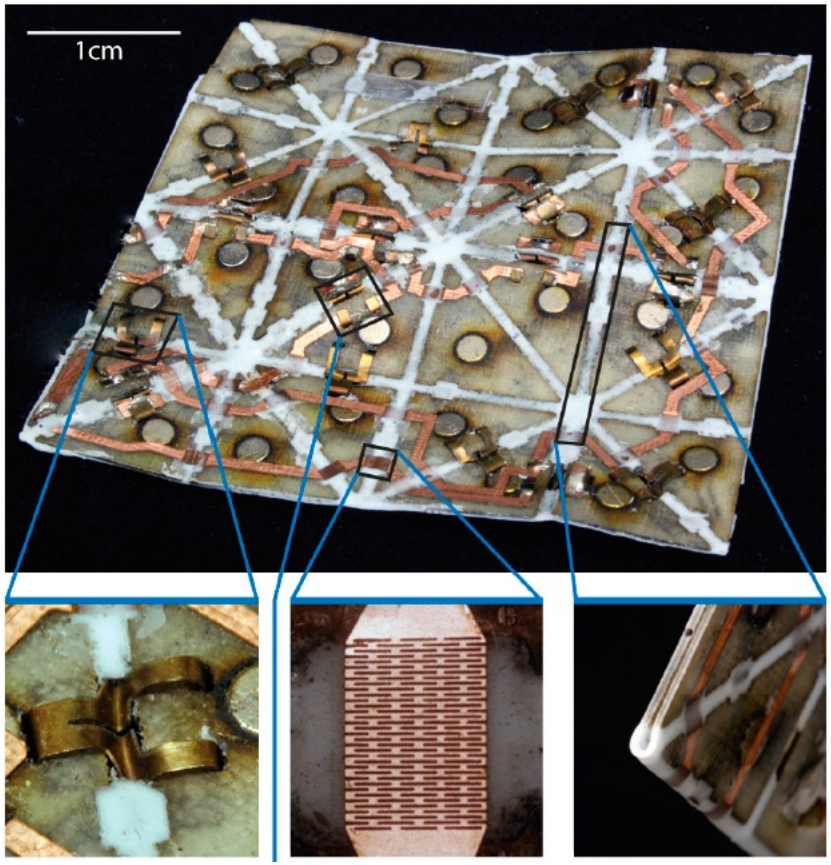
- Converting elastomer sheets patterned with magnetic dipoles into 3D objects by self-folding

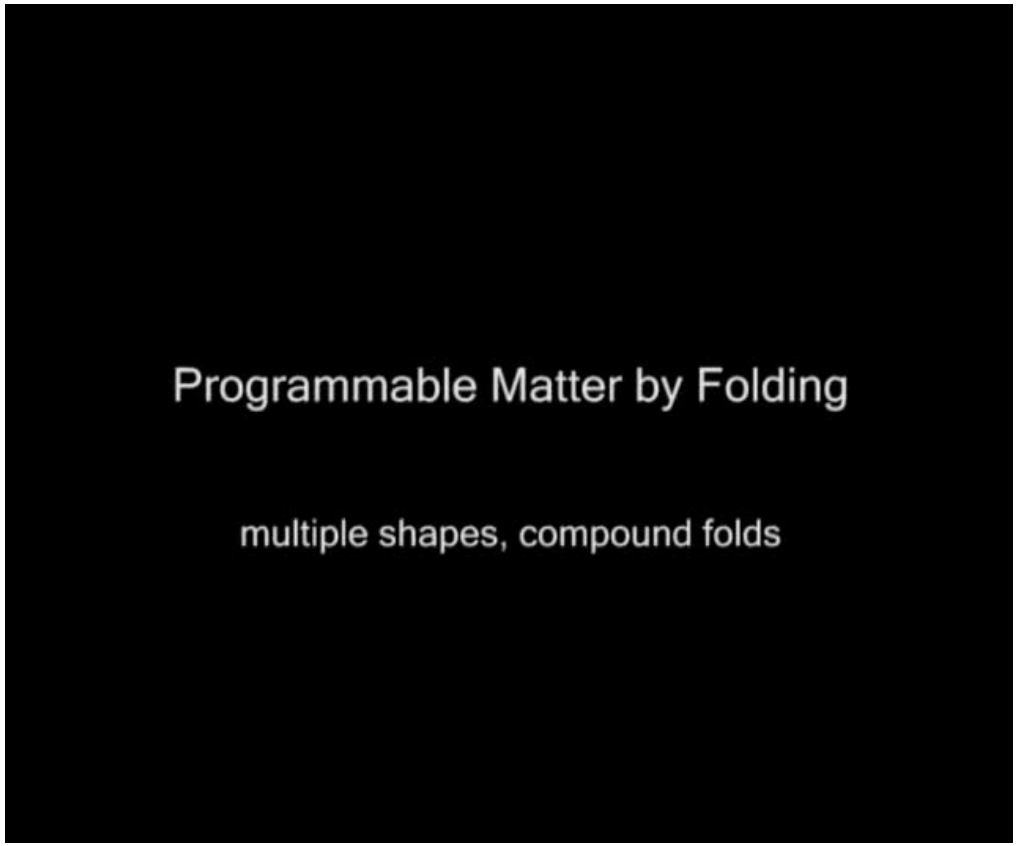




# Programmable matter by folding

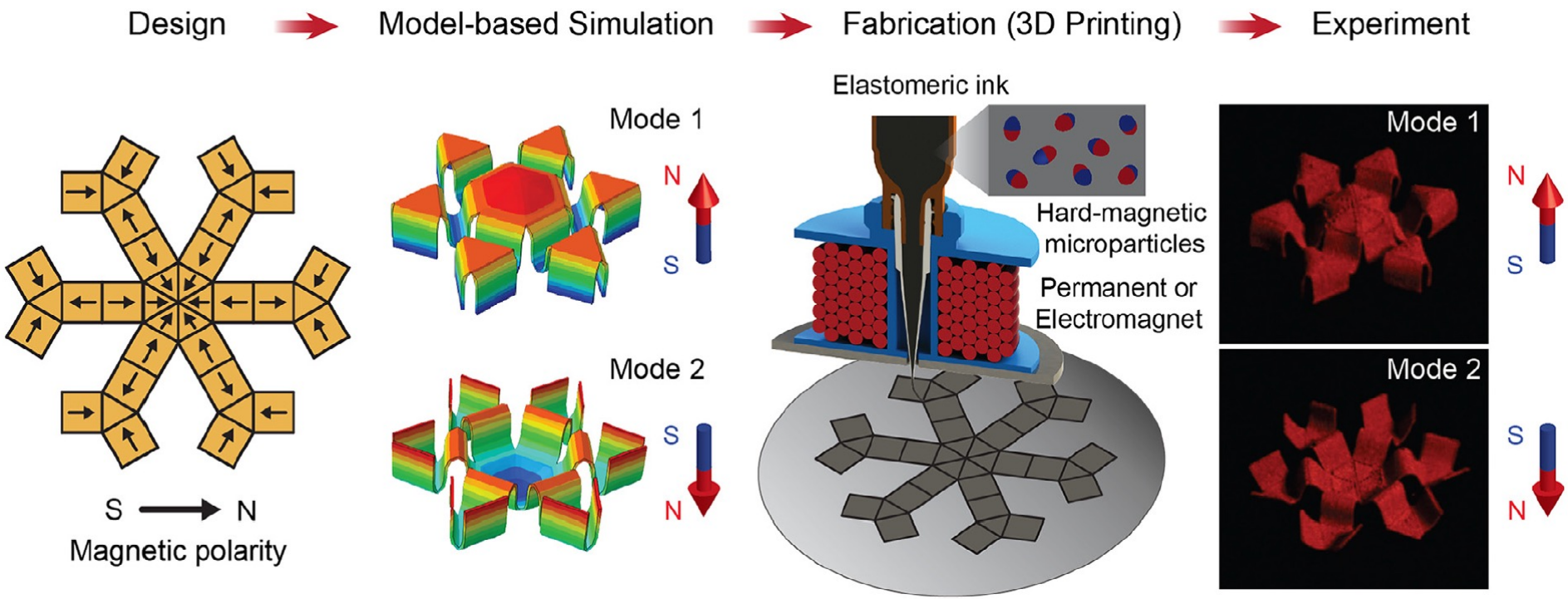
- Magnetic engagement for assembly



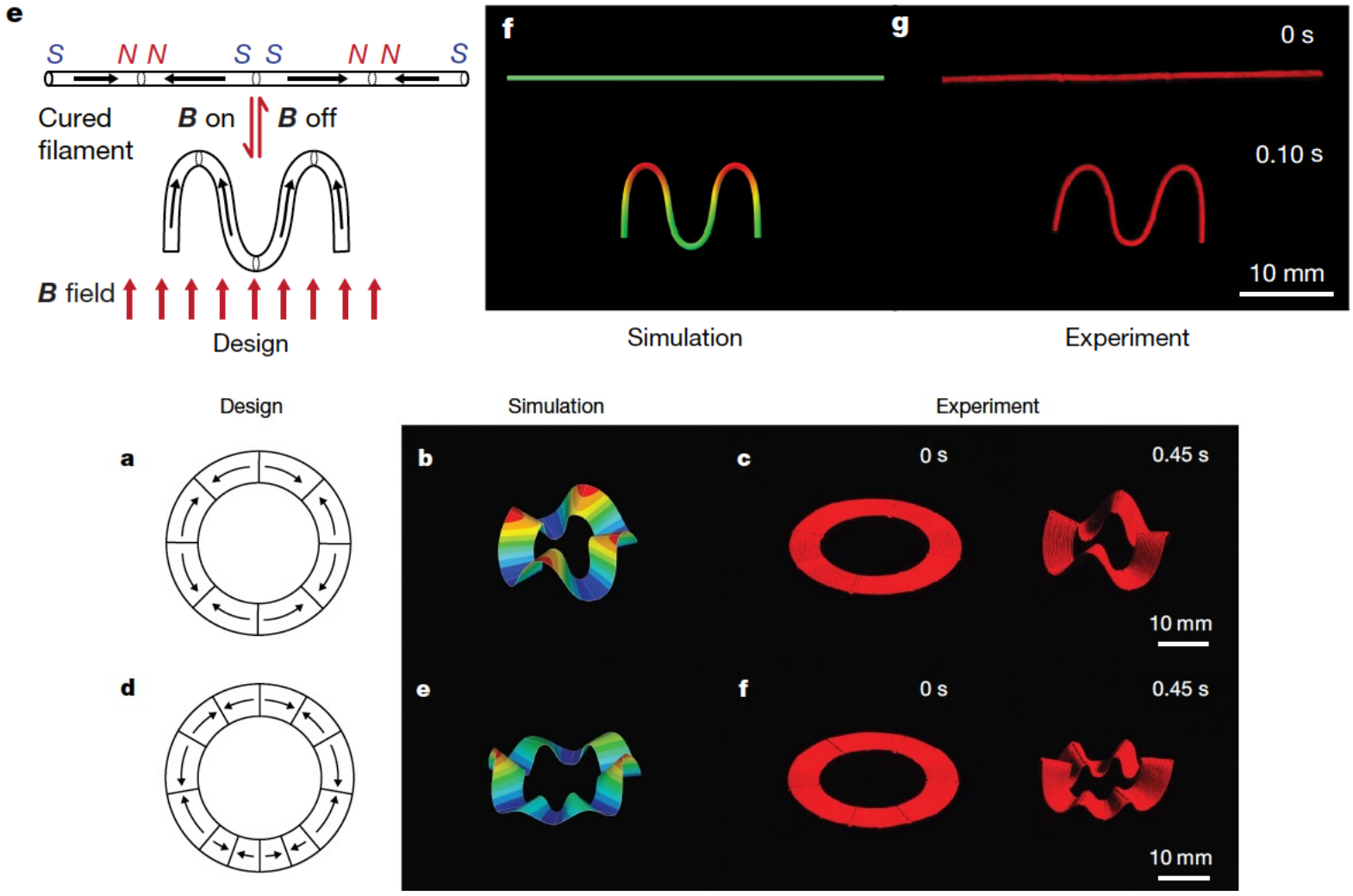



# Hard Magnetic Composites

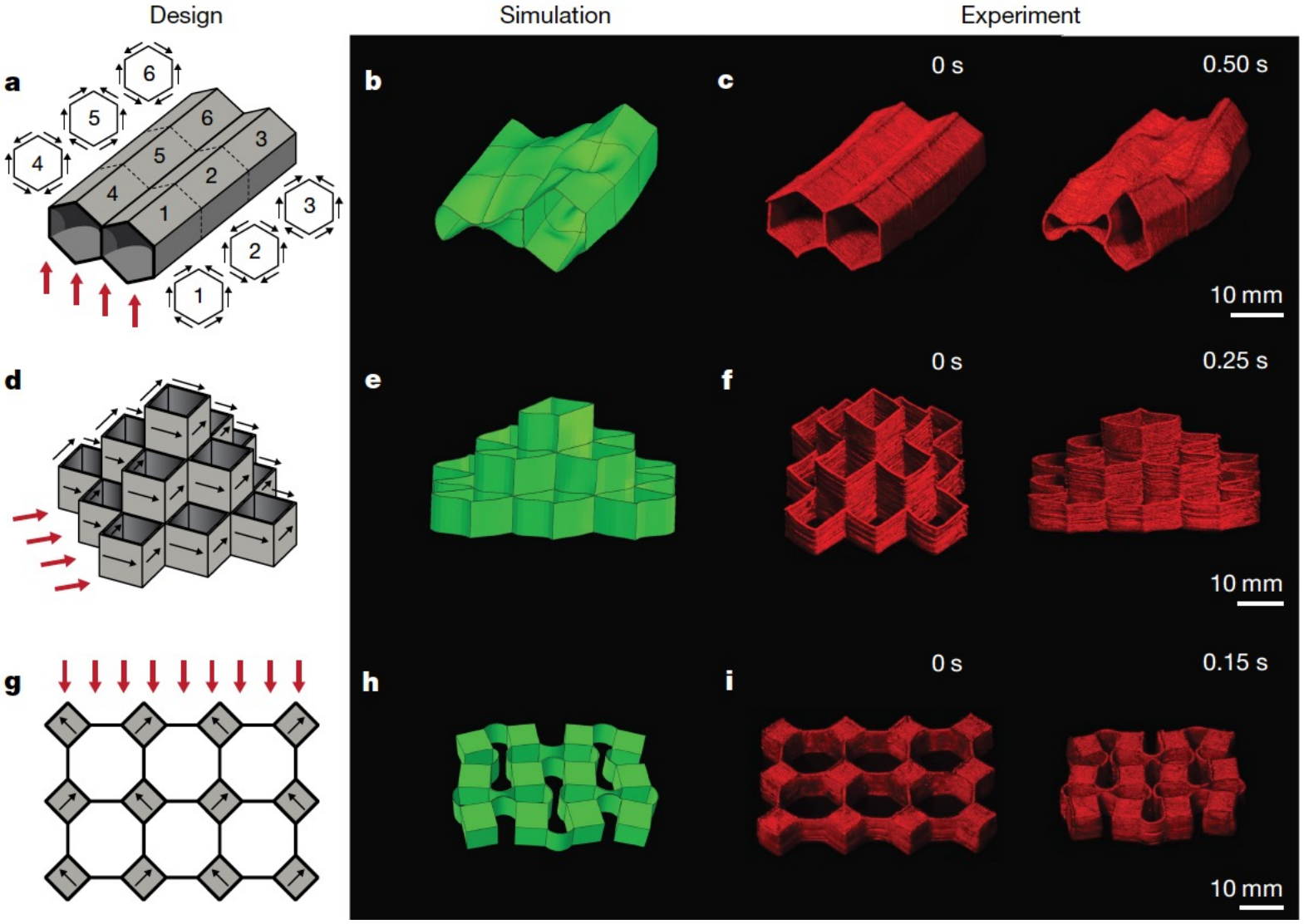
- Design of ferromagnetic domains in 3D printed soft materials



# Hard Magnetic Composites



# Hard Magnetic Composites



# Hard Magnetic Composites

## Printing ferromagnetic domains for untethered fast-transforming soft materials

Yoonho Kim[1,2*], Hyunwoo Yuk[1*], Ruike Zhao[1*], Shawn A. Chester[3], Xuanhe Zhao[1,4]

[1]*Soft Active Materials Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology*
[2]*Harvard-MIT Division of Health Sciences and Technology, Massachusetts Institute of Technology*
[3]*Department of Mechanical and Industrial Engineering, New Jersey Institute of Technology*
[4]*Department of Civil and Environmental Engineering, Massachusetts Institute of Technology*

*These authors contributed equally to the current work
Correspondence should be addressed to Xuanhe Zhao (zhaox@mit.edu)

Massachusetts Institute of Technology

SAMs Lab

Overall printing process and actuation of a shape-morphing structure with programmed ferromagnetic domains

# Hard Magnetic Composites

## Printing ferromagnetic domains for untethered fast-transforming soft materials

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*These authors contributed equally to the current work
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Massachusetts Institute of Technology

Fast transformation of a set of 2D structures into complex 3D shapes under applied magnetic fields

SAMs Lab

# Hard Magnetic Composites

## Printing ferromagnetic domains for untethered fast-transforming soft materials

Yoonho Kim[1,2*], Hyunwoo Yuk[1*], Ruike Zhao[1*], Shawn A. Chester[3], Xuanhe Zhao[1,4]

[1]*Soft Active Materials Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology*
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*These authors contributed equally to the current work
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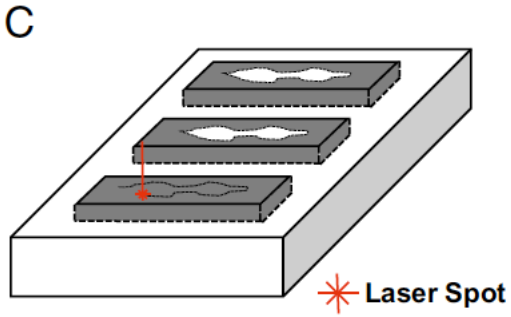
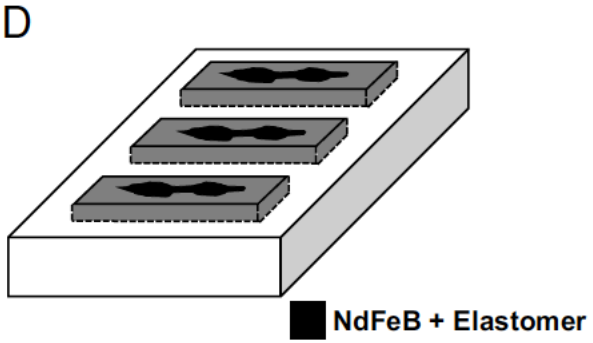
Massachusetts Institute of Technology

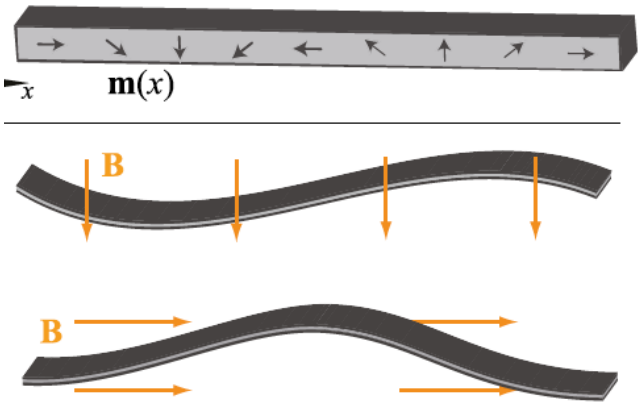
SAMs Lab

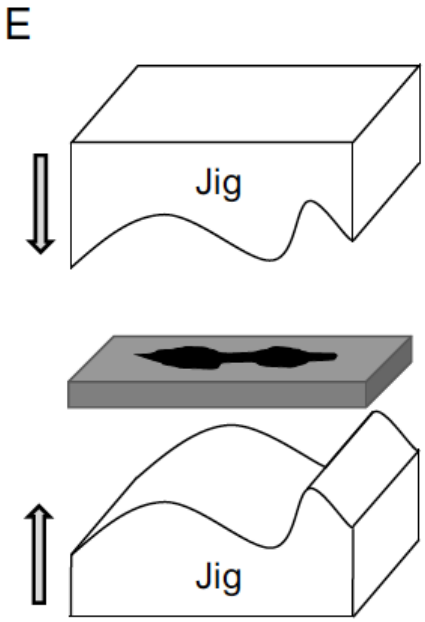
Rolling-based locomotion and delivery of a drug pill of the hexapedal structure under a rotating magnetic field

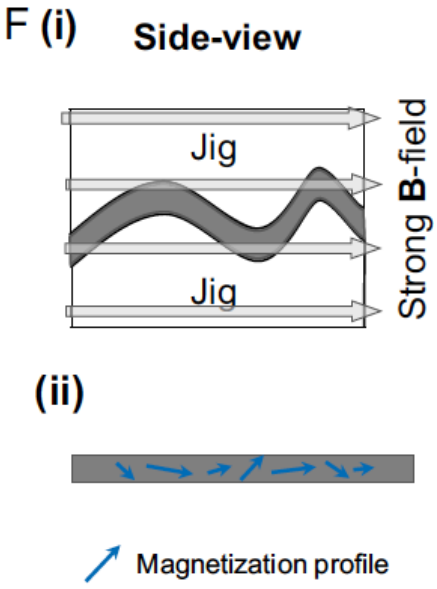
# Shape-programmable magnetic soft matter



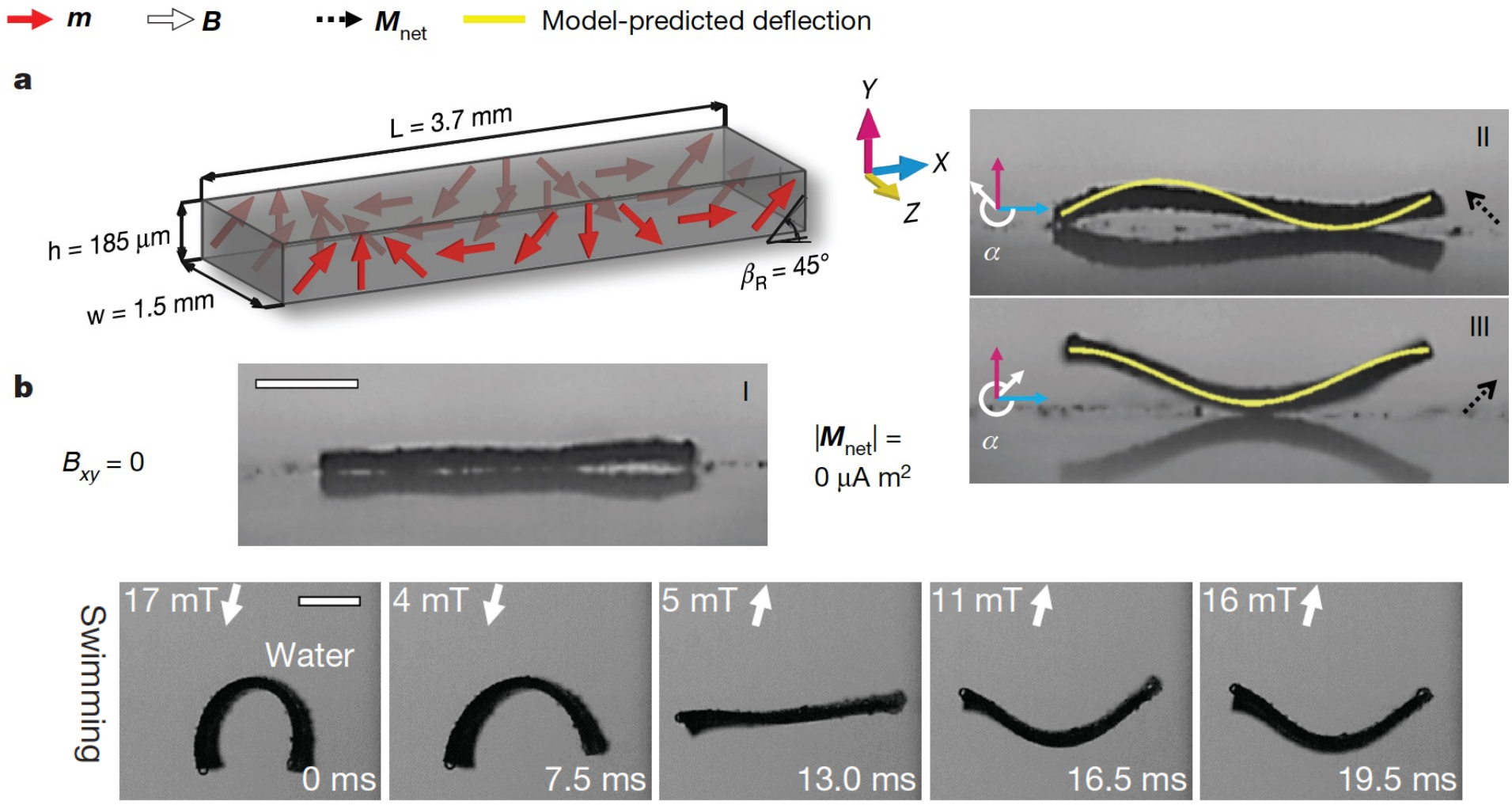




$$b = \frac{MA\lambda^3}{8\pi^3 EI}B$$

# Shape-programmable magnetic soft matter



# Small-scale soft-bodied robot with multimodal locomotion

Wenqi Hu, Guo Zhan Lum, Massimo Mastrangeli, Metin Sitti

Multimodal locomotion

(Play speed is indexed to real time)

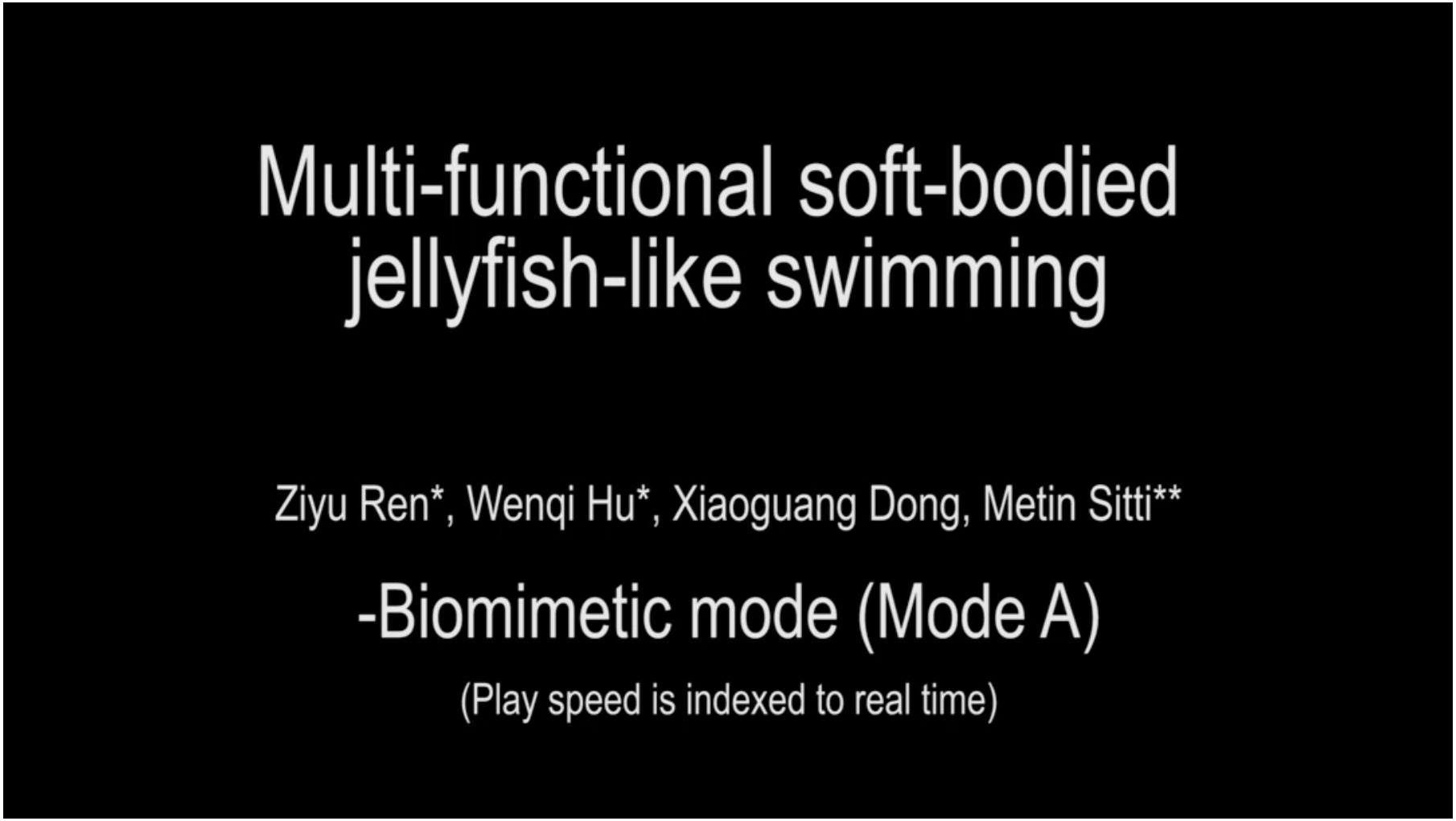
# Small-scale soft-bodied robot with multimodal locomotion

Wenqi Hu, Guo Zhan Lum, Massimo Mastrangeli, Metin Sitti

Cargo transport

(Play speed is indexed to real time)

# Magnetic jellyfish swimmer



# Magnetic cilia

## Magnetic Cilia Carpets with Programmable Metachronal Waves

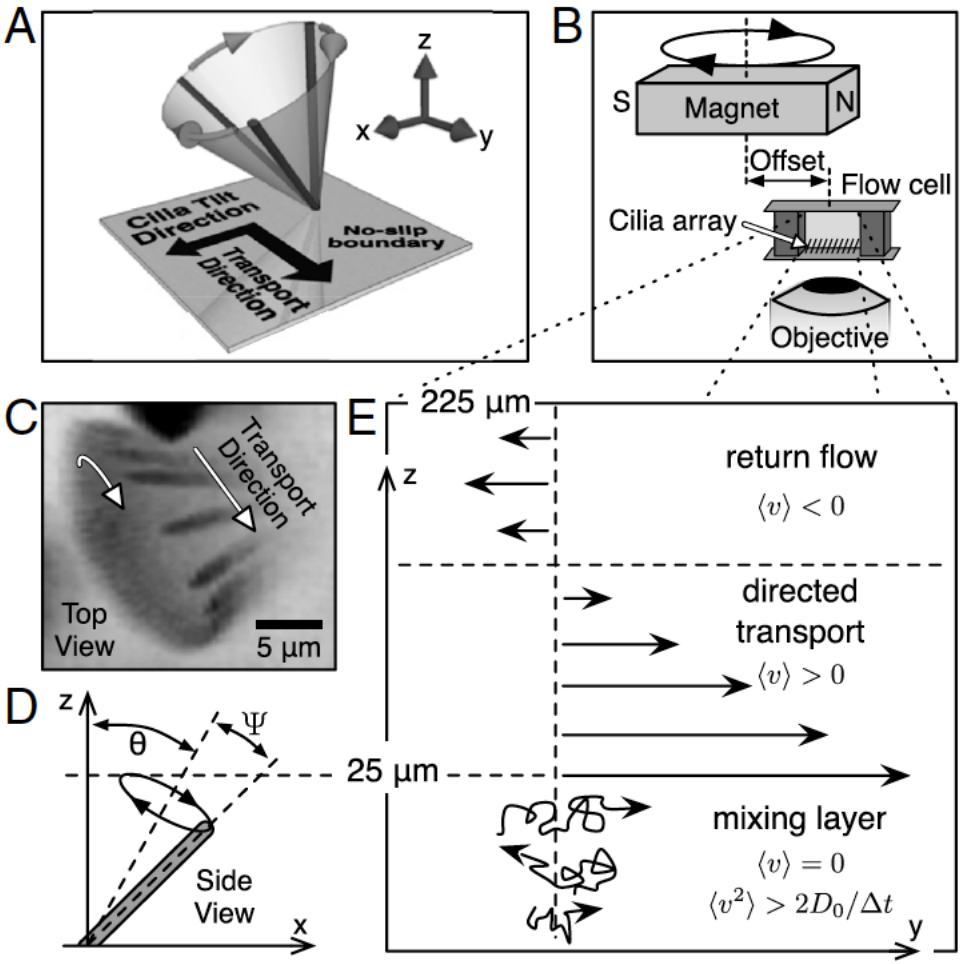
**Supplementary video 1:**
**Metachronal waves with different wavelengths**

Hongri Gu, Quentin Boehler, Haoyang Cui, Eleonora Secchi, Giovanni Savorana, Carmela De Marco, Simone Gervasoni, Quentin Peyron, Salvador Pane, Tian-yun Huang, Ann Hirt, Daniel Ahmed, Bradley J. Nelson

ETH zürich

MSRL
MULTI-SCALE ROBOTICS LAB

# Magnetically-actuated artificial cilia




## Peclet Number

$$Pe = \frac{ul}{D_0}$$

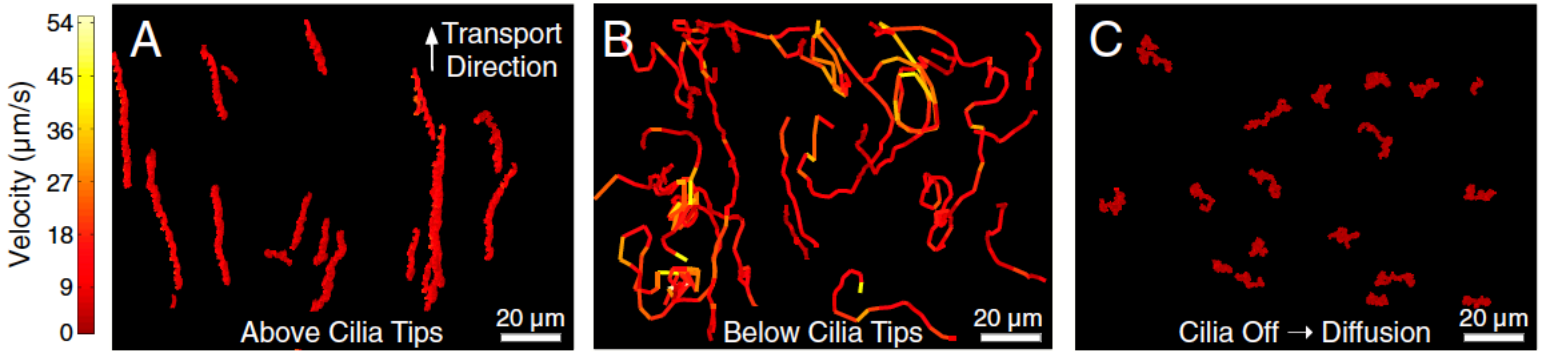
$u$: characteristic velocity
$l$: characteristic length
$D_0$: mass diffusivity

## Stokes-Einstein

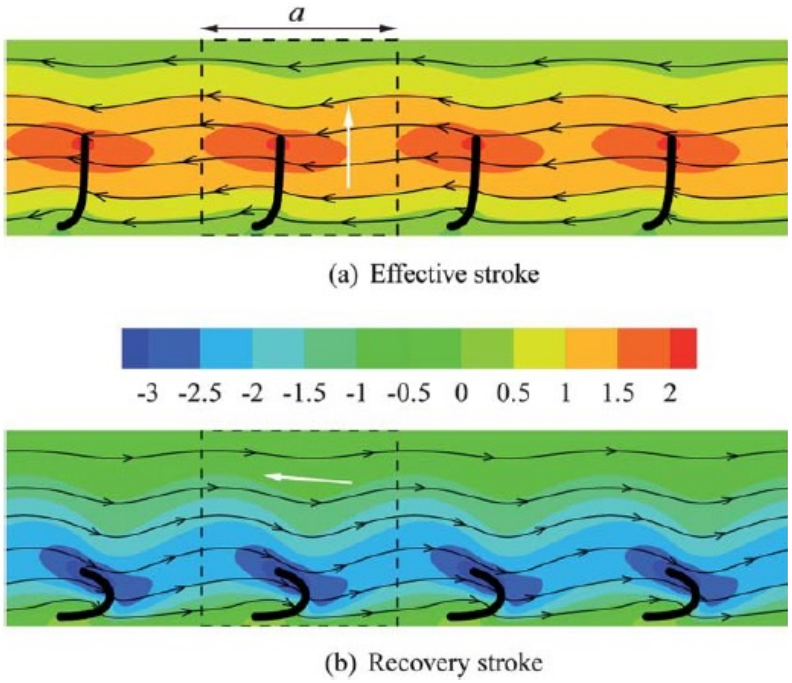
$$D_0 = \frac{kT}{3\pi\eta d} = 0.9\ \mu m^2/s$$

kT: thermal energy
$\eta$: viscosity
d: diameter

# Magnetically-actuated artificial cilia



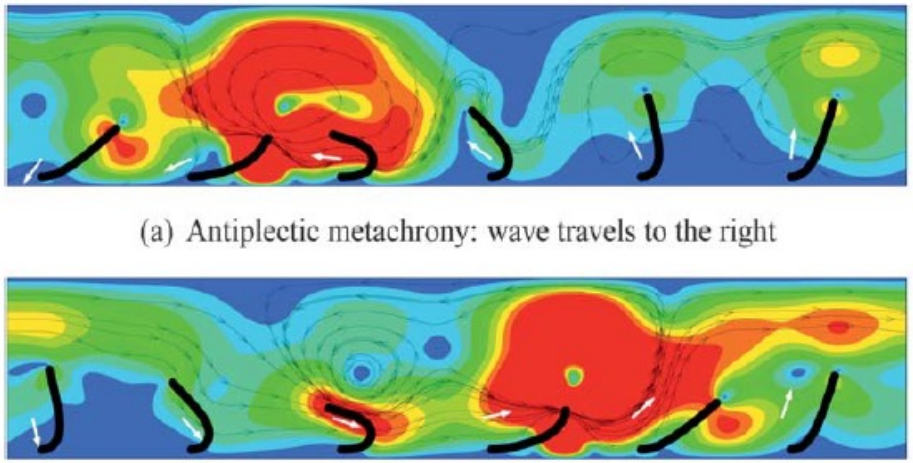

Synchronous beating




(a) Effective stroke

(b) Recovery stroke

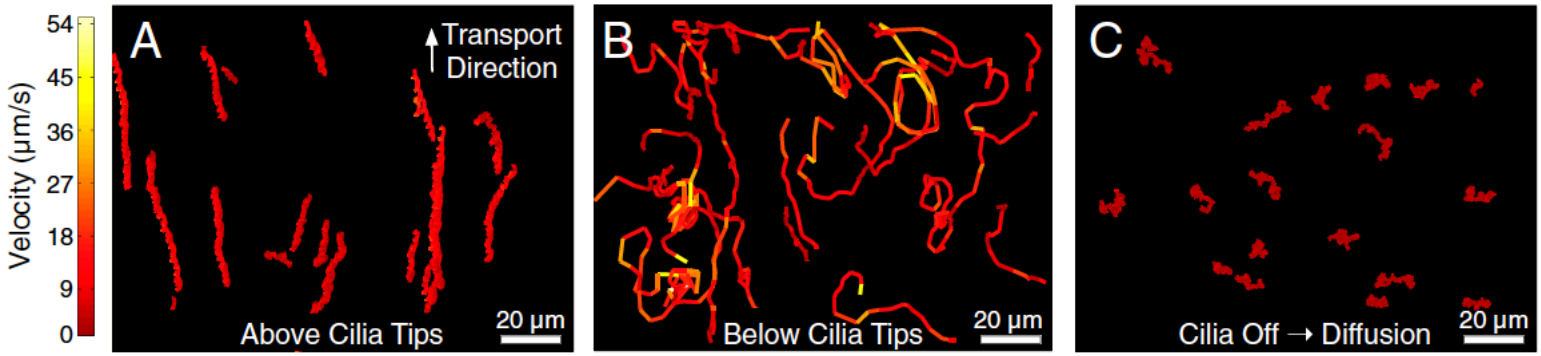
Out-of-phase movement



(a) Antiplectic metachrony: wave travels to the right

(b) Symplectic metachrony: wave travels to the left

# Magnetically-actuated artificial cilia



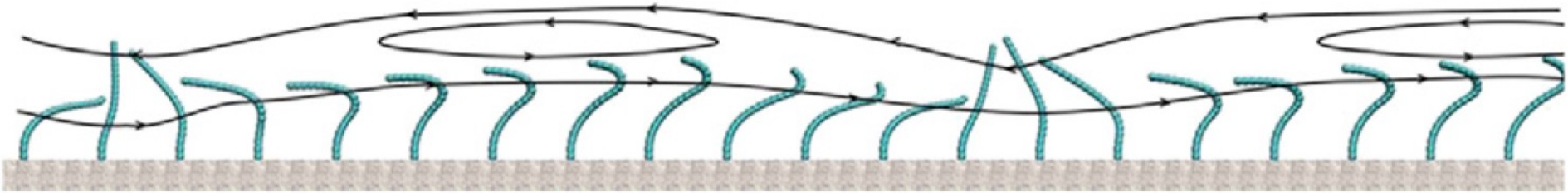
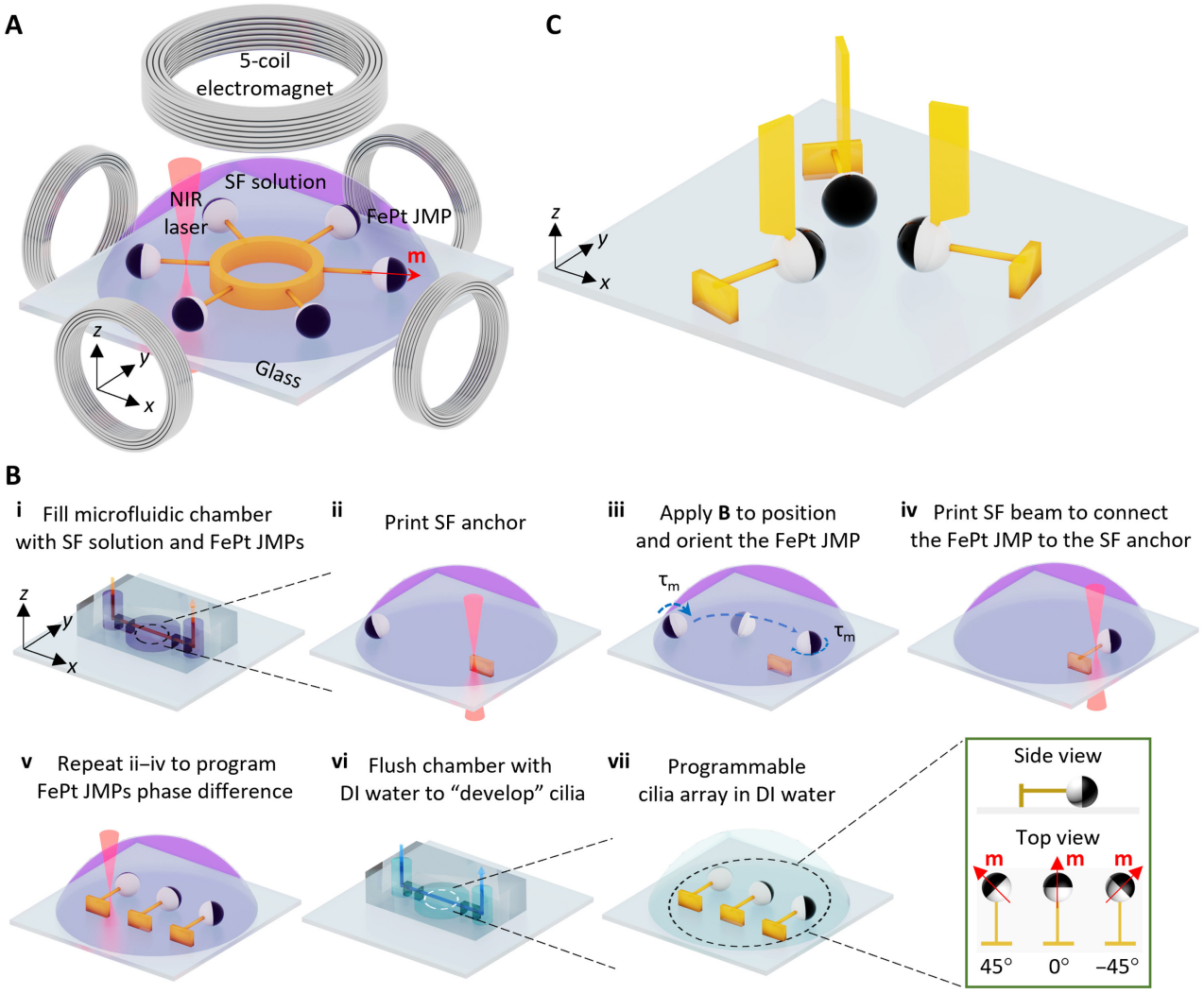



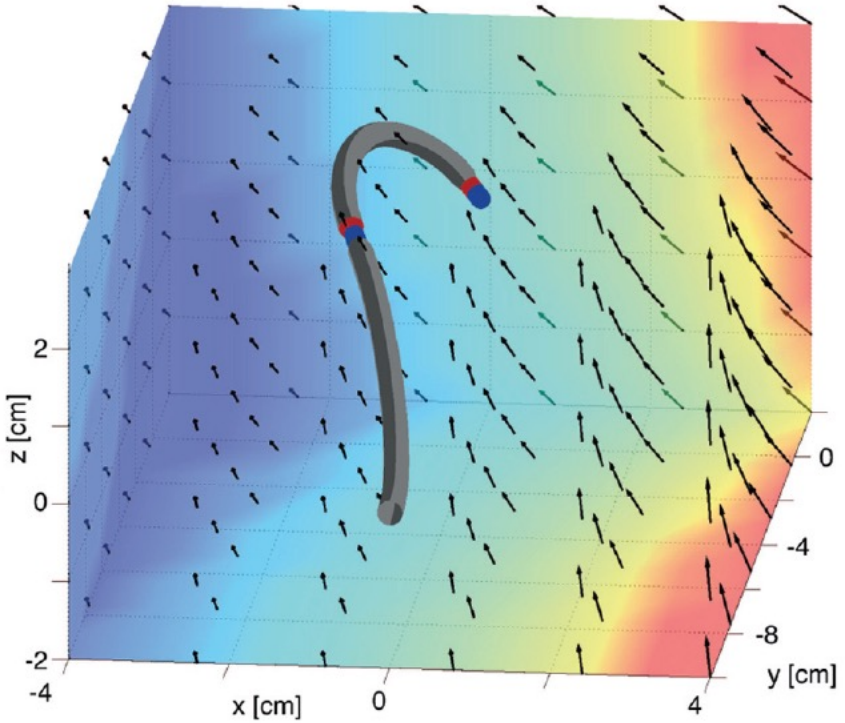
**Fig. 5.** Schematic view of metachronal beating to explain the origin of metachronal gain.

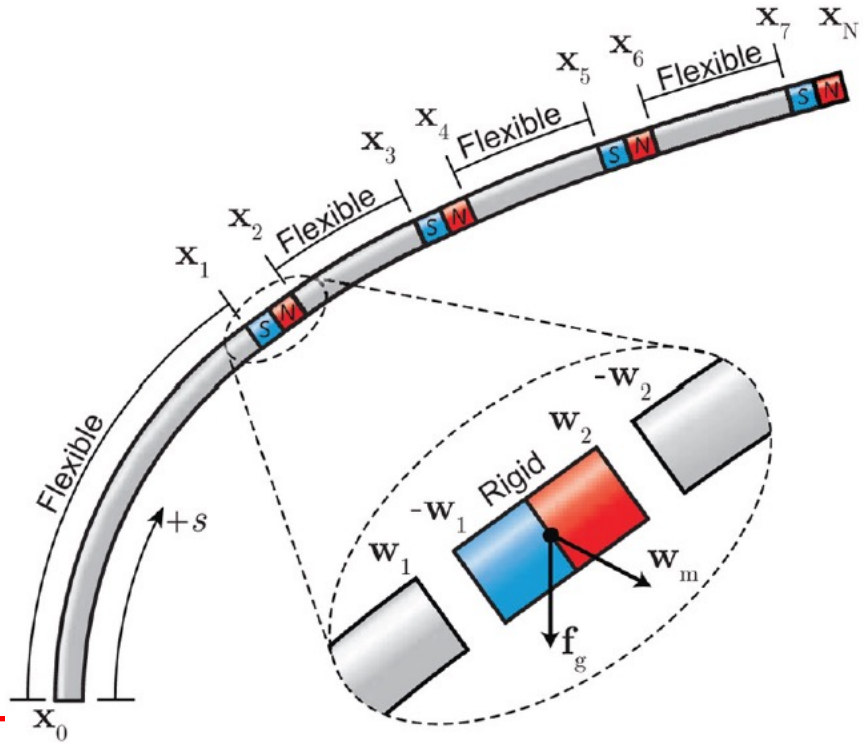
# Magnetically-actuated artificial cilia



# Magnetic control of continuum devices

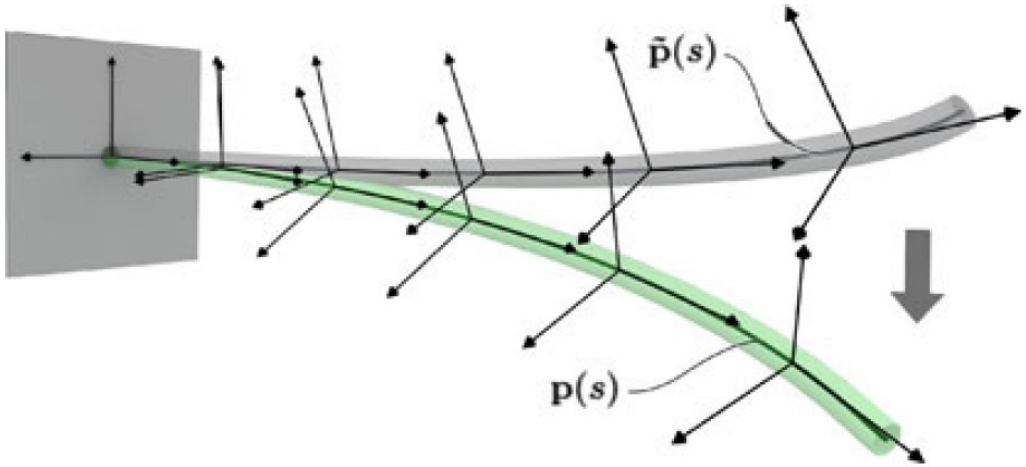
- Guiding the translation and/or deformation of elastic rods
  - Surgical tasks with catheters
  - Do not require pull wires or other bulky mechanisms
  - Forces and torques generated by the interactions between embedded hard magnets and magnetic vector field



# Magnetic control of continuum devices

- Rigid segments: standard rigid-body kinematics and force-torque equilibrium equations
- Flexible segments
  - Kirchhoff's theory: rod is not stretched, only bending strain
  - Cosserat-Timoshenko rod theory: with tensile and shear stiffness (flexibility of the rod in tension and shear)
  - Small strains and Hooke's law



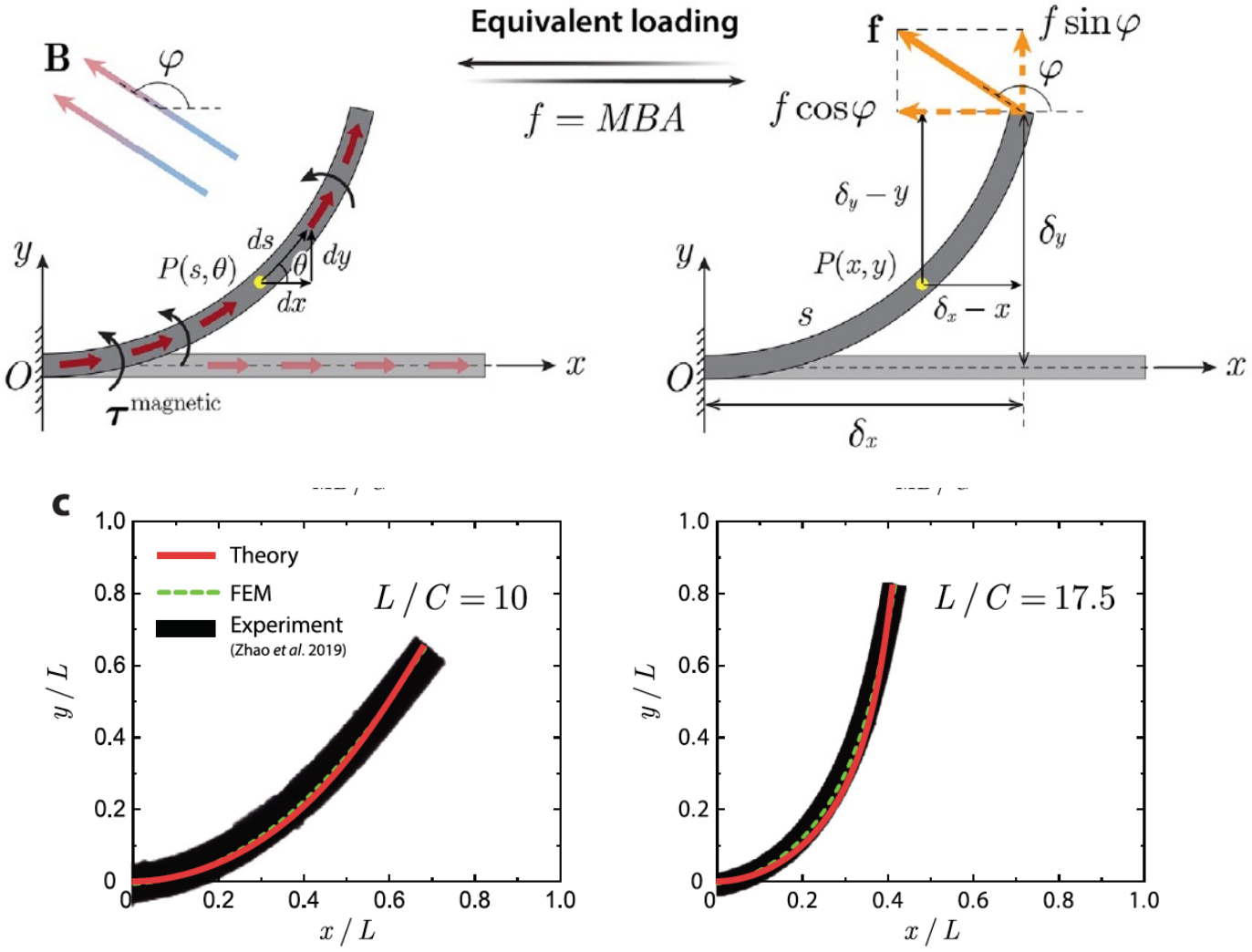
# Hard-magnetic elastica

- Thin, elastic rod with hard magnetic properties
- Assumptions
  - cross-section remains perpendicular to the centerline of the body during deformation ( i.e., no transverse shearing)
  - the centerline length of the elastica remains unchanged during deformation ( i.e., centerline inextensibility along the length direction)
  - the incompressibility of constituent materials
  - the twisting motion has low practical implications for the interest in magnetically steerable soft continuum robots

$$\frac{EI}{A}\frac{d^2\theta}{ds^2} + MB\sin(\varphi - \theta) = 0$$

$$\frac{MBAL^2}{EI} = \frac{1}{2}\Phi^2(\varphi, \theta_L)$$

# Hard-magnetic elastica



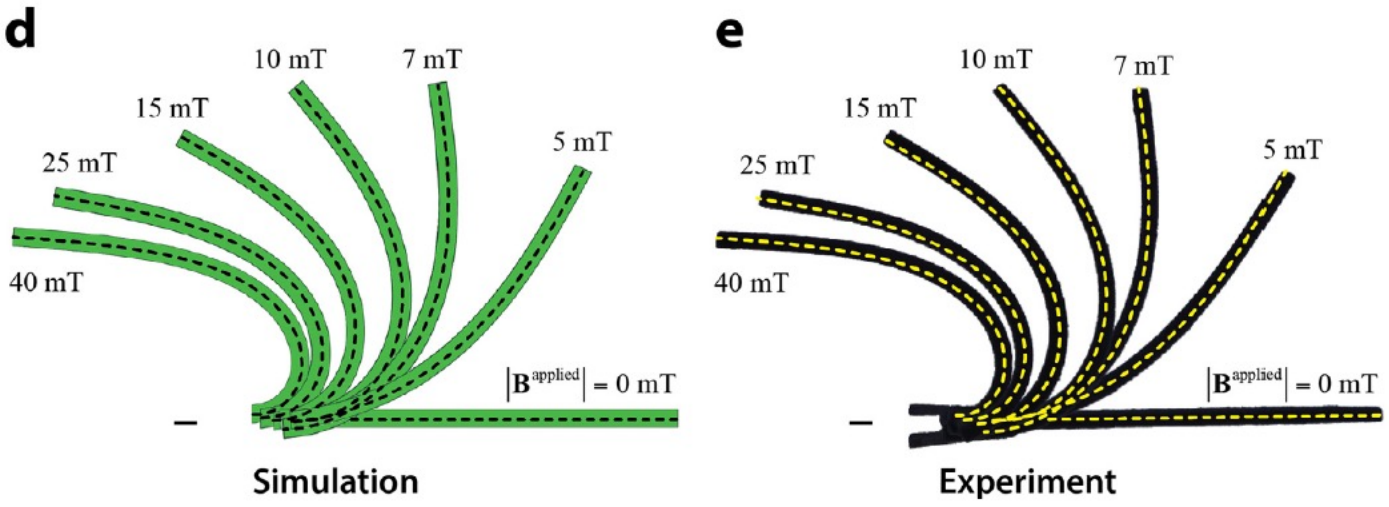
# Finite element modeling

- Induced magnetic flux density exhibits a linear relation with applied magnetic field

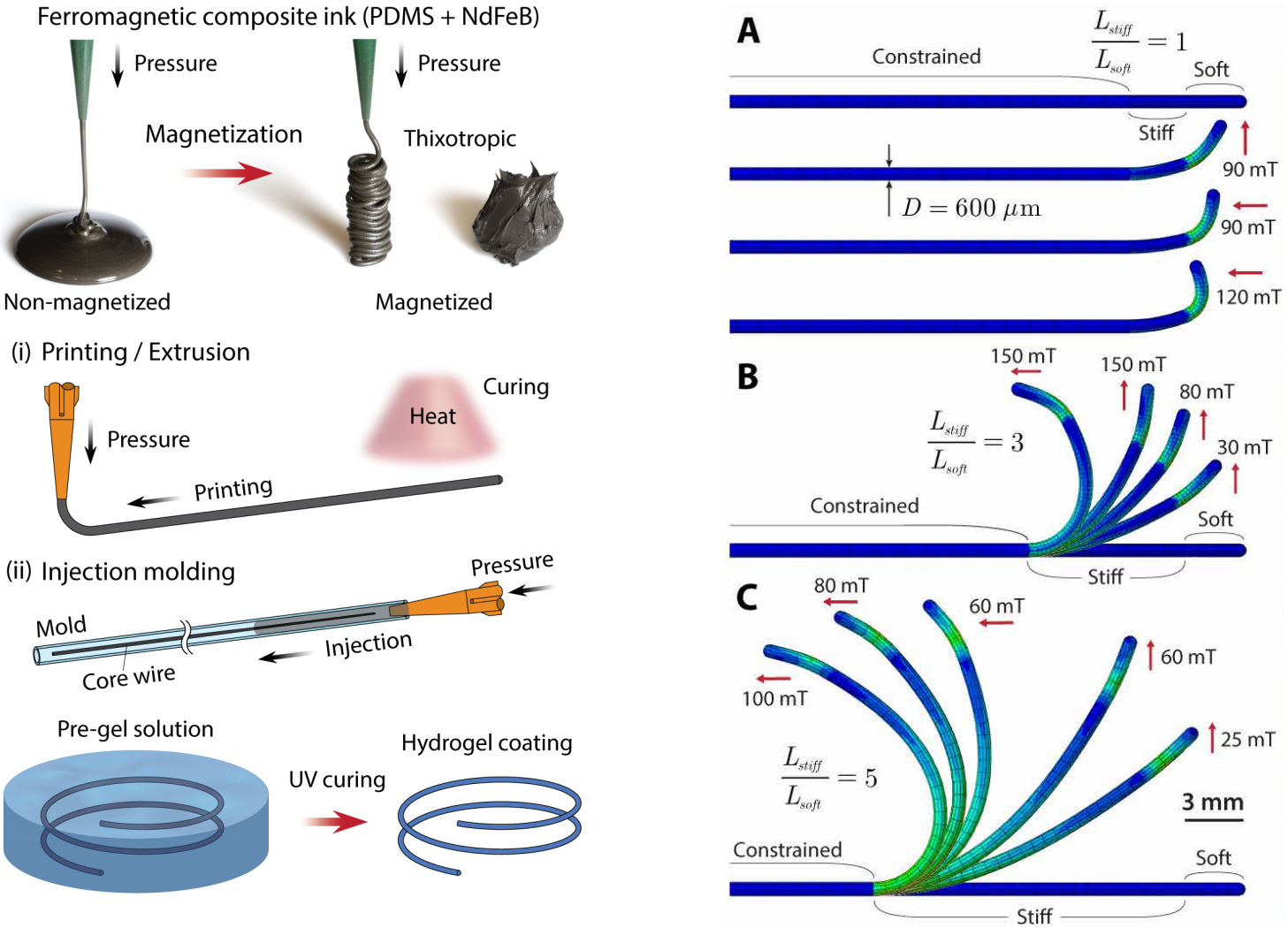
$$U = U_{\mathrm{e}}(\mathbf{F}) + U_{\mathrm{m}}(\mathbf{F}, \mathbf{B})$$

3D Elastic Energy  Magnetic Potential

$$U_{\mathrm{m}} = -\mathbf{FM} \cdot \mathbf{B}$$



# 3D printed magnetic catheters



# 3D printed magnetic catheters

## Ferromagnetic soft continuum robots

Yoonho Kim[1], German A. Parada[1,2], Shengduo Liu[1], Xuanhe Zhao[1,3*]

[1]*Department of Mechanical Engineering, Massachusetts Institute of Technology*
[2]*Department of Chemical Engineering, Massachusetts Institute of Technology*
[3]*Department of Civil and Environmental Engineering, Massachusetts Institute of Technology*

*Correspondence should be addressed to Xuanhe Zhao (zhaox@mit.edu).

**Movie S3.**

**Ferromagnetic soft continuum robot navigating through a highly nonlinear path based on multiple modes and degrees of actuation.**

Massachusetts Institute of Technology

ZHAO LAB

Kim et al., *Sci. Robot.* **4**, eaax7329 (2019)

# 3D printed magnetic catheters

## Ferromagnetic soft continuum robots

Yoonho Kim[1], German A. Parada[1,2], Shengduo Liu[1], Xuanhe Zhao[1,3*]

[1]*Department of Mechanical Engineering, Massachusetts Institute of Technology*
[2]*Department of Chemical Engineering, Massachusetts Institute of Technology*
[3]*Department of Civil and Environmental Engineering, Massachusetts Institute of Technology*

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**Movie S6.**

**Comparison of the navigating performance: ferromagnetic soft continuum robots vs commercial guidewires with passive steering.**

Massachusetts Institute of Technology

ZHAO LAB

Kim et al., *Sci. Robot.* **4**, eaax7329 (2019)

# Reprogramming magnetic properties