

Click Beetle-inspired wood robot for high-frequency continuous jumping

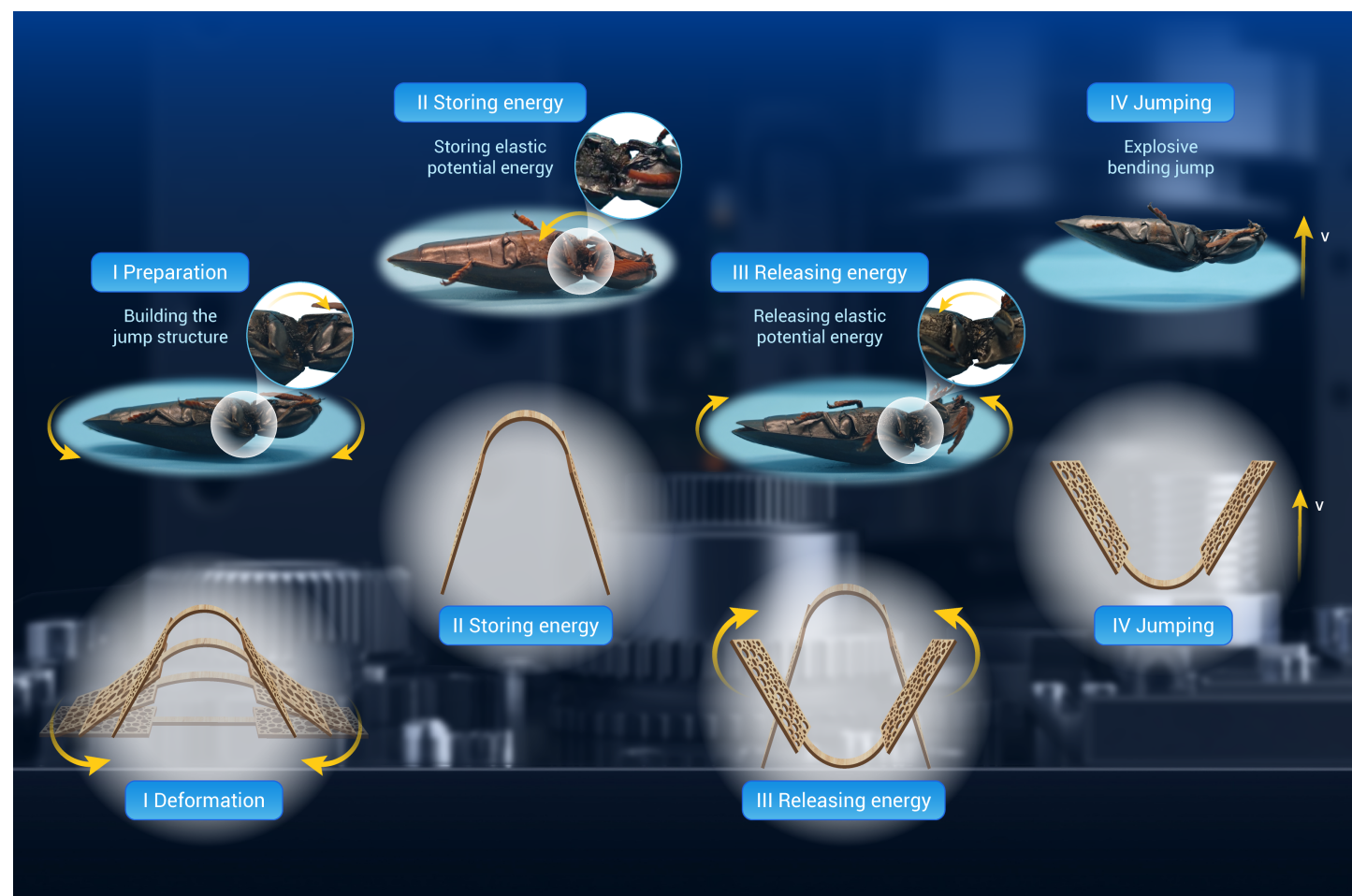
Xueqi Li,¹ Yaoxing Wang,¹ Quankuo Zhang,¹ Peng Jiao,¹ Ran Yin,¹ Yiqi Liu,² and Wentao Gan^{1,3,*}

*Correspondence: wtgan@nefu.edu.cn

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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Inspired by click beetles, the magnetic wood jumping robot (J-robot) realizes efficient energy release.
- The J-robot retains the mechanical advantages of wood, enabling continuous high-frequency jumping.
- Magnetic drive enables the J-robot achieves high-frequency jumps and precise directional control.
- J-robot can perform directional obstacle avoidance with high motion controllability in complex environments.

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Xueqi Li,¹ Yaoming Wang,¹ Quankuo Zhang,¹ Peng Jiao,¹ Ran Yin,¹ Yiqi Liu,² and Wentao Gan^{1,3,*}

¹Key Laboratory of Bio-based Material Science & Technology (Ministry of Education), Northeast Forestry University, Harbin 150040, China

²College of Computer Science and Engineering, Northeast Forestry University, Harbin 150040, China

³Heilongjiang Key Laboratory of Complex Traits and Protein Machines in Organisms, Northeast Forestry University, Harbin 150040, China

*Correspondence: wgtan@nefu.edu.cn

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Achieving continuous jumping in soft robots significantly enhances their movement efficiency. Inspired by the jumping mechanism of click beetles, we present a magnetically controlled wooden jumping robot (J-robot) constructed from delignified wood decorated with polydopamine-modified NdFeB microparticles. The mechanically robust wood structure serves as an effective elastic energy reservoir, while the incorporated NdFeB microparticles enable instantaneous magnetic activation within the composite system. A customized magnetization process programs the J-robot into “arch bridge” and “U-shaped” configurations, facilitating rapid conversion of stored elastic energy into kinetic energy via magnetic field switching. This design allows the J-robot to yield a jump initiation time of 0.1 s and a maximum jump height of 23.5 mm. By adjusting magnetic field parameters, the J-robot performs up to 257 jumps min⁻¹, a frequency surpassing most reported soft jumping robots. Additionally, the jump height scales proportionally with the elastic modulus of basic materials, offering valuable insight for soft jumping robot design. This work transforms conventional wood into a dynamic, high-performance actuation material, establishing a new paradigm for sustainable and environmentally adaptive soft robotics.

INTRODUCTION

Soft robots attract significant attention due to their inherent mechanical compliance, environmental adaptability, and human-safe interaction, which render them suitable for applications in constrained and unstructured environments.^{1–3} Recent artificial intelligence (AI) developments have enhanced the autonomous decision-making capabilities and environmental interaction efficiency of these soft robotic systems,^{4,5} opening up potential applications in critical scenarios, such as post-disaster search,⁶ minimally invasive medicine,^{7–9} and extreme environment exploration.^{10,11} Nevertheless, numerous application scenarios involve environments with complex three-dimensional (3D) topologies, such as the interiors of ruins, and biological tissue interstices. In contrast, current soft robotic systems rely on two-dimensional (2D) locomotion modes (e.g., crawling, rolling, and swimming),^{12–14} severely limiting their navigation in complex 3D spaces.¹⁵

Jumping can overcome this bottleneck by expanding the motion into 3D space, enabling soft robots to overcome higher obstacles and adapt to unstructured terrain, with obvious advantages in navigating and inspecting confined spaces (such as gravel crevices).^{16–18} However, achieving high-frequency continuous jumping is extremely challenging, as it requires the robot to complete the entire cycle from energy release to structural reset for the next jump within an extremely short timeframe.^{15,19} This poses dual challenges in mechanical design and driving method of the robot. The current actuation methods for soft jumping robots have limitations: light drive responds slowly,^{20–22} electric drive responds quickly but lacks reset accuracy,^{23,24} spring drive relies on manual reset,^{25,26} which hinders the realization of continuous jumping. Magnetic actuation represents an ideal strategy for achieving high-frequency continuous jumping due to its fast response, programmability, and precise remote-control capabilities.^{27–29} Nevertheless, existing magnetic systems still face material and energy efficiency challenges, prompting researchers to seek breakthrough inspiration from nature.^{30–32}

Click beetles (Coleoptera, Elateridae) exhibit a unique “explosive” jumping pattern propelled by rapid ventral bending.^{33,34} This ability stems from the

specialized thoracic structure of the insect: the mesonotum forms a saddle-shaped biological spring, while coordinated muscles and sclerites including the prosternal process and mesoventral cavity constitute an integrated elastic energy storage system.³⁵ During preparatory phase, the prothoracic dorsal plate bends toward the dorsal surface, followed by engagement of the prothoracic ventral process with the anterior end of the mesothoracic ventral plate to establish the “trigger joint” (Figure 1A I). Subsequent muscle contraction deforms the thoracic structures, storing elastic potential energy (Figure 1A II). Once the latching threshold is exceeded, the beetle flexes ventral, releasing stored energy instantaneously. The jump is completed within 0.59 s via elytral-ground reaction (Figure 1A III–IV), reaching a height up to 14.7 cm.³⁵ This biomechanical strategy demonstrates that exceptional jumping performance requires the synergistic interaction of intelligent latching mechanism and materials capable of efficient elastic energy management.

Wood is a renewable material with a multi-scale hierarchical structure and excellent mechanical properties.³⁶ It exhibits excellent energy storage properties, allowing for efficient energy accumulation and release during robot jumping cycles. Conventional soft robot substrates like shape memory alloys and elastomers often suffer from response hysteresis, limited energy storage, and control inaccuracy due to low modulus.^{13,37} In addition, the natural porous structure and abundance of hydroxyl groups on the wood surface facilitates its integration with magnetically responsive materials.³⁸ However, currently reported magnetic woods are mostly block-shaped rigid structures that resist controlled deformation, significantly limiting their application in soft jumping robots.

Herein, we develop a magnetic jumping soft robot (J-robot) by processing wood into a thin film, mimicking the jumping pattern of the click beetle. The robot achieves high-frequency continuous jumping through efficient energy conversion among magnetic, elastic potential, and kinetic energy. It is prepared by surface deposition of polydopamine-modified NdFeB microparticles (PDA@NdFeB) onto a 30-μm thick wood film (Figure 1B). The wood-derived structural skeleton enables mechanical support, enabling efficient energy storage and release during the J-robot jumping cycles. Subsequently magnetization induces alignment of magnetic domains inside the magnetic wood (Figure 1C), endowing the J-robot with a pair of magnetic field-induced bending configurations (Figure 1D), accumulating elastic potential energy. Reversing the magnetic field direction triggers a rapid transition between these configurations, releasing the stored elastic potential energy. We divide the jumping cycle into four phases including deformation, storing energy, releasing energy, and jumping (Figure 1E). Through the alternating magnetic field control, the J-robot achieves remarkable continuous jumping at 257 jumps min⁻¹, surpassing most reported polymer-based counterparts and organisms (Figure 1F). Moreover, direction control via field gradients allows the J-robot to traverse maze obstacles along a pre-set route (Figure 1G). This work proposes a novel biomimetic design paradigm by combining the mechanical advantages of wood with precision magnetically controlled technology. The resulting jumping robot enables precise operations in complex settings, such as search-and-rescue in rubble and inspection in narrow gaps. This paves new avenues for soft robotics applications in unstructured environments.

MATERIALS AND METHODS

Materials and chemicals

Poplar wood blocks (30 × 40 × 40 mm) were obtained from a local sawmill (Shijiazhuang, Hebei, China). Dopamine hydrochloride (C₈H₁₁NO₂·HCl, 98%)

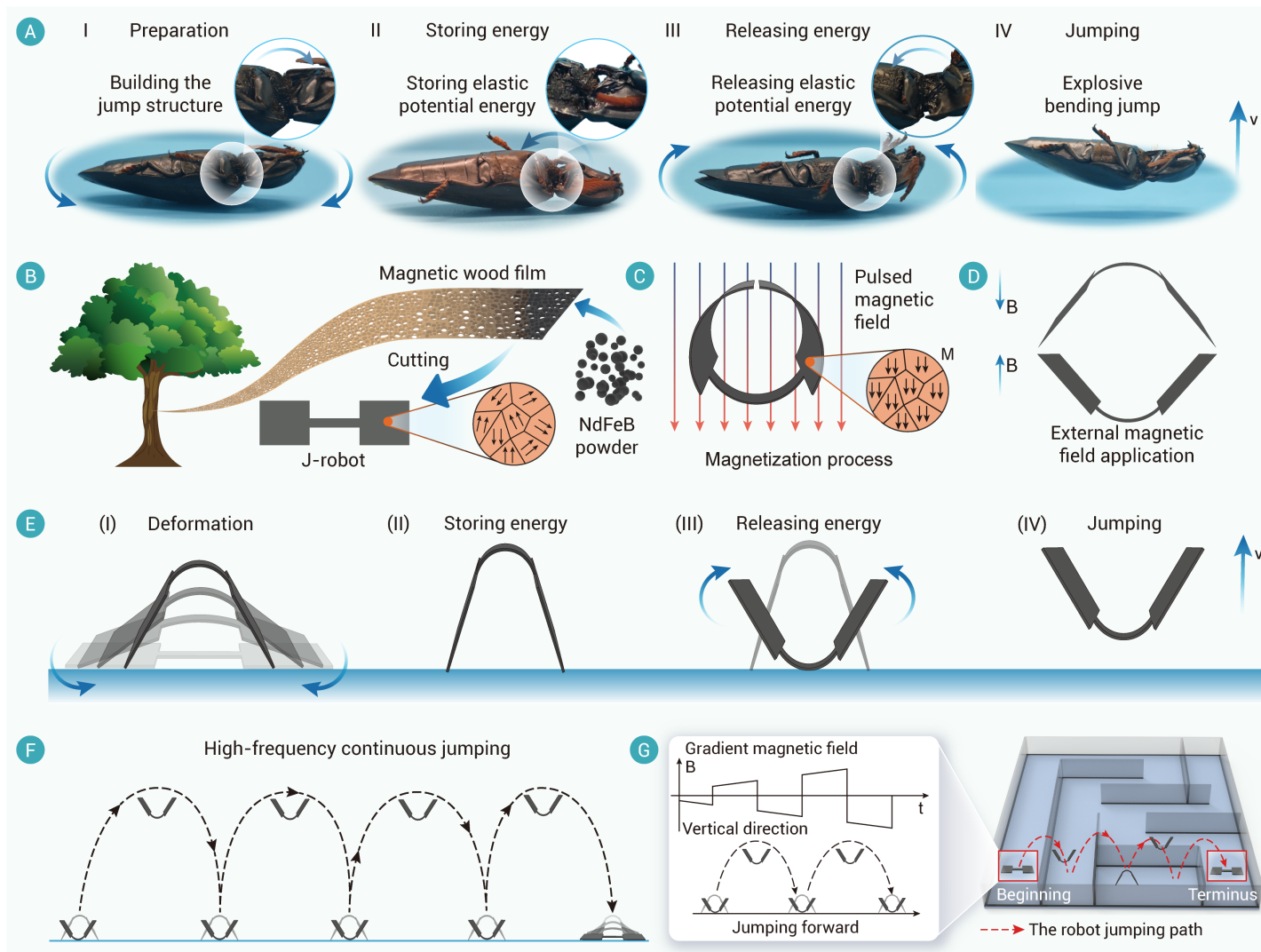


Figure 1. The concept of click beetle inspired J-robot (A) Mechanism of the explosive bending jumping of the click beetle. (B) The preparation of J-robot. (C) Schematic of the magnetization process. (D) Deformations of the J-robot after applying external magnetic field. Schematic of (E) single jumping and (F) high-frequency continuous jumping of J-robot. (G) Directed cross-barrier jumping motion of the J-robot under the gradient magnetic field.

and Tris-HCl buffer solution (pH = 8.5) were purchased from Shanghai Macklin Biochemical Technology Co., Ltd. Sodium chlorite (NaClO_2 , 80%) and acetic acid (CH_3COOH , 99.5%) were purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. Magnetic NdFeB particles were supplied by Guangzhou Xinnuode Transmission Components Co., Ltd.

Preparation of natural wood film

A poplar block ($30 \times 40 \times 40$ mm) was immersed in distilled water at 85°C for 7 days to achieve full saturation. After the wood was fully saturated and softened, it was sectioned into $30\text{-}\mu\text{m}$ -thick films using a rotary microtome (KH-Q330, Hubei Xiaogan Cuohai Medical Technology Co., Ltd., China).

Preparation of delignified wood film

Natural wood film was immersed in a 1 wt% NaClO_2 solution, with the pH adjusted to 4.6 using the acetic acid/sodium acetate buffer. The wood film was then heated at 150°C for 6 h until visually observed to transition from yellow to white. Finally, the wood film was rinsed with distilled water to remove residual chemicals.

Preparation of PDA@NdFeB suspension

NdFeB particles (4 g) and dopamine hydrochloride (0.3 g) were suspended in Tris-HCl buffer solution (100 mL, pH = 8.5). The mixture was then placed on a mechanical stirrer (OS20-S, DLAB Scientific Co., Ltd., China), and stirred at 500 rpm for 1 h to obtain the black PDA@NdFeB suspension.

Preparation of magnetic wood film

The delignified wood film was placed flat on a smooth glass sheet which was positioned above a magnet. The rubber-tipped burette was used to draw up the PDA@NdFeB suspension and drop it onto the wood film surface. This leveraged the magnetic force between the magnet and the magnetic particles to load the magnetic powder onto the surface and into the pores of the wood. The glass sheet was heated to 80°C until the water in the wood film evaporated. Finally, the unloaded NdFeB powder was removed from the wood film surface, yielding the magnetic wood film.

Fabrication of the J-robot

The magnetic wood film was cut into a dumbbell shape (5×5 mm magnetic feet connected by a 5×1 mm linkage). This structure was then bent 360° to form a closed loop and mechanically fixed. The fixed ring-shaped sample was then placed in the capacitive pulsed power supply (YY-MAG12C20, Hunan Pai Sheng Technology Co., Ltd., China) and subjected to five magnetization pulses in 2 T magnetic field. Finally, unfolded to obtain the J-robot.

Characterization

Micro morphology of the materials was characterized using Scanning Electron Microscopy (SEM, Apreo S) and High-resolution 3D X-ray microimaging system (Micro-CT, SKYSCAN I273). Crystal structure was analyzed using X-ray diffraction analysis (XRD, SHIMADZU 6100) at a scan-

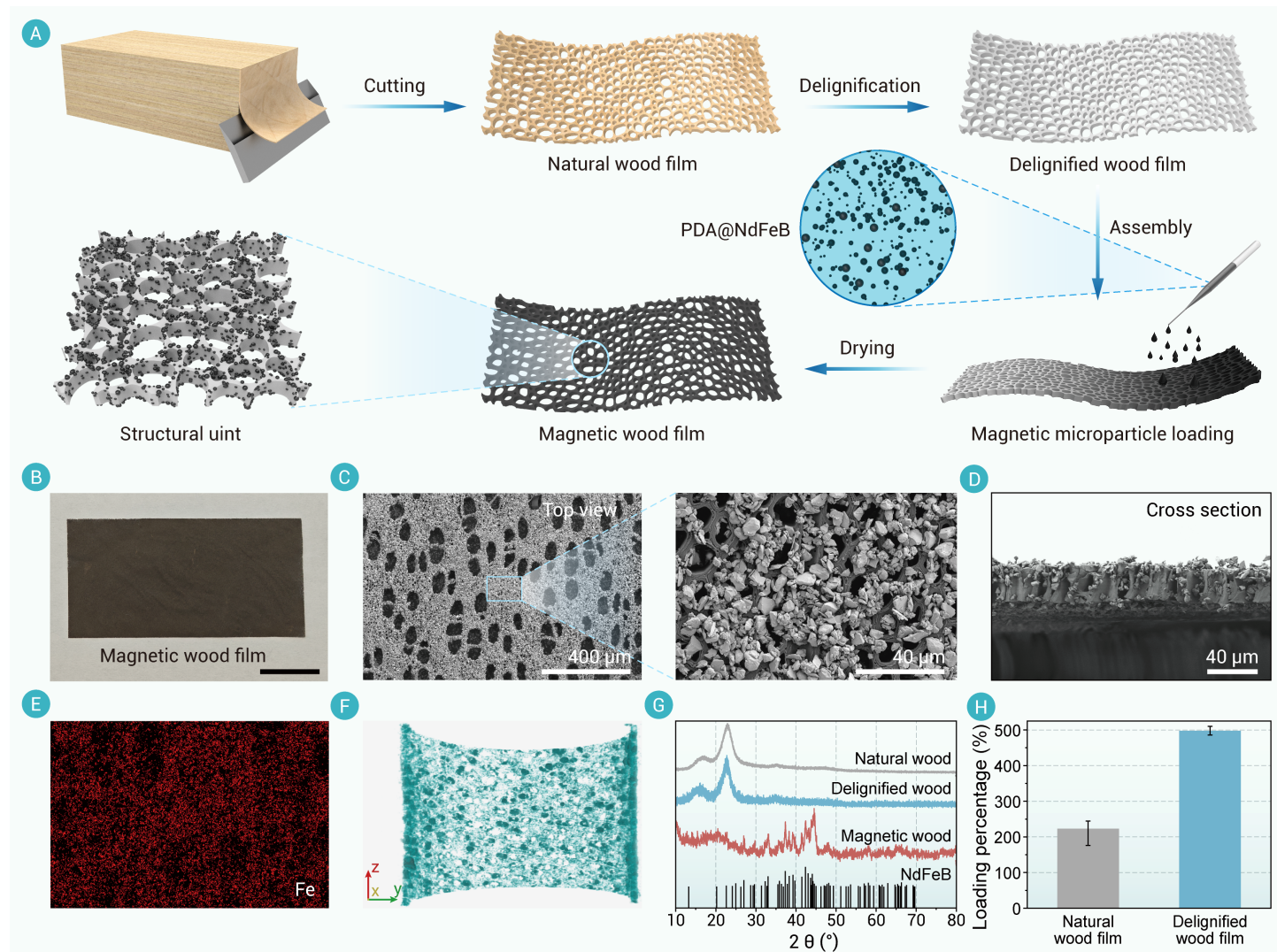


Figure 2. Preparation and characterization of the magnetic wood film (A) Flow chart of the preparation of the magnetic wood film. (B) Photograph of the magnetic wood film. Scale bar: 1 cm. The (C) top view and (D) cross-sectional SEM images of the magnetic wood film, showing the successful loading of the magnetic particles onto the wood substrate. (E) The EDS elemental mapping of Fe in the magnetic wood. (F) The Micro-CT image of the magnetic wood film. (G) The XRD spectra of natural wood film, delignified wood film, and magnetic wood film. (H) The comparison of magnetic particles loading of natural wood film and delignified wood film (30 × 40 mm), showing the increase of particle loading after delignification.

ning rate of $4^{\circ} \text{ min}^{-1}$ and a scanning range of $5 \sim 80^{\circ}$. Magnetic properties were characterized using the Physical Property Measurement System (PPMS, PPMS-9) at $\pm 4 \text{ T}$. The 3D Helmholtz coil (PS-3HM400) provided square-wave magnetic fields for actuation, and the magnetic response, jump height, and frequency of the J-robot were evaluated.

RESULTS

Morphology characteristics of magnetic wood film

We prepare J-robot films by depositing PDA@NdFeB onto wood substrate (Figure 2A). Natural wood films with a thickness of $30 \mu\text{m}$ are prepared via precision slicing (Figure S1A), exhibiting smooth cell walls and preserved cellular microstructure (Figure S1B). Reducing the film thickness below typical wood fiber length creates vertically aligned through-pores (Figure S1C), significantly enhancing permeability for magnetic particle infiltration. Subsequent delignification converts the film to white (Figure S1D), and exposes cellulose microfibrils on the cell wall surface (Figures S1E-F), generating abundant hydroxyl groups that enhance particle interfacial bonding. We immobilize PDA@NdFeB inside the modified wood substrate, yielding black magnetic wood films (Figure 2B; particle morphology in Figure S2). SEM images confirm uniform particle dispersion on surfaces and inside pores (Figures 2C-D), while the EDS elemental mapping of Fe further proves the homogeneous distribution of the NdFeB powders (Figure 2E). Micro-CT

reconstructs the 3D spatial arrangement of particles in the film (Figure 2F), corroborating SEM observations. The uniform microparticle distribution enables rapid magnetic response, which establishes the basis for the rapid energy accumulation and release required for continuous jumping.

Both natural and delignified wood films retain cellulose I crystal structure, with characteristic peaks at 15.7° and 22.3° .³⁸ Magnetic wood exhibits additional NdFeB phase characteristic peaks (PDF# 36-1296), verifying successful particle loading (Figure 2G). The Fourier Transform Infrared Spectroscopy (FT-IR) analysis reveals the specific vibrational peaks characteristic of lignin aromatic skeletal in the natural wood at 1591 , 1505 , and 1422 cm^{-1} , which disappear after delignification, indicating substantial lignin removal from 23.3% to 16.52% (Figures S3-4). Gravimetric analysis shows delignified wood achieves a particle loading of 496.91 wt.%, significantly higher than the 222.07 wt.% of natural wood (Figure 2H), due to the enhanced surface reactive sites of the delignified wood film. This enhanced loading strengthens magnetic actuation force, ensuring sufficient energy buildup for continuous jumping. Thermogravimetric (TG) analysis reveals higher residual mass in magnetic wood, correlating with NdFeB content (Figure S5), while the mass increase above 500°C stems from NdFeB oxidation. The magnetic wood film also shows good mechanical stability with minimal material loss (total loss < 12 %) after 6,000 cyclic bending (Figure S6), demonstrating the structural and magnetic durability essential for long-term reliable jumping.

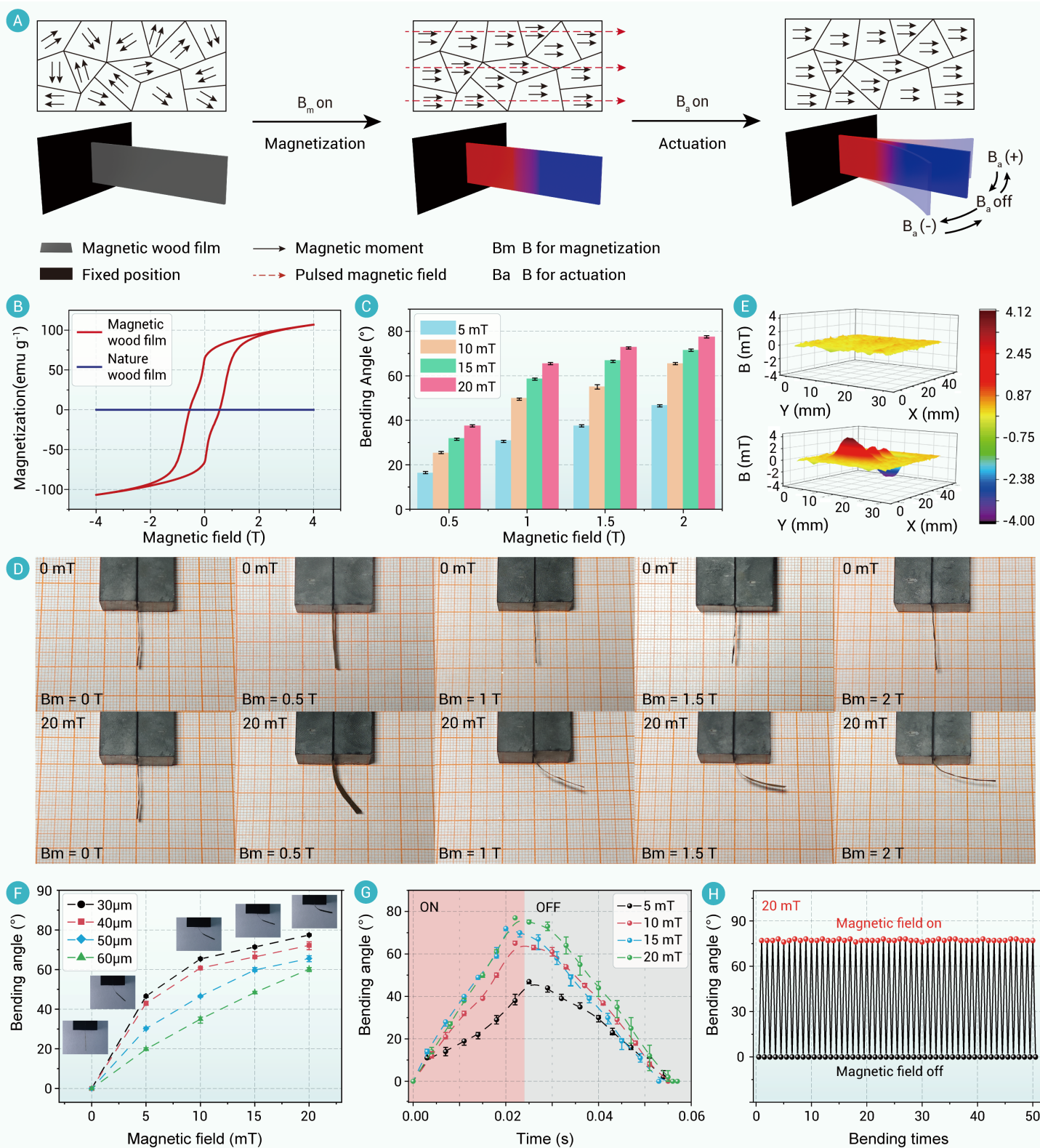


Figure 3. Magnetism of as-prepared wood samples (A) Schematic of the magnetization and actuation for the magnetized wood film. (B) PPMS plots of the magnetic and natural wood film. (C) Relation between the magnetization field strength and the maximum bending angle of magnetized wood films. (D) Photographs of magnetized wood films deformed in a 20 mT actuation magnetic field after 0–2 T magnetization. (E) Surface magnetic distribution of the magnetized wood film after magnetization at 2 T. (F) Variation of maximum bending angle of magnetized wood films with different thicknesses and magnetic field strength. (G) Response and recovery of the magnetized wood film with the assistance of different magnetic fields. (H) Cyclic stability of the magnetized wood film driven by a magnetic field of 20 mT.

Magnetic responsiveness of magnetic wood film

The controlled actuation of the magnetic wood relies on the orientation of the magnetic moments within the material. As shown in Figure 3A, non-magnetized wood exhibits disordered magnetic domains, whereas magne-

tized wood possesses a bipolar magnetic structure with aligned magnetic moments, endowing it with magnetic response capabilities. The magnetized wood demonstrates two field-responsive actuation mechanisms: torque-induced bending under uniform fields when the magnetization direction ($\mathbf{M}$)

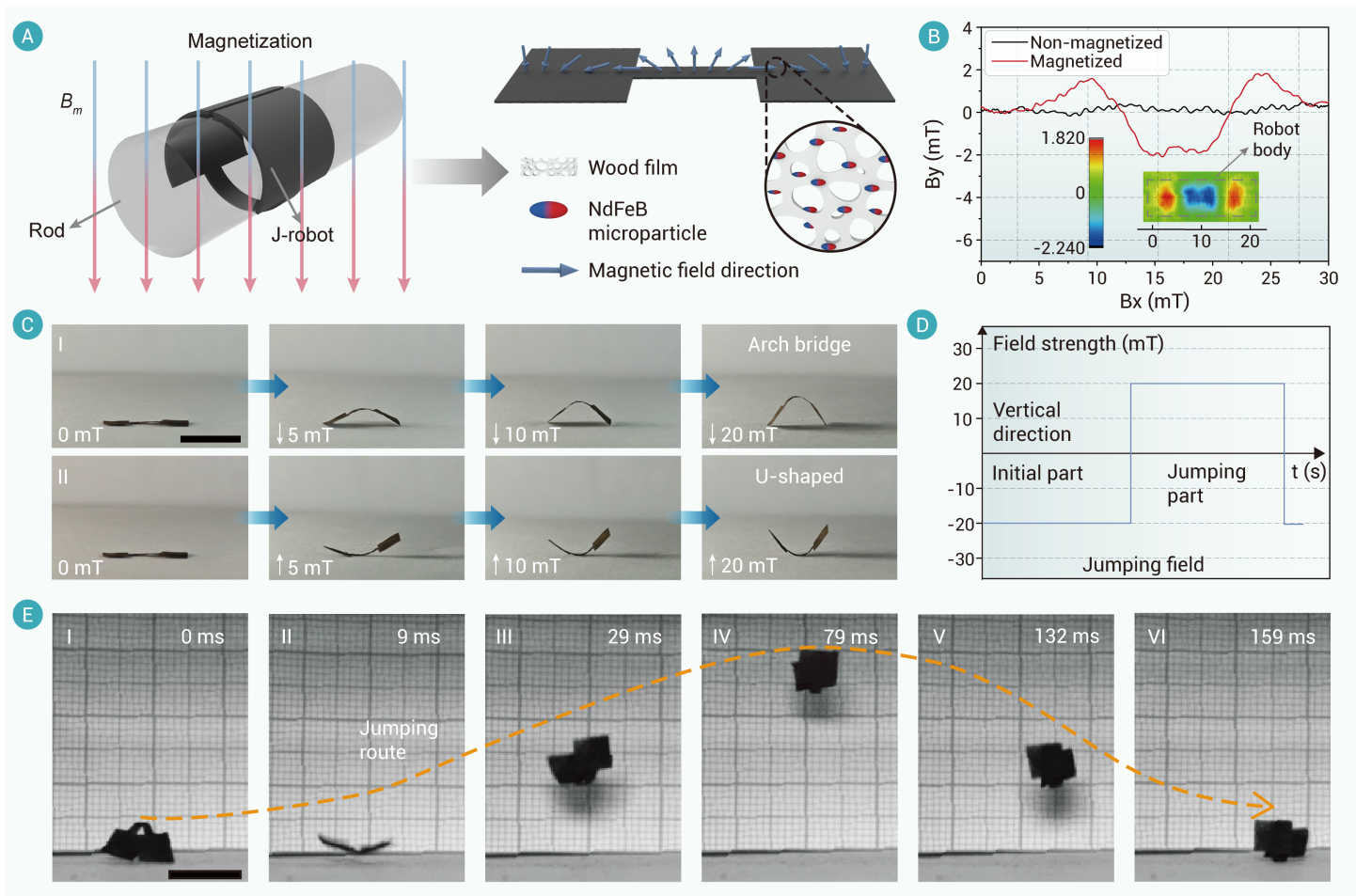


Figure 4. Magnetically controlled shape reconstruction and motion for the J-robot (A) Schematic of the magnetization and internal magnetic field direction of the J-robot. (B) Distribution of magnetic intensity on the surface of the J-robot. (C) Photographs of the “arch bridge” and “U-shaped” states in different actuation magnetic field. Scale bar: 2 cm. (D) The waveform of the actuation magnetic field during a jumping motion. (E) Macroscopic photographs of the jumping process of the J-robot. Scale bar: 1 cm.

differs from the actuation field (B_a), and magnetic force-driven translation in gradient magnetic fields. The equation of torque (τ) acting on the magnetized wood during deflection is given as follows:

$$\tau = V(\mathbf{M} \times \mathbf{B}_a) \quad (1)$$

where V and $\mathbf{M}$ are the volume and magnetization strength of the magnetized wood, respectively, and $\mathbf{B}_a$ is the magnetic induction strength of the actuation magnetic field. The equation of force ($\mathbf{F}$) acting on the film during movement is:

$$\mathbf{F} = V(\mathbf{M} \cdot \nabla) \mathbf{B}_a \quad (2)$$

where ∇ denotes the gradient magnetic field magnitude. By synergizing these two modes, the magnetized wood film achieves programmable deformation and locomotion, establishing a foundation for remote manipulation of the J-robot.

Unlike natural wood which shows negligible magnetism, the magnetized wood film exhibits strong ferromagnetic behavior in PPMS tests (Figure 3B), with a saturation magnetization (M_s) of 106.9 emu g⁻¹ and remanence (M_r) of 64.8 emu g⁻¹ under a ± 4 T magnetic field. This confirms effective integration of NdFeB microparticles in wood.

We systematically investigate the influence of the $\mathbf{B}_a$ and magnetization field strength (B_m) on the magnetized wood film actuation performance. At fixed B_m , the bending angle of the film increases with B_a , reaching 77.4° at 20 mT (Figure 3C), thus providing a parametric basis for the motion amplitude control of the J-robot. Increasing the B_m from 0.5 T to 2.0 T substantially enhances the intrinsic magnetic properties of the material: the M_s and M_r exhibit progressive increases from 21.49 mT to 90.32 mT and from 6.27 mT to 59.73 mT, respectively (Figure S7), consequently improving the magnetic

responsiveness of the film. The bending angle of the film with a B_m of 2 T increases by 51.7% compared to that of 0.5 T, driven by the same $\mathbf{B}_a$ (Figure 3D). Surface magnetic distribution reveals the magnetic wood film shows weak magnetism (< 0.5 mT), while the magnetized wood film confirms bipole magnetization topology (Figure 3E). The combination of significantly enhanced magnetic properties (high M_s , M_r) and optimized magnetization conditions (high B_m) ensures that adequate τ and $\mathbf{F}$ are generated during actuation, providing ample energy input to the J-robot for each jump.

To optimize the motion behavior, we systematically investigate the influence of the wood film thickness on actuation efficacy. The bending angle of the film decreases with increasing thickness under the identical $\mathbf{B}_a$, declining from 77.4° at 30 μ m to 60.2° at 60 μ m (Figure 3F). Films below 30 μ m lack mechanical strength for reliable NdFeB loading. Based on the coordination of magnetically driven deformation and structural integrity, we identified 30 μ m as the optimal thickness parameter for J-robot preparation.

The magnetized wood exhibits excellent dynamic response characteristics (Figure 3G), reaching maximum bending angle in 0.024 s and resetting in 0.055 s. This millisecond actuation response time facilitates efficient energy conversion in the J-robot. Over 50-cycle stability testing (Figure 3H), the bending angle of the magnetized wood remains at 76° to 78°, indicating structural durability for the continuous jumping motion.

Jumping motion of J-robot

Leveraging the magnetic responsiveness and durability of magnetized wood, we develop a J-robot by mimicking the rapid energy release of click beetles (Figure S8). Using the template-assisted magnetization protocol, the magnetic moments of the J-robot are distributed as designed (Figure 4A). Surface magnetic distribution testing confirms an alternating S-pole to N-

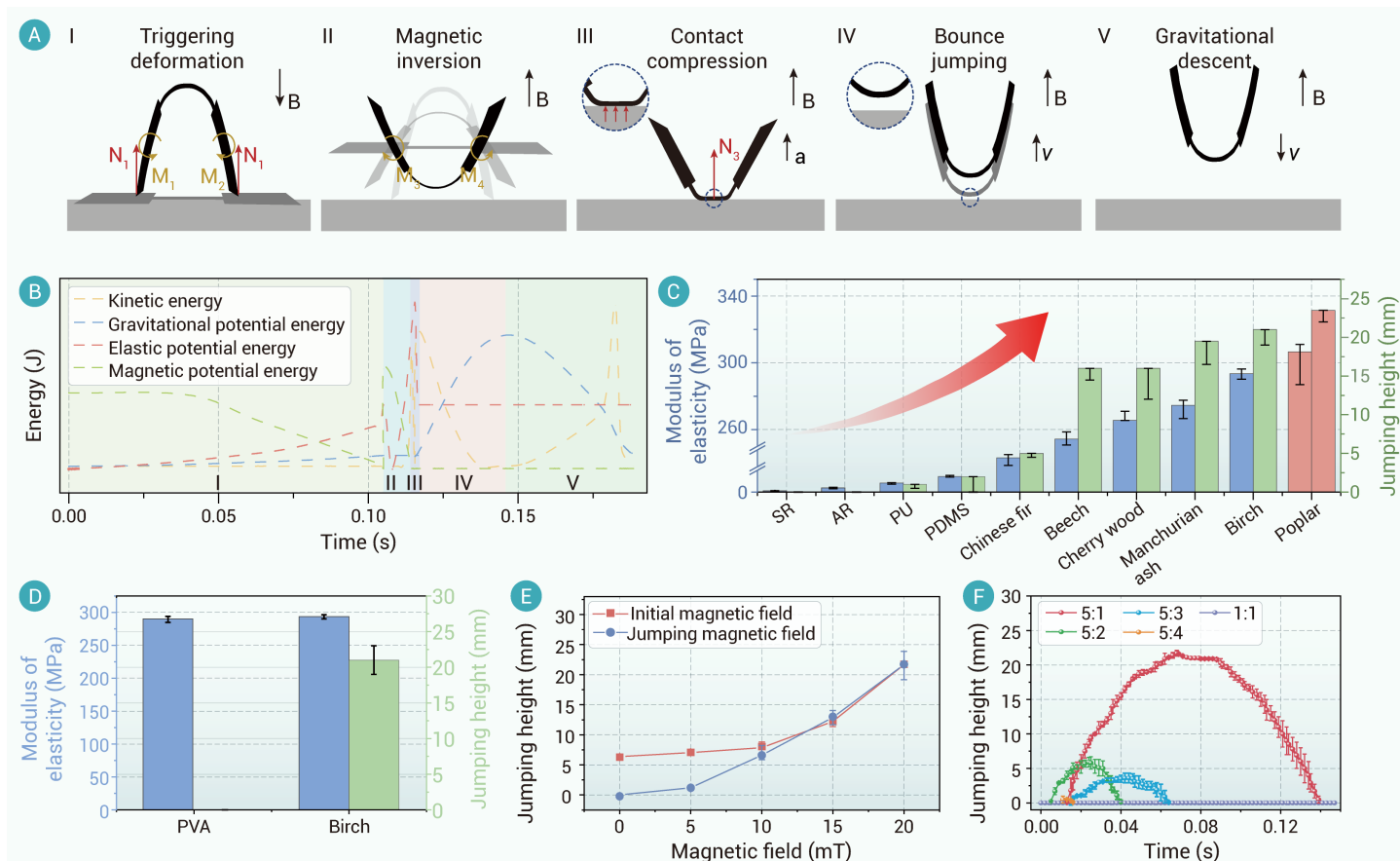


Figure 5. Analysis of J-robot jumping process and factors affecting jumping height (A) Schematic of the force analysis of the jumping process. (B) Energy conversion trend of one jumping motion of J-robot. (C) Robot jumping height and E prepared from different polymers and wood species. (D) Robot jumping height and E prepared from polymers and wood with similar elastic moduli. (E) Comparison of the effect of actuation magnetic field strength on the jumping height of the J-robot. (F) Correlation analysis between J-robot length-to-diameter ratio and jump height.

pole configuration along the feet and linkage tip, unlike the unmagnetized version which shows negligible magnetization (Figure 4B). The J-robot demonstrates distinct deformation under different magnetic fields. (Figure 4C). Integrating the two deformation modes, the J-robot enables a snap-through energy conversion, replicating the biomechanical process of click beetle through magnetic latching-release between the feet and linkage tip.

The jumping motion of J-robot is regulated by a vertical square-wave magnetic field. The magnetic field comprises two sequential phases: the initial part and the jumping part (Figure 4D). At the initial part, the robot forms an "arch bridge" posture, storing elastic potential energy (Figure 4E I). An instantaneous field reversal triggers a counteractive τ , deforming the robot into a U-shaped (Figure 4E II). The subsequent collision of the linkage tip with the ground propels the robot vertically (Figure 4E III–VI). High-speed cinematographic analysis shows the complete jumping cycle takes 159 ms, achieving a maximum vertical displacement of 23.5 mm (Movie S1).

Force analysis and energy conversion during J-robot jumping

Force analysis during jumping references five successive phases (I–V, Figure 5A): triggering deformation (Phase I, 0–0.1 s), magnetic inversion (Phase II, 0.1–0.108 s), contact compression (Phase III, 0.108–0.112 s), bounce jumping (Phase IV, 0.112–0.171 s), and gravitational descent (Phase V, 0.171–0.246 s). Initially stationary, the robot undergoes buckling deformation under a 20 mT downward field, with magnetic feet generating torques M_1 and M_2 and ground supporting forces N_1 and N_2 on both feet of the robot. Magnetic field reversal then produces upward deflecting torques M_3 and M_4 , which start the transformation of the J-robot structure into "U-shaped" structure (Phase II). Before the U-shaped completely forms, the linkage tip contacts the ground and undergoes compressive deformation, producing a vertical propulsive force N_3 (Phase III). As the resulting acceleration surpasses the gravitational acceleration, J-robot launches upward, and the

final jumping height reached 21 ± 2.5 mm ($n = 10$ trials) (Phase IV and V).

To elucidate the energy conversion mechanisms governing the jumping dynamics of the J-robot, we analyze the full motion energy conversion cycle (Figure 5B). Without magnetic field, the J-robot remains relaxed. Upon applying a downward field, the J-robot acquires magnetic potential energy (Figure 5BI), which is subsequently converted into elastic and gravitational potential energy through "arch bridge" deformation. Magnetic field polarity reversal provides additional magnetic potential energy, triggering rapid conversion of stored elastic and magnetic potential energy into kinetic energy at the robotic foot and link tips (Figures 5A II & B II). This causes the magnetized feet to rotate upward and generates a downward impact load at the linkage tip, producing dynamic contact forces with the substrate through inertial coupling (Figure 5B III). The resulting ground reaction compresses the linkage tip, storing elastic energy. In the linkage tip deformation recovery phase, ground support propels the J-robot upward, initiating propulsion. Elastic potential energy decreases as the robot enters the jumping phase (Figure 5B IV–V). Kinetic energy transforms into gravitational potential energy until the trajectory peak, then back into kinetic energy during descent (aerodynamic drag neglected). The energy formulas and derivation process are detailed in Note S1. Analysis confirms that the jumping kinetic energy, primarily originating from elastic potential energy accumulated during ground impact, is governed by the material elastic modulus (E) as the key parameter controlling both energy storage and jump height.

Jumping optimization of J-robot

We compare four types of polymer (silicone rubber (SR), acrylic resin (AR), polyurethane (PU), polydimethylsiloxane (PDMS)) with six types of wood (Chinese fir, beech, cherry wood, Manchurian ash, birch, poplar). Elastic modulus tests and jumping kinematical analysis (Figure 5C) demonstrate that the jump height of robot increases from 0 to 23.5 mm as the E of the

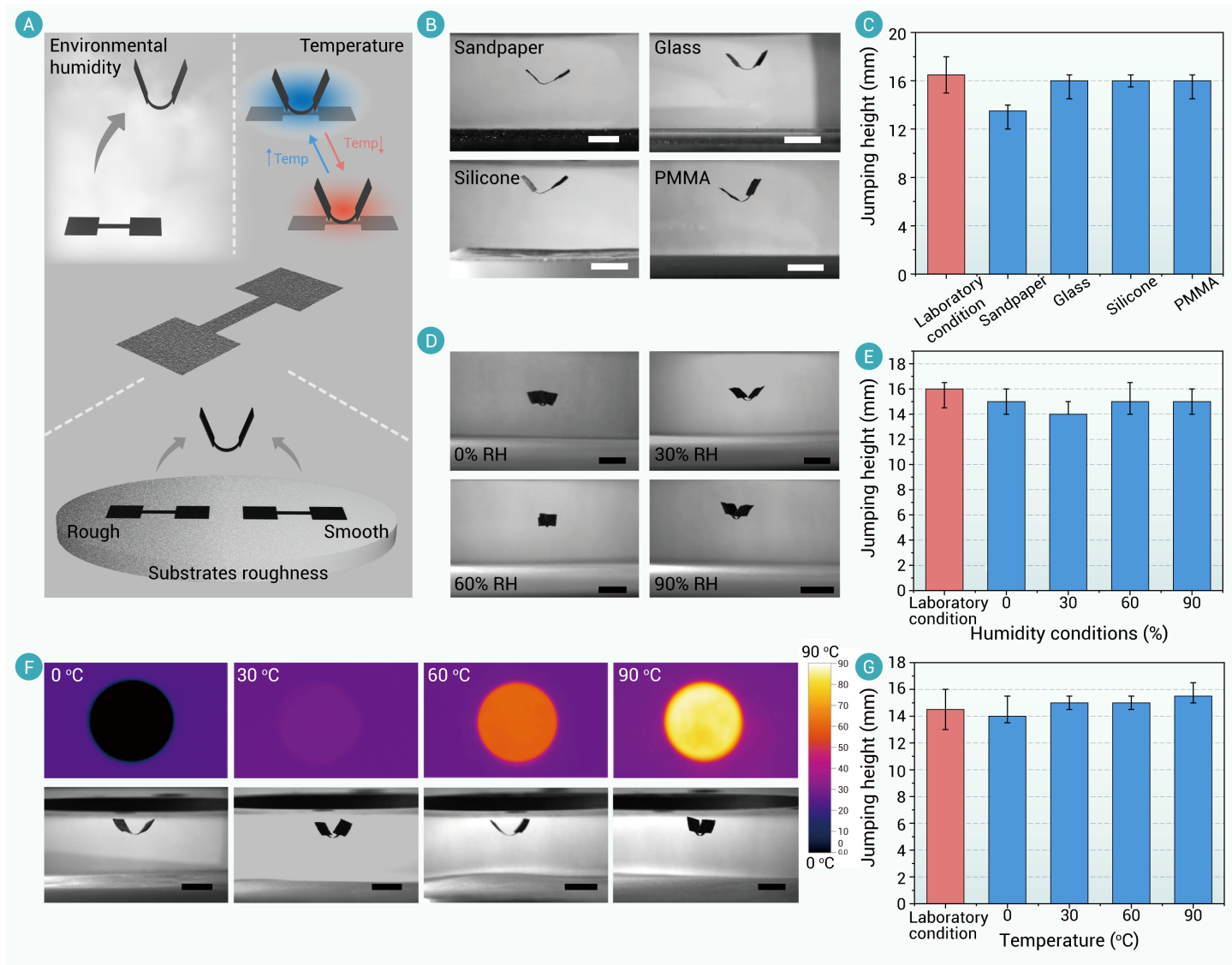


Figure 6. Environmental adaptability of the J-robot (A) Environmental stability test schematic for J-robot (B) Photographs of the J-robot jumping on surfaces including 60-grit sandpaper, glass, silicone, and PMMA. Scale bar: 1 cm. (C) The jumping height of J-robot on different material surfaces compared to the jumping height under laboratory condition. (D) Jump photographs of the J-robot and (E) comparison of jump height with laboratory condition at 0%, 30%, 60%, and 90% relative environmental humidity. Scale bar: 1 cm. (F) Photographs and (G) height comparisons of J-robot jumps in environments of 0 °C, 30 °C, 60 °C, and 90 °C. Scale bar: 1 cm.

materials increases from 0.8 MPa to 306.6 MPa. Wood-based robots (55.4–306.6 MPa) outperform polymer-based ones (0.8–9.3 MPa), as higher E enables efficient elastic energy accumulation and transformation. This investigation establishes E as the determinant of bioinspired jumper performance. Furthermore, the porous structure of wood significantly enhances energy release efficiency. As shown in Figure 5D, under similar elastic moduli ($E_{PVA} = 290.08$ MPa, $E_{birch} = 293.48$ MPa) and actuating magnetic field, the dense PVA film shows limited deformation and jumping ability, whereas the porous wood-based robot achieves effective deformation and successfully executes jumps. The comparison demonstrates that the pore structure within wood effectively promotes the bending deformation by coordinating strain.

The jumping performance of J-robot also correlates with magnetic field parameters and geometry. To elucidate the individual actuation mechanisms of the initial magnetic field (B_i) and the jump triggering field (B_j) on the J-robot, we conduct vertical jumping performance quantification. Increasing the initial field B_i (0–20 mT, B_j fixed at 20 mT) enhances jump height from 6.7 mm to 23.5 mm by creating greater initial arch predeformation and elastic energy storage (Figure 5E red & S9). Similarly, increasing the jump trigger field B_j (0–20 mT, B_i fixed at 20 mT) raises jump height, as τ is proportional to B_j , where higher B_j values increase torque during jumping actuation, thereby enhancing ground reaction force generation on the linkage tip (Figure 5E blue

& S10). The optimal field strength of $B_i = 20$ mT and $B_j = 20$ mT maximizes energy storage, meeting the jump control requirements.

In addition, we systematically investigate the actuator geometric design parameters of the J-robot by fabricating versions with aspect ratio ($\lambda = l/d$) ranging from 1 to 5. J-robots with high λ achieve higher jump heights (Figure 5F). This is attributed to the fact that higher λ reduce linkage tip stiffness, increasing buckling deformation and elastic energy storage capacity of the robot, thereby improving jump height. Conversely, robots with lower aspect ratios ($\lambda = 1$) exhibit minimal structural deformation. To indicate the scalable production of the J-robot, we fabricate centimeter scale robots and test their drive performance under a 20 mT magnetic field. The centimeter scale robots can still achieve stable, high-frequency continuous jumping motion, maintaining structural integrity even after 50 cycles of jumping (Figure S11).

Environmental adaptability of the J-robot

To evaluate the application potential of the J-robot in complex environments, we investigate the jumping performance of the robot under varying substrates roughness, relative environmental humidity, and temperatures (Figure 6A). According to experimental results, the J-robot maintains stable continuous jumping on substrates with varying roughness and softness (60-grit sandpaper, glass, silicone, and polymethylmethacrylate (PMMA)) (Figure 6B).

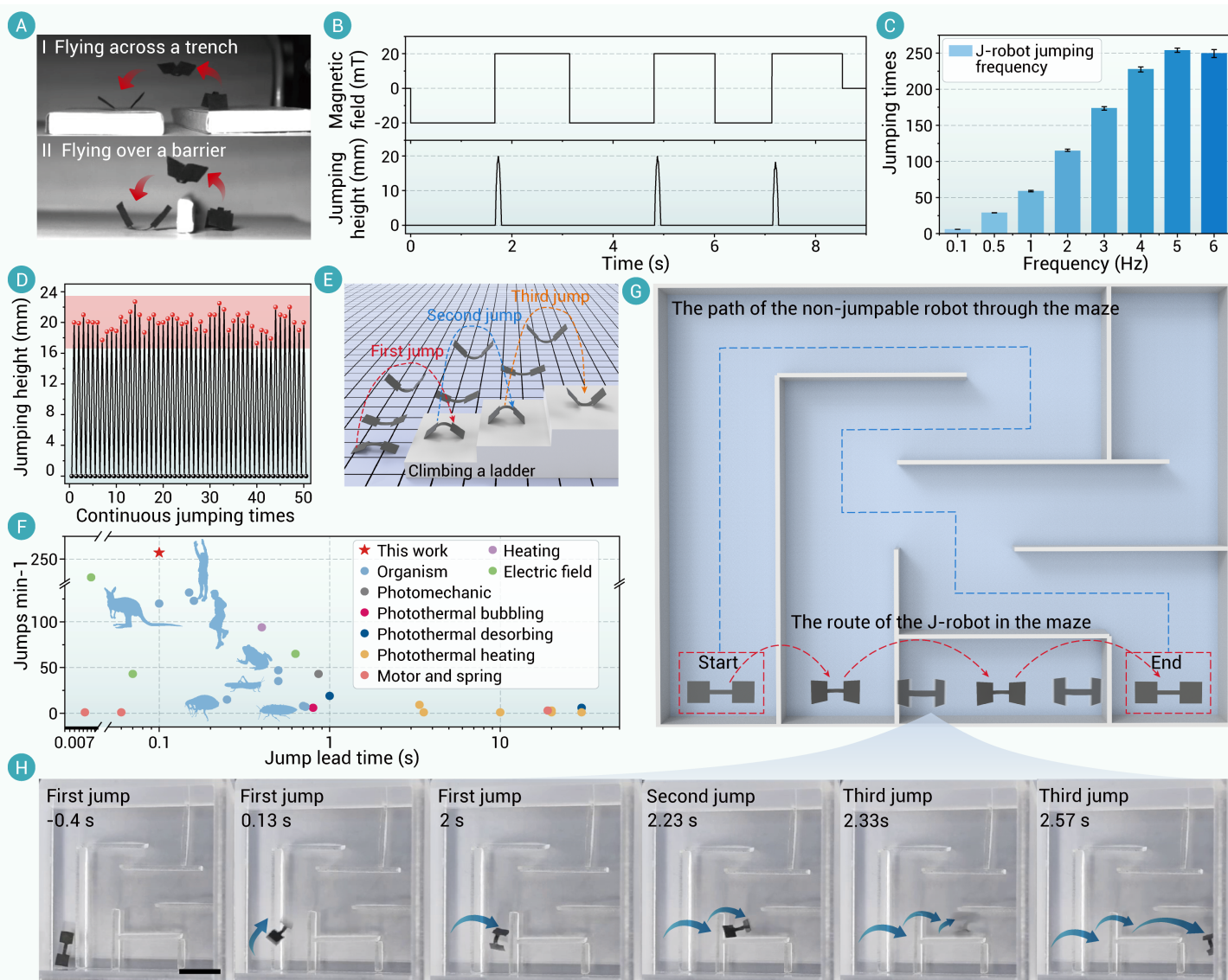


Figure 7. Continuous jumping motion of the J-robot (A) Photographs of the J-robot jumping across the trench and jumping over a barrier. (B) The relationship between the actuation magnetic field and the jump height during continuous jumping of the J-robot. (C) J-robot jumps min^{-1} versus magnetic field frequency. (D) The jumping stability of the J-robot. (E) Schematic of J-robot jumping up the steps continuously. (F) Comparison of jump lead time and number of jumps min^{-1} for J-robot, other jumping robots and organisms. (G) Schematic and (H) photographs of the J-robot rapidly traversing the maze using continuous jumping. Scale bar: 2 cm.

Despite a slight reduction in the jumping height of the J-robot due to friction losses on rough surfaces, its dumbbell-shaped structure endows it with strong terrain adaptability and a high success rate of movements (Figure 6C). Furthermore, the J-robot performs jumps successfully across a relative environmental humidity of 0–90% and a wide temperature range of 0–90 °C (Figures 6D & F), with consistent jump height, demonstrating exceptional environmental adaptability (Figures 6E & G). This robustness originates from the excellent dimensional stability of the wood film and the bio-inspired structural design, which maintain mechanical integrity and flexibility of the wood skeleton, ensuring efficient magnetic-elastic-kinetic energy conversion. This demonstrates the potential of J-robot for real-world applications such as outdoor inspection and disaster relief.

Continuous jumping motion

Unlike traditional robots requiring continuous ground contact, jumping robots can traverse discontinuous terrain, making them ideal for complex scenarios such as disaster rescue, industrial inspection, and deep space exploration. The J-robot with “dumbbell” structure achieves synergistic energy conversion, enabling ultrafast energy storage (0.1 s) and high-frequency continuous jumping (257 jumps min^{-1}). To evaluate terrain traversal capability quantitatively, we construct test platforms simulating a trench

(10 mm span) and a vertical barrier (5 mm height) (Figure 7A). Under a 20 mT field, the J-robot stably crosses trenches and barriers (Movie S2), demonstrating efficient obstacle-crossing in complex, unstructured environments.

Under bipolar field modulation (Figure 7B), the J-robot exhibits exceptional continuous dynamic response. Reversal of magnetic polarity induces rapid deformation via magnetic torque, enabling J-robot to complete full jump cycles within 0.246 s. Jumping frequency increases with actuation field frequency (Figure 7C), reaching 257 jumps min^{-1} at 5 Hz while maintaining a jump height of 18–22 mm over 50 cycles (Figure 7D). Moreover, the J-robot demonstrates excellent landing stability, maintaining an upright posture over 30 consecutive landings using only foot contact points (Table S1). This stability originates from the dumbbell-shaped structure and magnetic field, enabling rapid balance recovery and providing a stable pivot for subsequent leaps. To verify the structural durability of the J-robot under high-frequency impact, we characterize the linkage grounding contact area and magnetic foot connection section using SEM after continuous jumping test. The microstructure of the J-robot remains intact after consecutive jumps, with no cracking or magnetic particle detachment, demonstrating excellent impact resistance and structural integrity (Figure S12).

The durability of J-robot ensures long-term operational reliability for application such as environmental surveillance and pipeline maintenance. Lever-

aging its continuous jumping capability, the J-robot climbs a three-step staircase with a total vertical height of 15 mm (Figure 7E & Movie S3), demonstrating goal-directed locomotion in 3D space. We compare the continuous jumping performance of the J-robot with previously reported soft jumping robots and natural organisms (Figure 7F & Table S2). Unlike existing soft jumpers with slow energy accumulation, J-robot overcomes these limitations through its bionic magnetic drive. Its “dumbbell” structure, innovative energy conversion mode, and high magnetic responsiveness enable remarkably fast jumping preparation (0.1 s) and high jumping frequency (257 jumps min^{-1}), surpassing most soft jumping robots and some jumping creatures. A comparative analysis further reveals that J-robot offers advantages in structural complexity, manufacturing cost, and control simplicity compared to other magnetically driven robots, highlighting its practical appeal for sustainable soft robotics (Table S3).

Directionally controllable continuous jumps are essential for practical applications. Based on mechanical analysis of the J-robot in gradient magnetic fields, we developed a continuous jumping pattern with path planning capability. According to equation (2), the jump trajectory aligns with the magnetic field gradient, allowing precise directional control. Directional accuracy tests show that the deviation between preset and actual jumping directions across 10 trials is below 8° (Figure S13), proving precise magnetic control of the targeted movement of the J-robot. This capability lays the foundation for applications such as instrument inspection and environmental exploration.

In a customized maze, the J-robot jumps over the obstacles under magnetic field guidance and completed full traversal in 2.57 s (Figures 7G-H). In contrast, conventional crawling robots must follow predefined channels, leading to longer traversal durations. Quantitative comparison of maze completion times confirms the superior efficiency of the J-robot (Figure S14 & Table S4). The spatially programmable trajectories capability of J-robot endows the exceptional maneuverability in constrained environments, offering advantages for precision tasks such as internal equipment maintenance and minimally invasive surgery. Systematic validation confirms the advantages of the J-robot in motion efficiency, adaptability, and continuity.

To achieve fully autonomous operation of J-robot in complex environments, implementing closed-loop feedback control represents a key future development direction. The porous structure and flexibility of the wood film provide an ideal substrate for micro-sensors, laying the material foundation for closed-loop control systems.

CONCLUSION

Inspired by the rapid energy release in click beetle jumping, we develop a magnetically actuated J-robot capable of high-frequency, directional continuous jumping. This biomimetic design combines mechanically elastic wood structures with PDA@NdFeB particles to achieve efficient elastic energy storage. Driven by the non-contact magnetic field, the J-robot releases energy within milliseconds. Subsequent magnetization under a 2 T pulsed field programs the J-robot into two distinct morphologies resembling an “arch bridge” and a “U-shaped”. By instantaneous switching of magnetic field directions, the J-robot transitions between these states, rapidly transducing elastic potential energy into kinetic energy via ground impact. The J-robot thus achieves a 0.1 s jump preparation time and a jumping rate of 257 jumps min^{-1} , surpassing most existing soft robots and biological counterparts. This capability enables autonomous navigation through unstructured 3D terrains with dynamic obstacle avoidance. The J-robot design combines the structural advantages of wood with efficient magnetic actuation, enabling precise motion in complex environments, demonstrating significant application potential in pipeline maintenance and precision inspection, and providing new insights for developing high-efficiency jumping soft robots.

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AUTHOR CONTRIBUTIONS

W. G. and Y. L. conceived the idea and designed the experiments. X. L., Q. Z. and P. J. carried out the experiments and analyzed the data. Y. W. and R. Y. carried out the review and editing. W. G. provided valuable advices in robot locomotion control. X. L., Y. W. and W. G. collectively wrote the paper. All authors commented on the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

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