Wireless Millimeter-Size Soft Climbing Robots With Omnidirectional Steerability on Tissue Surfaces

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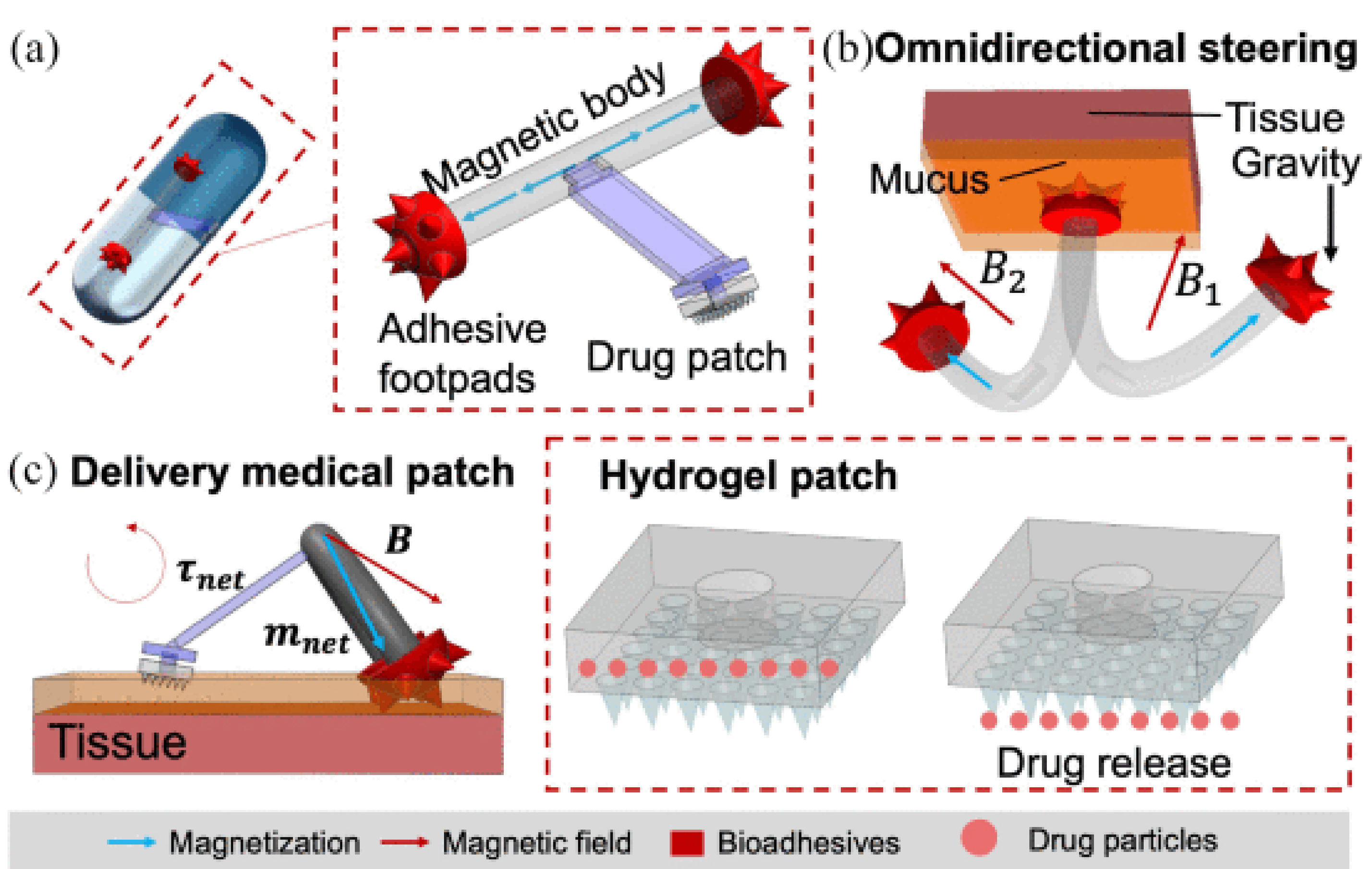
Background and Motivation

- **Background**: Wireless soft-bodied robots at the millimeter-scale allow traversing very confined unstructured terrains with minimal invasion and safely interacting with the surrounding environment.
- **Existing works**: Exciting advances have been made in recent years on soft miniature robots which can traverse complex terrains using bioinspired locomotion modes, such as rolling, crawling, and swimming, as well as realizing cargo-delivery and manipulation functions for biofluid pumping and drug delivery.
- **Challenge:** However, existing untethered soft millirobots still lack the ability of climbing, reversible controlled surface adhesion, and long-term retention on unstructured three-dimensional (3D) surfaces, limiting their use in biomedical and environmental applications.
- **Proposed method**: Here we report a fundamental peeling-and-loading mechanism to allow untethered soft-bodied robots to climb 3D surfaces, by utilizing both the soft-body deformation and whole-body motion of the robot under external magnetic fields [1].

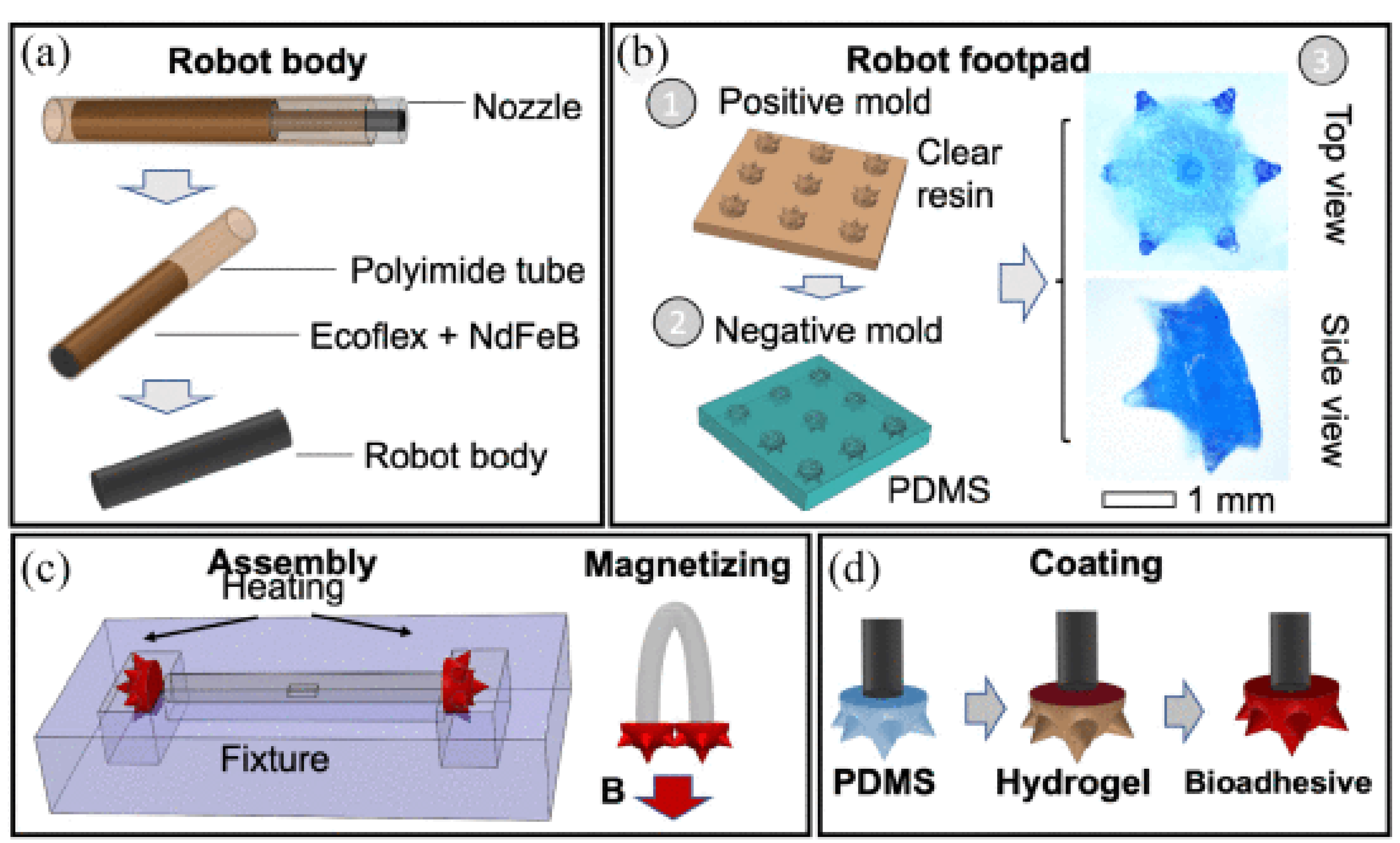
Research Significance



Major contribution:
- The rod-shaped body that allows for omnidirectional steering and climbing through a unique peeling-and-loading mechanism
- The rod-shaped body allows for a unique side peeling-and-loading mechanism

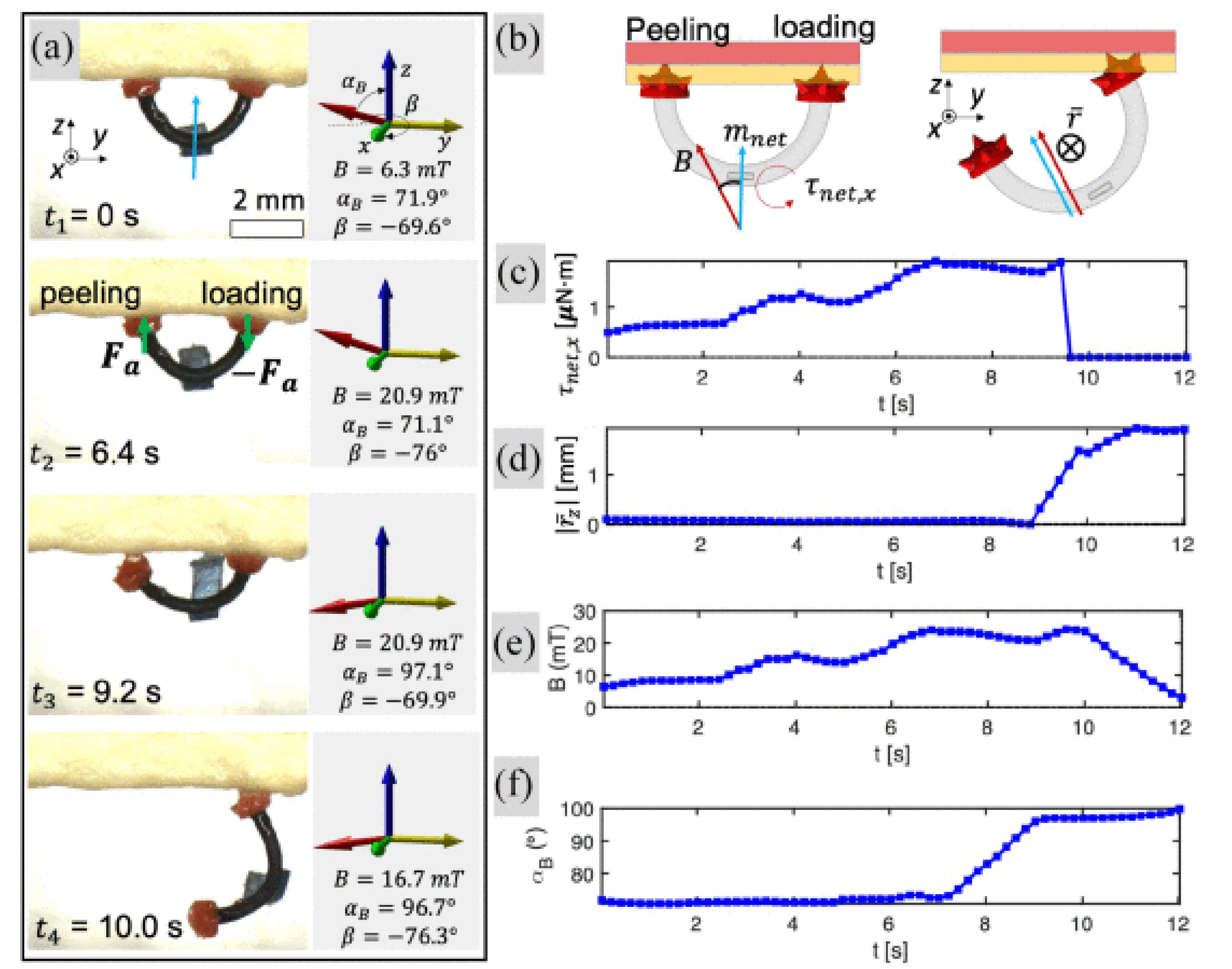
Practical application
- The wireless soft climbing robots could traverse complex 3D tissue surfaces in enclosed and confined spaces, and perform minimally invasive delivery of drugs and biosensors.

Fabrication and Design



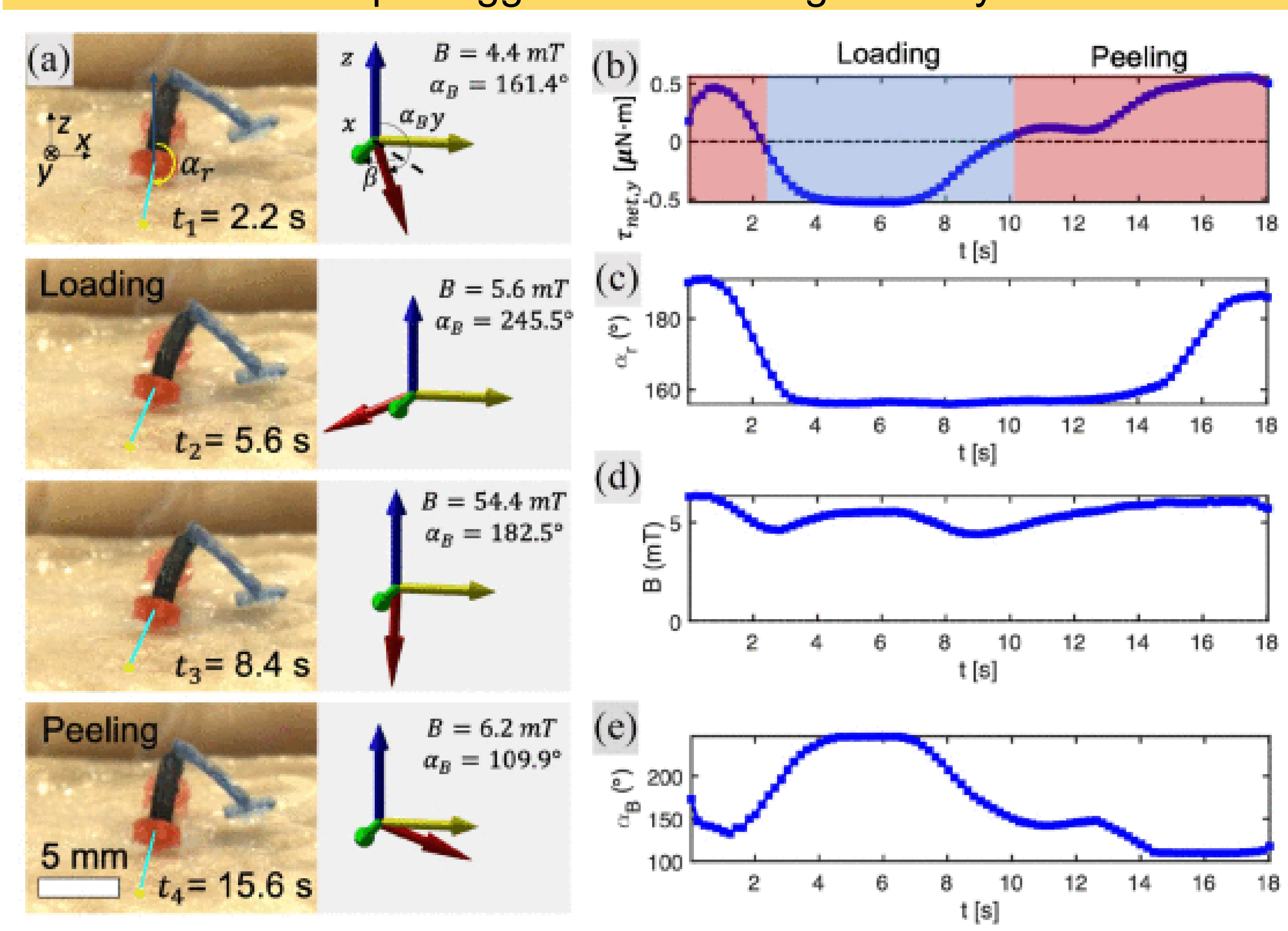
Fabrication Process of the Robot Body and Footpads
(a) Illustration of the fabrication process for the robot body using injection molding. **(b)** Illustration of the fabrication process for the robot footpads using transfer molding. **(c)** Illustration of the assembling process of the robot body and footpads and the magnetizing process for the robot body. **(d)** Illustration of the coating process for the robot footpad with hydrogel and bio-adhesive.

Peeling and Loading Locomotion Mechanism



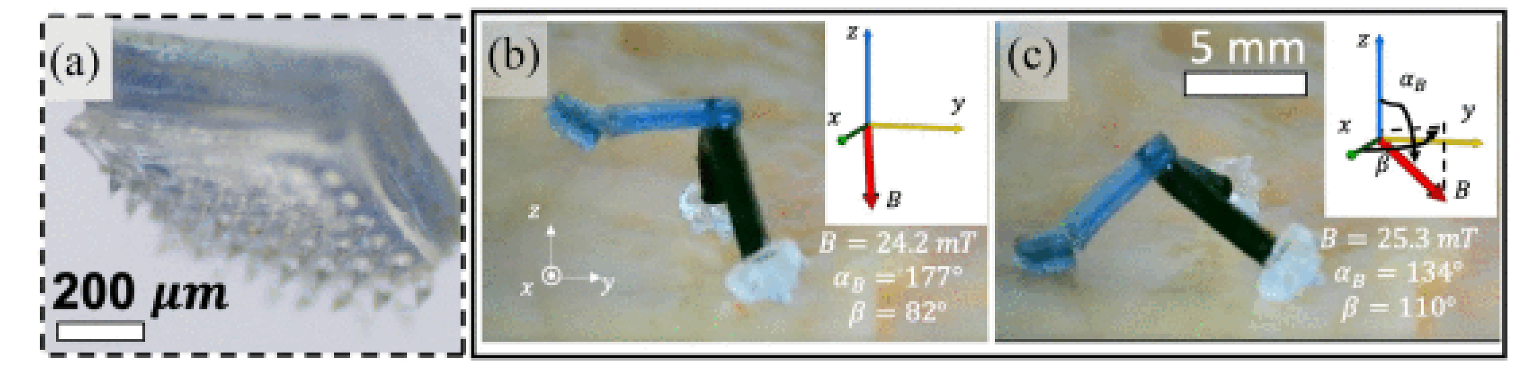
Controllable peeling-off of a robot footpad from tissue surfaces.
(a) Video snapshots of a robot being peeled off from the tissue by applying an external magnetic field. **(b)** Schematics of the peeling process. **(c)** The external magnetic field for peeling and rotating. **(d)** Net magnetic torque exerted on the robot. **(e)** Applied external magnetic field magnitude. **(f)** The angle between the external magnetic field and the robot body symmetric axis..

pH-triggered Local Drug Delivery



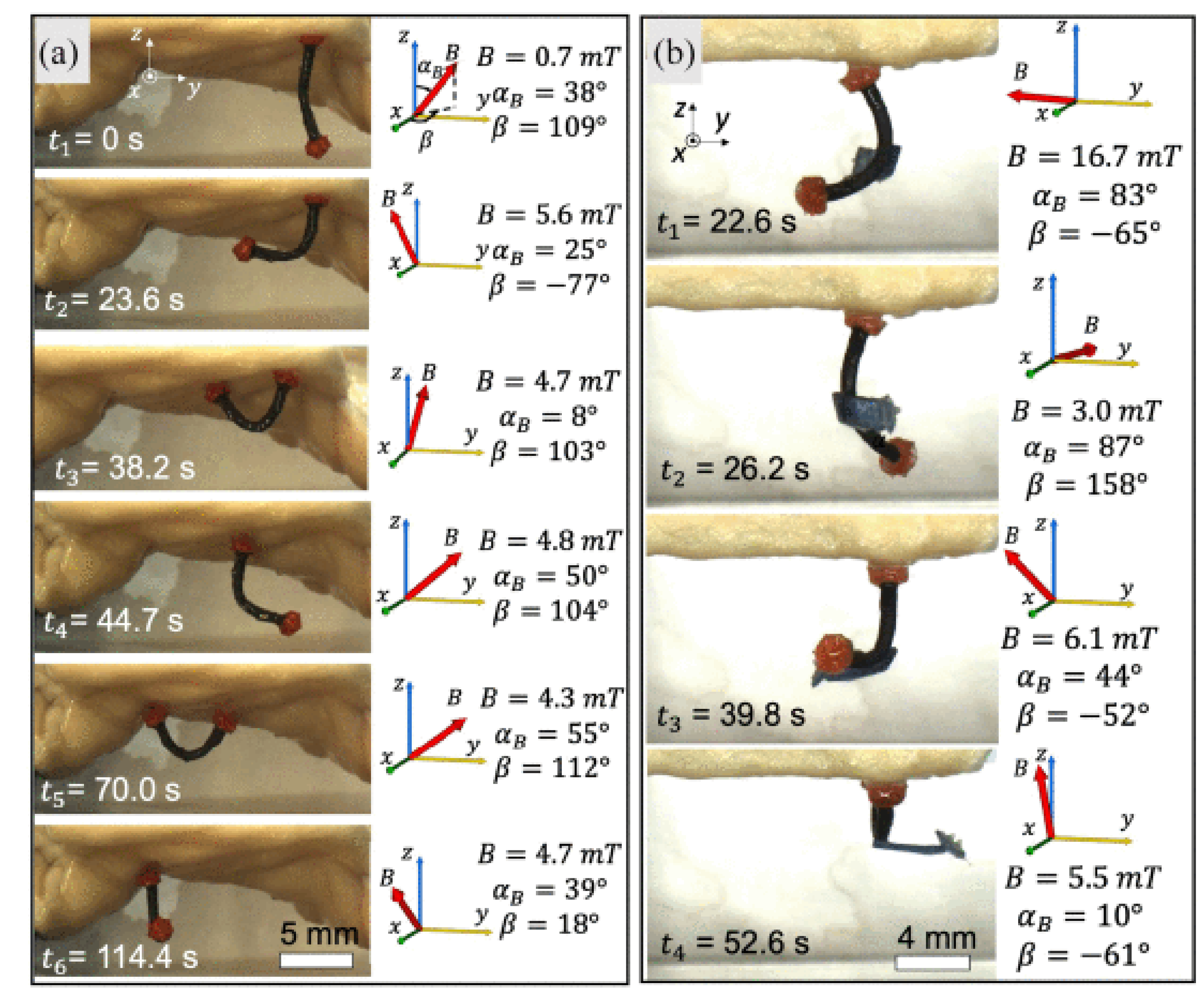
Side peeling-and-loading to attach a drug patch on soft tissues.
(a) Video snapshots and magnetic fields when a robot carrying a patch on a cantilever beam and loading the patch on a soft tissue. The light blue line indicates the robot magnetic moment direction (yellow circle: end point). **(b)** Calculated net magnetic torque exerted on the robot. **(c)** The tracked robot body angle as a function of time. **(d), (e).** The measured external magnetic field magnitude (d) and angle (e) in the workspace.

Delivery of a Hydrogel Patch



Demonstration of loading a medical patch made of hydrogel on porcine colon tissues.
(a) Image of the hydrogel medical patch with microspikes for drug delivery. **(b), (c)** Video snapshots of a rod-shaped soft robot loading (b) and loaded (c) on a medical patch on porcine colon tissues.

Climbing Porcine GI Tissues *Ex Vivo*



Robot navigation on colon tissues with the omnidirectional steering ability.
(a) Video frames of a rod-shaped soft robot climbing colon tissues with omnidirectional steerability and the corresponding magnetic field for enabling the motion. **(b)** Video frames of a rod-shaped soft robot climbing colon tissues with omnidirectional steerability while carrying a cantilever beam for delivering a medical patch.

Discussion

- The robot could be used to reach target locations rapidly and precisely by controlling their steering angle
- Towards future applications, our soft climbing robots can be used to deliver drugs through microneedle patches or for the delivery of sensors such that can measure physiological properties such as mucus viscosity or pH
- In the respiratory tract, it is also important to retrieve the robot with the help of other medical tools. For the GI tract, the robot could get out of the human body through the digestive passage after completing its tasks.

References.

[1] Y. Xu#, B. Xiao#, L. Balakumar, K. L. Obstein and X. Dong*, "Wireless Millimeter-Size Soft Climbing Robots With Omnidirectional Steerability on Tissue Surfaces," in *IEEE Robotics and Automation Letters*, vol. 8, no. 9, pp. 5720-5726, Sept. 2023.