



A lightweight fabric-based adhesive winding actuator with high load capacity for slender rod-climbing robots

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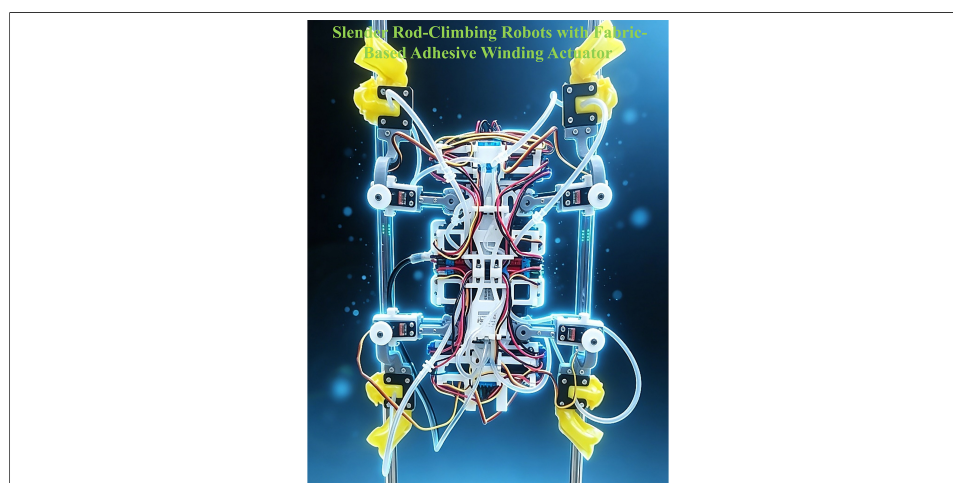
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Abstract

Slender rod-climbing robots require end-effectors that are lightweight, capable of supporting large axial loads, and able to switch reliably between attachment and detachment during cyclic locomotion. However, existing soft coiling actuators struggle to balance three-dimensional (3D) winding capability, load-bearing performance, structural lightweighting, and controllable release. Herein, we present a fabric-based adhesive winding actuator (FAWA) inspired by biological adhesion-coiling mechanisms. The actuator integrates a wrinkle-guided pleated chamber, constraining-layer bladder, and biomimetic dry adhesive interface within a lightweight fabric pneumatic architecture. This coupled design enables 3D helical winding around rod-like objects while simultaneously supporting adhesive load transfer and release regulation. Experimental results showed that the actuator weighs approximately 2 g and can sustain axial loads exceeding 1,000 times its own weight (> 2 kg) at 50 kPa. It achieved effective adhesive winding on rods over a practical diameter range, with the best performance observed at diameters of 10–12 mm. When integrated into a 430 g rod-climbing robot, the actuator enabled stable climbing on



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inclined slender rods without external tethered support. These results demonstrate a lightweight robot-oriented actuator design that addresses the coupled requirements of winding generation, load-bearing attachment, and controllable release for slender rod-climbing applications.

INTRODUCTION

Soft robots are highly promising for operations in geometrically complex and hard-to-reach infrastructures because their compliance improves conformability, safety, and environmental adaptability^[1]. For these applications, rod-climbing robots for the inspection and maintenance of cables, pipelines, suspended cables, and other rod-like structures are particularly challenging to develop^[2,3]. Their end-effectors must not only wrap tightly around curved supports but also resist axial slip, accommodate diameter variation, and coordinate reliably with repeated stance-swing gait transitions^[4]. Although recent rod-climbing robots have demonstrated excellent compliant attachment mechanisms, balancing load-bearing capacity, structural lightweighting, and cyclic reliability remains a major challenge^[5].

Various soft coiling and wrapping actuators have been explored to achieve stable attachment to rod-like objects. Silicone-based pneumatic actuators can achieve programmable three-dimensional (3D) deformations through carefully designed chamber and crease structures; however, they often require relatively high driving pressures and provide limited load-bearing capabilities under coiling conditions^[6-8]. By contrast, fabric-based inflatable actuators are attractive because of their low mass, fast response, and compatibility with scalable sheet-based fabrication processes^[9-11]. Nevertheless, many existing fabric or textile coiling actuators were originally developed primarily for shape morphing or wearable assistance, rather than for high-load attachment on slender rods^[12-14]. Other soft robotic solutions for rod or cable climbing have also been explored. Cable-driven winding devices and thermally actuated tendril-inspired grippers can generate 3D wrapping or grasping deformation^[15,16], while loop-closure grasping strategies and growing soft robots provide alternative mechanisms for strong enclosure or adaptive navigation^[17,18]. However, their system complexity, dependence on external peripherals, or overall form factor make them less suitable for lightweight multi-limb climbing robots. Overall, a compact end-effector that integrates 3D winding, high axial load capacity, low-pressure actuation, and repeatable release is still lacking for practical slender rod-climbing applications.

Slender rod-climbing robots are inspired by the chameleon tail, which can flexibly and stably wind around target objects in 3D^[19-21], and its epidermal setae-based adhesive-friction system enhances contact friction and reduces slip^[22,23]. For slender rods, coiling can establish distributed normal loading and geometric enclosure, whereas an adhesive interface can further suppress axial slip without relying entirely on mechanical clamping^[24-26]. However, adhesion-assisted coiling cannot be achieved simply by adding an adhesive layer. Effective dry adhesion depends on the contact state, load-sharing behavior, and precise control of the peeling process during release^[27,28]. Therefore, in cyclic rod-climbing tasks, the end-effector must coordinate winding deformation, load distribution, and attachment/detachment behavior while maintaining lightweight construction and ensuring high repeatability across successive stance and swing phases.

Motivated by these coupled requirements, we propose a fabric-based adhesive winding actuator (FAWA), inspired by the adhesion-assisted coiling strategy of the chameleon tail. The actuator integrates a wrinkle-guided pleated chamber, a constraining-layer bladder, and a biomimetic dry adhesive interface^[29,30] into a lightweight fabric pneumatic architecture. Through the coupled deformation of wrinkle-guided pleats and the constraining-layer bladder, the actuator can generate controllable and reversible 3D helical winding around rod-like objects, thereby enabling load-bearing attachment together with controllable release. In addition to presenting the actuator design, we further analyze the effects of the structural parameters on

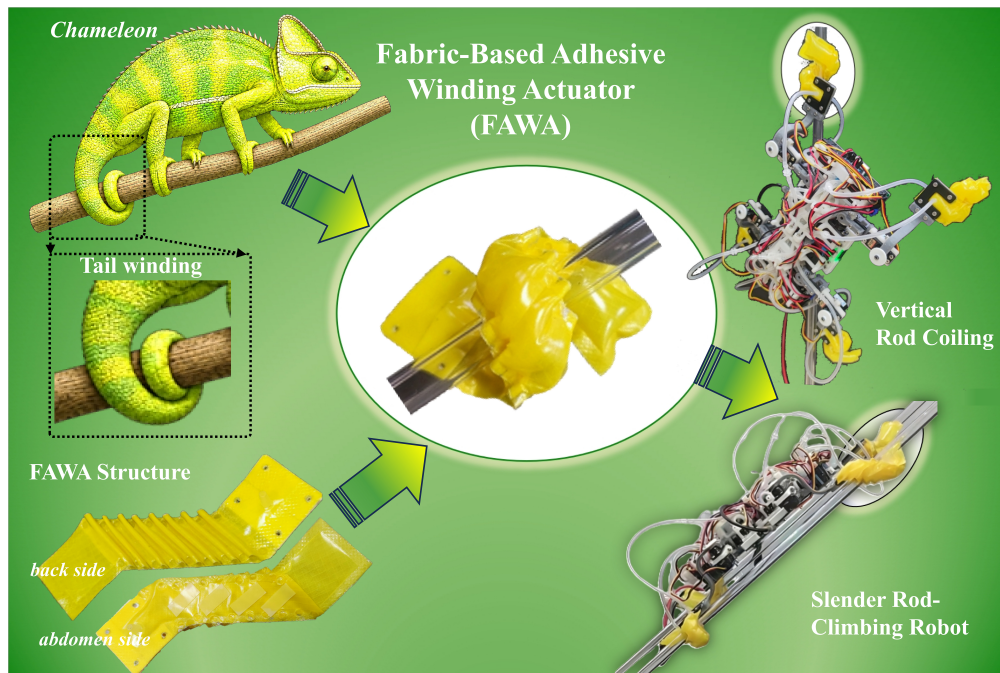


Figure 1. FAWA inspired by biological adhesion-coiling mechanisms for slender rod-climbing robots. FAWA: Fabric-based adhesive winding actuator.

coiling morphology and the stability of axial adhesive winding. Furthermore, we develop a phase-coordination strategy to integrate the actuator into a multi-limb rod-climbing robot [Figure 1].

EXPERIMENTAL

The FAWA was fabricated from double-sided thermoplastic polyurethane (TPU)-coated 20D nylon woven fabric. The actuator patterns were generated from the unfolded 3D model, cut using a laser cutting system, sealed by heat pressing, and assembled by ultrasonic welding of the pleated bladder onto the constraining-layer bladder. Biomimetic dry adhesive patches were discretely attached to the ventral surface of the actuator. The detailed fabrication procedure is described together with Figure 2.

The actuator deformation and adhesive-winding performance were evaluated using a combination of high-speed imaging, pressure recording, and axial pulling tests. The transient inflation process was recorded using a high-speed camera at 800 fps, while the internal pressure–time response was recorded synchronously. Axial adhesive-winding tests were performed on acrylic rods using a custom testing platform consisting of two-dimensional (2D) moving rails, a small vise, a force sensor, and a portable pneumatic actuation system. Unless otherwise specified, the axial pulling speed was 50 mm/min, and the driving pressure was varied according to the corresponding test condition.

For robotic validation, four baseline FAWAs were integrated onto a 430 g multi-limb rod-climbing robot. The robot used a tripod gait, and the actuator pressure was set to 50 kPa during climbing. Climbing tests were conducted on 20° and 45° inclined acrylic rods, and the robot displacement and instantaneous velocity were quantified from the recorded climbing videos.

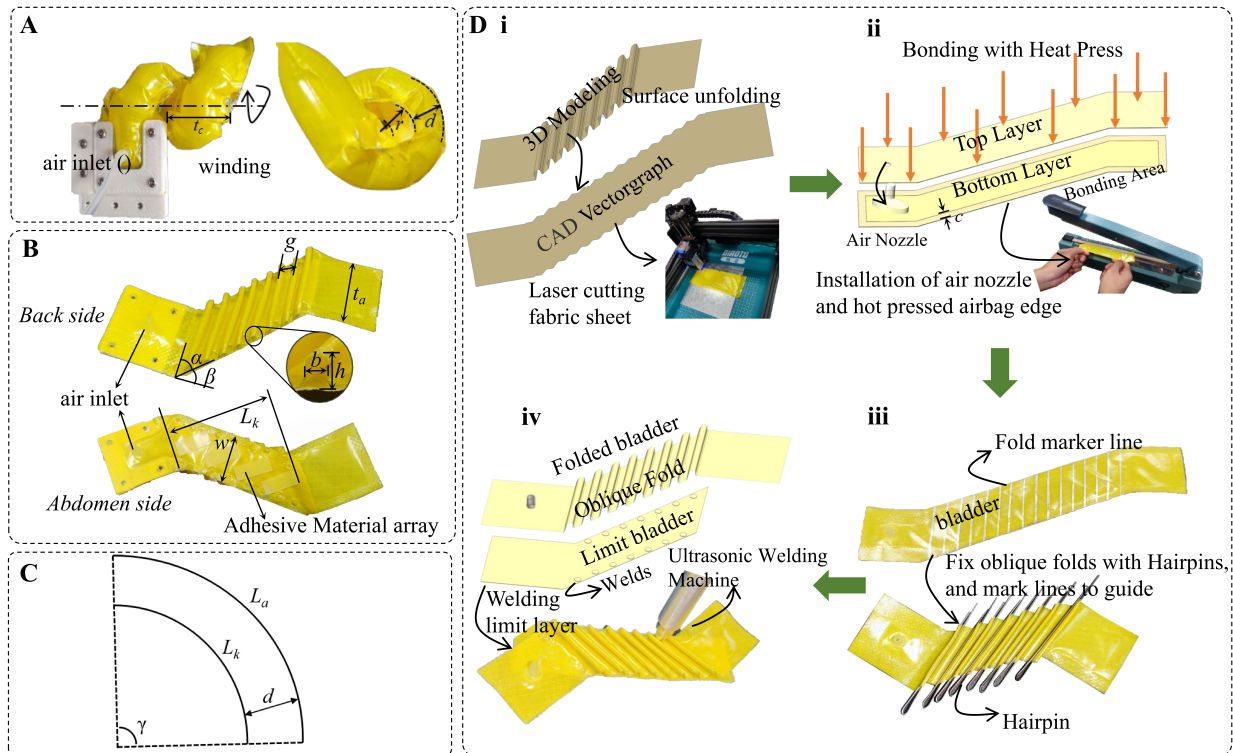


Figure 2. Structural parameters and fabrication of FAWA. (A) Structural parameters in inflated (coiling) states ($P = 50$ kPa); (B) Structural parameters of FAWA based on the pleated bladder structure, shown in uninflated states; (C) Non-intersecting cylindrical helical lines formed by the constraint layer and the top layer are projected onto a plane perpendicular to the axial direction; (D) (i) 3D model surface unfolding and laser cutting of the fabric. (ii) Edge sealing of the bladder via heat pressing. (iii) Design and fixation of the pleats. (iv) Welding of the pleated bladder onto the constraining layer bladder using an ultrasonic welder. FAWA: Fabric-based adhesive winding actuator; 3D: three-dimensional; CAD: computer-aided design.

RESULTS

Bionic design and analysis of FAWA

Design of FAWA

Inspired by the coiling attachment mechanism of the chameleon tail, we designed a bioinspired winding actuator based on a pleated bladder architecture [Figure 1]. The actuator consists of a dorsal array of inclined pleated bladders, a middle inextensible constraining layer, and a ventral flat bladder. Under positive pneumatic pressure, the pleated chambers expand and elongate along the pleat axis; constrained by the middle layer, the actuator bends ventrally. Because the pleats are intentionally inclined relative to the actuator axis, this bending is converted into 3D helical coiling around rod-like objects. The ventral flat bladder is also segmented by weld points and internally connected in series, enabling coordinated deformation during coiling. This architecture was designed not only to generate coiling motion but also to support load transfer and controlled release in rod-climbing applications.

To further enhance attachment stability, we bonded a biomimetic dry adhesive material to the ventral flat bladder, inspired by the setae-based adhesive structures of the chameleon tail^[23]. Rather than acting only as a friction layer, this adhesive interface functions together with the constraining-layer bladder to form a coupled load-bearing and release-regulating structure. When both bladders are pressurized, the actuator tightly winds around a target and transfers pneumatic loading to the adhesive patches, thereby increasing axial load capacity. When only the ventral flat bladder is pressurized, the actuator extends, and the detachment angle increases, enabling rapid release. By modulating the pneumatic input pattern, the actuator can reliably switch between adhesive winding and release, which is essential for load-supporting attachment

and cyclic rod climbing. The upper-right inset in Figure 1 demonstrates that a single FAWA can support a robot on an acrylic rod oriented at 90° relative to the horizontal ground plane. The lower-right inset illustrates the FAWA-based multi-limb robot climbing along an inclined slender rod.

Structural parameter selection of FAWA

The design of FAWA must satisfy the requirements of high load capacity and geometric adaptability to slender rod-like targets. Upon inflation and deformation, the actuator can be simplified into a cylindrical helical model. The radius of the axial projection circle enclosed by the helix is defined as the ideal effective winding radius r , and the circumference of this enclosing circle is $L_c = r \cdot 2\pi$. The axial distance between corresponding points on adjacent turns is the helix pitch t_c . The complementary angle β of the angle between the pleats and bladder corresponds to the helix angle. The vertical distance between the constraining and top layers is denoted as d [Figure 2A]. FAWA is fabricated using flexible woven fabric, resulting in lower structural stiffness than rigid actuators while remaining suitable for lightweight end-effector integration. For enhanced winding stability, the actuator structure must be compact, necessitating a small pitch t_c . Furthermore, appropriately reducing r improves the actuator's adaptability to the target diameter. Therefore, to satisfy performance optimization requirements, when FAWA achieves its minimum effective winding radius upon full inflation (i.e., when the pleats are fully expanded), the axial deformation pitch t_c should be simultaneously minimized. For the optimal performance design criteria to be satisfied, upon full expansion of the pleats during FAWA operation, when r reaches its minimum value, t_c should also be minimized. The following equations were derived from the simplified cylindrical-helix geometry of the proposed actuator rather than directly adopted from previous analytical models. Under this condition,

$$t_c = 2(t_a - 2c/\sin \alpha)/\pi + 2c/\sin \alpha, \quad (1)$$

where c is the width of the heat-sealed area of the bladder, t_a is the length of a single pleat in the uninflated state, and α is the angle between the pleat array and bladder edge [Figure 2B]. Given $t_c = w/\sin \alpha$, where w is the width of the constraining layer bladder, we obtain

$$t_c = 2(w - 2c)/(\sin \alpha \cdot \pi) + 2c/\sin \alpha. \quad (2)$$

Furthermore, the winding radius r is given by $r = t_c \cdot \tan \alpha / 2\pi$.

Therefore,

$$r = (w - 2c + c\pi)/(\pi^2 \cdot \cos \alpha). \quad (3)$$

Equation (3) indicates that the ideal winding radius of the circle enclosed by the constraining layer bladder can be calculated when the three parameters w , c , and α are determined. The value of c is typically selected within the range of 3–5 mm^[31], constrained by the fabrication equipment $c = 4$ mm in this study. The value of the bladder width w depends on the intended ideal radius r of the constraining layer circle, with w and r expected to be positively correlated. Referring to the proportional relationship between a chameleon's tail and the branches it can coil around and considering the influence of the heat-sealed edge width c , a preliminary selection is $4r \leq w \leq 6r$. Subsequently, the range for α between the pleats and bladder can also be determined: $35^\circ \leq \alpha \leq 55^\circ$.

Furthermore, after the deformation of the pleated bladders, the bottom, constraining, and top layers form three non-intersecting spatial cylindrical helices. Projecting these spatial cylindrical helices onto a plane perpendicular to the axial direction, the projected arc length of the constraining layer can be approximated as

L_k , and the projected arc length of the top layer helix is approximately L_a . The arcs of the constraining and top layers subtend the same central angle γ [Figure 2C]. With the distance between the constraining and top layers denoted as d , a simplified model for the actuator's enveloping central angle is established:

$$\gamma = (L_a - L_k)/d \quad (4)$$

Assuming the constraining layer passes through the center of this circle, then the distance d corresponds to the radius of this circle:

$$d = (t_a - 2c/\sin \alpha)/\pi. \quad (5)$$

Thus,

$$\gamma = \sin \alpha \cdot \pi(L_a - L_k)/(w - 2c). \quad (6)$$

Given the parameters w , c , and α , the enveloping central angle γ achieved by the bladder upon deformation is solely dependent on the difference between L_a and L_k . L_k determines γ , i.e., the number of turns the bladder achieves upon deformation. During design, specifying the constraining layer radius and the desired number of winding turns enables determination of L_k , and subsequently, L_a can be calculated using Equation (6). Chameleons typically employ approximately 1.5–2.2 tail coils during grasping. This biological range was used as a reference for a multi-turn enclosure rather than being directly scaled to FAWA. For the actuator, fewer than one winding turn would provide insufficient geometric enclosure and reduce axial anti-slip stability. Conversely, increasing the target turn number beyond approximately 1.7 would require a longer pleated region and larger adhesive contact area. This may introduce redundant distal winding, adjacent-coil interference, higher release resistance, and slower recovery during cyclic locomotion. Moreover, previous biological observations showed that removing a small distal portion of the chameleon tail does not significantly reduce tail-gripping performance^[32], suggesting that the distal tail portion does not dominate the overall gripping capability. Therefore, the target winding range of FAWA was selected as 1.0–1.7 turns to balance geometric enclosure, structural compactness, and controllable release, corresponding to $2\pi \leq \gamma \leq 3.4\pi$.

Guided by the analytical design model described above, the feasible ranges of w and α were first constrained by the intended effective winding radius, target winding turns, and the heat-sealing width $c = 4$ mm. Within this feasible design window, $w = 20$ mm and $\alpha = 45^\circ$ were selected as practical baseline values according to the parametric simulation analysis described in [Supplementary Figure 1](#) (the influence of actuator parameter changes on deformation are presented in [Supplementary Section 1](#)).

In the simulated baseline configuration, the actuator reached the desired deformation state in which the helix lead matched the inflated bladder length along the pleat direction. Additionally, adjacent coils contacted at the heat-sealed regions without apparent interference. Therefore, these values were used as the baseline structural parameters for subsequent prototype fabrication and performance comparison, as summarized in [Table 1](#).

Fabrication of FAWA

The proposed actuator relies on structural deformation rather than intrinsic material stretchability to generate motion. Compared with highly extensible elastomers, woven fabrics provide a favorable combination of high modulus, low elongation, high strength, and sufficient deformability. Therefore, they are suitable for structurally programmable soft actuators. In this study, the actuator was fabricated from TPU-coated woven nylon fabric (20D; TPU coating thickness: 0.03 mm; total thickness: 0.1 mm; areal

Table 1. Parameters of FAWA

Parameters	Values
Angle between pleats and bladder α	45°
Bladder width w	20 mm
Pleat spacing g	5 mm
Pleat height h	3.9 mm
Pleat width b	2.5 mm
Number of pleats n	8

FAWA: Fabric-based adhesive winding actuator.

density: 118 g/m²; Jiaying Inch Eco-Materials). A detailed justification for material selection is provided in [Supplementary Sections 2 and 3](#), including mechanical property test of nylon fabric [[Supplementary Figure 2](#)] and comparative actuator performance evaluations [[Supplementary Figures 3 and 4](#)]. The fabrication procedure is described as follows:

(a) A 3D model of the upper-layer pleated bladder of FAWA was constructed using SolidWorks (Dassault Systems SOLIDWORKS Corp., Waltham, MA, USA). The developable surface of the model was then unfolded to generate digital pattern pieces for the pleated bladder. Subsequently, DXF format files of the digital patterns for the unfolded pleated bladder (length L_a , width t_a) and the constraining layer bladder (length L_k , width w) were imported into a laser cutting system (T1; DIAOTU) for high-precision cutting of the woven fabric and creating necessary openings [[Figure 2D\(i\)](#)].

(b) The cut fabric pieces were then edge-sealed using a heat-sealing machine (FR-400B; Blueberry) to form the unfolded pleated and constraining layer bladders (heat-sealed width $c = 4$ mm). Subsequently, pneumatic fittings were assembled and sealed onto both bladders; one end was designated the proximal end, and the other the distal end [[Figure 2D\(ii\)](#)].

(c) Crease marker lines were drawn on the unfolded pleated bladder. Temporary fixtures (such as hair clips or custom molds) were used to accurately position each pleat for preliminary shaping of the pleated bladder. An ultrasonic welding system (ZT-800; KeHai) was then employed to weld an array of n pleats uniformly onto the upper surface of the constraining layer bladder. The weld points were symmetrically distributed along the edges of the constraining layer with a spacing of g . Each pleat had a width b , height h , and length t_a . The angle between the pleat array and edge of the constraining layer is denoted as α (β is the complementary angle of α), satisfying the relationships $t_a = w/\sin\alpha$, $L_k = (n - 1)g + b$, $L_a = n(2h - b + \pi b/2)$ [[Figure 2D\(iii\)](#)].

(d) Adhesive material was discretely bonded onto the ventral surface of the FAWA constraining layer bladder at a certain inclination. This material exhibits a tangential adhesion strength of approximately 3 N/cm² and normal adhesion strength of approximately 4 N/cm². Individual adhesive patches measured 6 mm $\times$ 15 mm. This discretized adhesive layout optimized the contact-area ratio, reduced the energy required for detachment, and preserved the anisotropic adhesion characteristics, thereby balancing contact efficiency and controllable interfacial detachment. The complete FAWA weighs approximately 2 g, highlighting its highly lightweight construction [[Figure 2D\(iv\)](#)].

To facilitate actuator performance testing and system integration, we attached a modular clamping mechanism to the distal ends of the bladders while maintaining the seal integrity of the pneumatic system.

Adhesive-winding performance of FAWA

Tests of the deformation-winding-adhesion performance of FAWA

The winding deformation process of the actuator during transient inflation was recorded from a top view using a high-speed camera (QianYanLang ISP502, ZhongKeShiJie, Hefei, China; 800 fps), while the corresponding internal pressure–time response was recorded simultaneously [Figure 3A and Supplementary Video 1]. The six subpanels labeled i–vi in Figure 3A represent representative deformation states during transient inflation and are marked on the pressure–time curve at 0, 63, 96, 113, 152, and 285 ms, respectively. The eight dorsal pleats are sequentially numbered from the root to the tip as pleat levels 1 to 8. In the initial state i, the actuator is uninflated and in its natural, undeformed state. In state ii, pleat level 1 expands significantly first, followed by a slight expansion of pleat level 2; the pleat expansion velocity is relatively low at this stage. In state iii, pleat level 2 expands significantly. In state iv, pleat levels 3–5 expand sequentially. However, the expansion pattern does not require a complete expansion of a preceding level before the next begins: The next level initiates expansion while the preceding level is only slightly expanded, after which they expand together. During this stage, the pleat expansion velocity increases. In state v, pleat levels 5–7 expand sequentially, following a pattern similar to state iv but with a faster expansion deformation rate. In state vi, pleat level 8 and the distal end of the actuator expand, and the actuator reaches its final deformed state. The entire inflation deformation process completes within 300 ms, demonstrating a rapid response suitable for efficient adhesive winding.

To evaluate the axial adhesion and winding capability of the actuator, we constructed a performance testing platform for FAWA, including 2D moving rails (in the x -direction and z -direction), a small vise, a force sensor, and a miniature portable pneumatic system (Supplementary Figure 5 and Supplementary Tables 1–3; the functional parameters of the testing platform are presented in Supplementary Section 4). The actuator was fixed to the force sensor by the fixture, and the force sensor was fixed on the base of the 2D moving rails. The acrylic tube was clamped at the end of the small vise, and the small vise was connected to the 2D moving track by screws. The miniature portable pneumatic system provided stable and controllable pressure to the actuator. The experimental procedure was conducted as follows: ① The 2D moving rails drive the clamping device (acrylic tube) to reach the designated position to facilitate the adhesive winding of the actuator; ② Turn on the data acquisition system of the force sensor, and the pneumatic system drives the actuator to deform to achieve adhesion and winding of the acrylic tube; ③ Control the 2D moving rails to move upward at a specified speed, record the data of the force sensor until the adhesive winding fails, and select the peak value as the maximum axial adhesive-winding force to evaluate the winding capability of the actuator. These steps were repeated for FAWA with different structural parameters to test the adhesion-winding performance.

Figure 3B depicts the morphological evolution and adhesive-winding force variation of the baseline parameter actuator during adhesive winding around an acrylic rod and subsequent axial pulling. The acrylic rod has a diameter of 11 mm. The actuator is driven at a pressure of 50 kPa, and the axial pulling speed is 50 mm/min. In the initial phase i, the actuator has fully inflated and formed a stable winding around the rod; no axial displacement of the rod has occurred, and the adhesive-winding force is near zero. During phase i to ii, the acrylic rod moves upward. The upper part of the actuator moves synchronously with the rod, whereas the lower part, constrained by the fixed end, undergoes relative slippage. The overall helix angle of the actuator gradually increases, and the axial adhesive-winding force increases rapidly correspondingly. In phase ii to iii, the lower part of the actuator continues to slip relatively, but the overall winding morphology tends to stabilize. Concurrently, slight slippage occurs in the upper part, causing a gradual decrease in the enveloping central angle. During this phase, the axial adhesive-winding force continues to increase, reaching its peak value at phase t_3 . At this point, the enveloping central angle of the actuator around the acrylic rod is approximately 270° . From phase iii to iv, the actuator undergoes continued minor slippage, and the

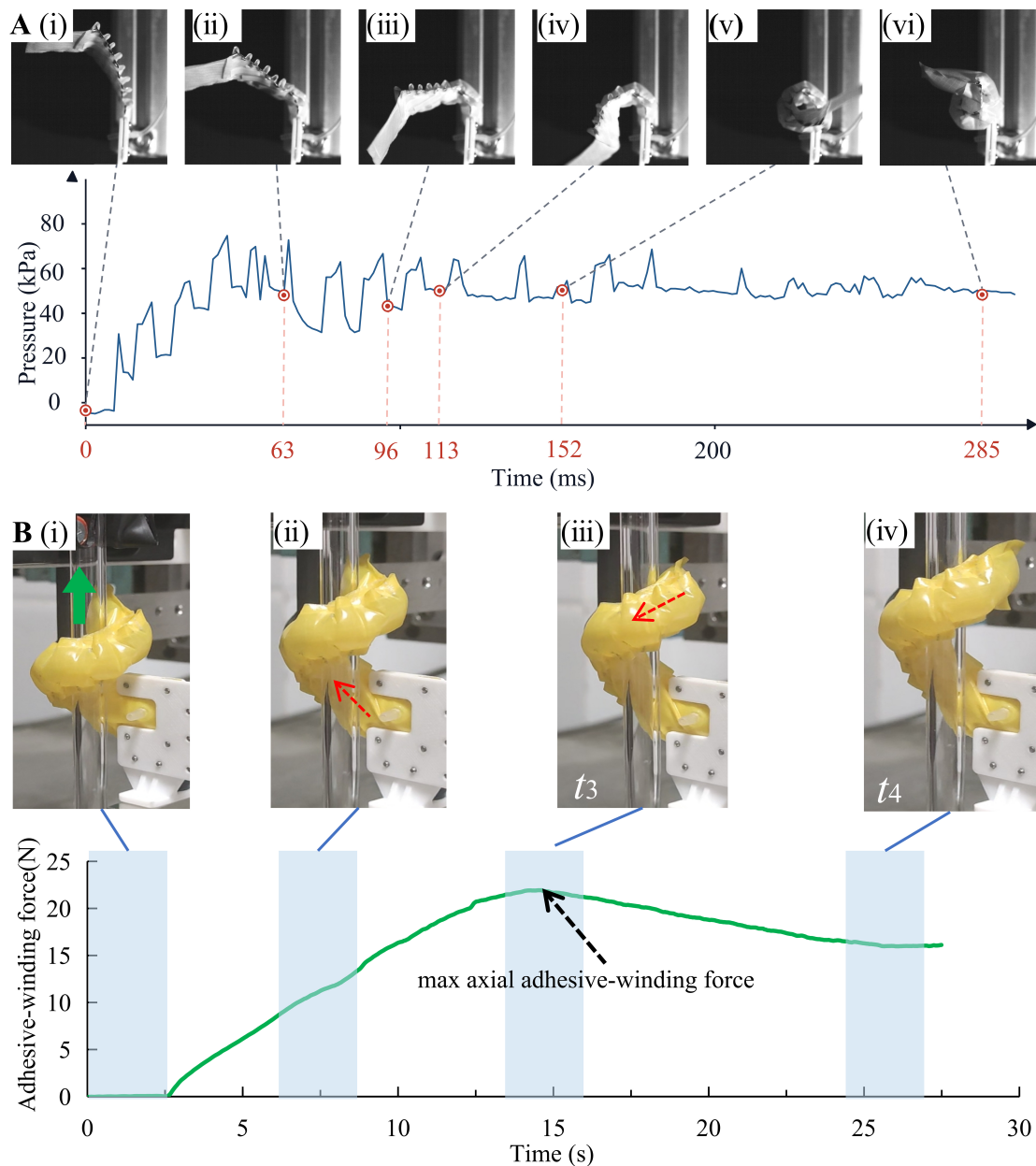


Figure 3. Tests for the deformation-winding-adhesion performance of FAWA. (A) Synchronized high-speed images and internal pressure–time response during the transient inflation and deformation process of FAWA; (B) Morphological changes and corresponding adhesive-winding force variation of the actuator during pulling. FAWA: Fabric-based adhesive winding actuator.

enveloping central angle further decreases. This reduction leads to a decrease in the effective adhesive contact area and contact pressure, resulting in a gradual decline in the axial adhesive-winding force. Upon reaching phase iv, the actuator morphology and adhesive-winding force stabilize, and the system enters a working state dominated by sliding friction. In summary, the adhesive-winding performance of FAWA is closely related to its helical winding morphology and contact state. During failure, increases in the helix angle and pitch, together with a decrease in the enveloping central angle, reduce the effective contact area and are associated with a decline in the axial adhesive-winding force. These observations suggest that the actuator load capacity depends on the combined effects of coiling geometry and adhesive contact.

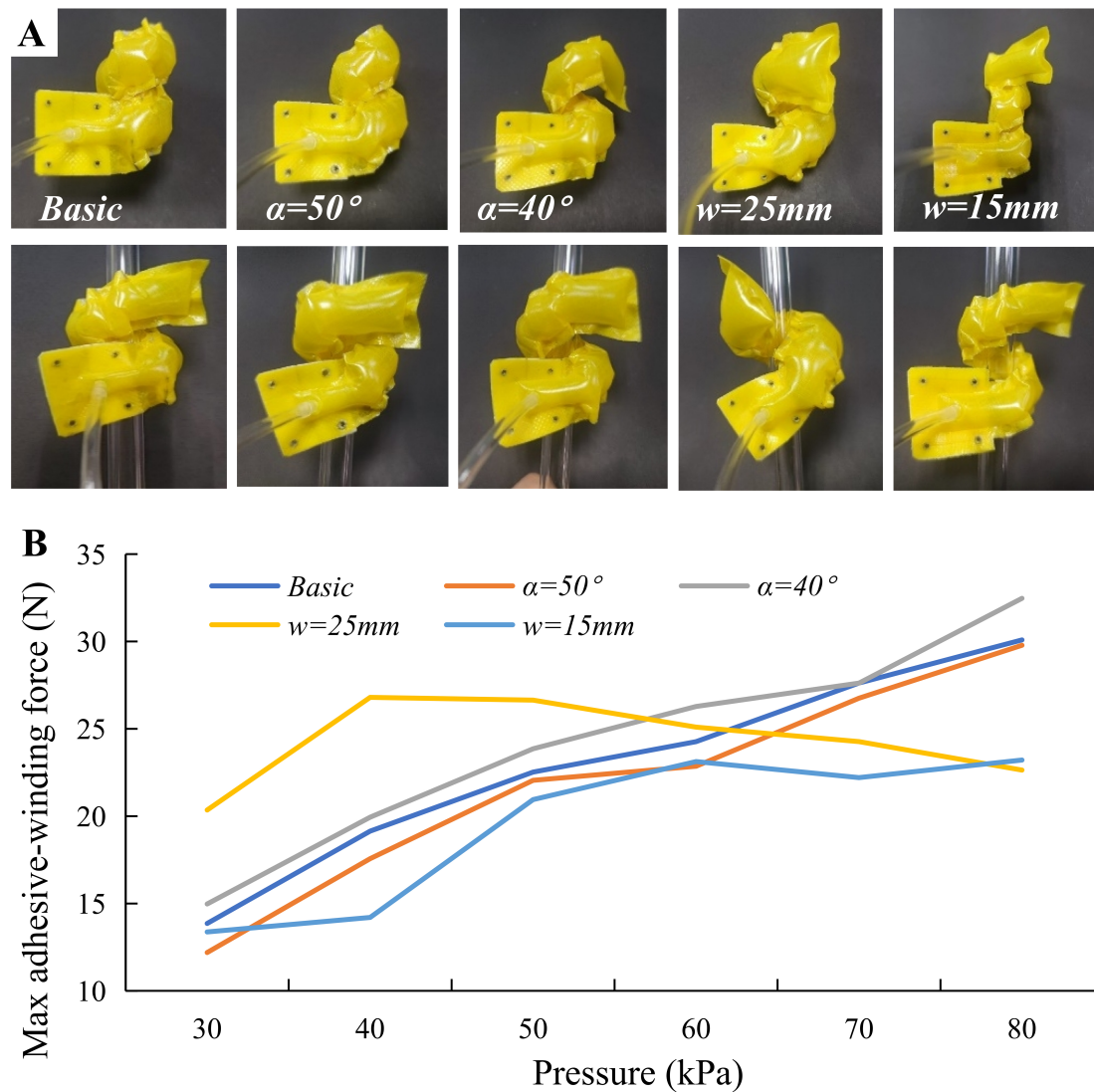


Figure 4. Effects of angle α and width w on the deformation-winding-adhesion performance of FAWA. (A) Inflation and winding/grasping states of FAWAs with different α and w ; (B) Maximum adhesive-winding force when adhesively winding around an 11 mm diameter acrylic rod for actuators with different α and w . FAWA: Fabric-based adhesive winding actuator.

Effects of structural parameters on the adhesive-winding performance of FAWA

To analyze the impact of structural parameters on the adhesive winding and grasping performance of the actuator, we fabricated a set of comparative actuators by varying a single structural parameter based on the baseline parameters listed in Table 1. As shown in Figure 4A, these variations included angles between the pleats and bladder of $\alpha = 50^\circ$ and $\alpha = 40^\circ$, and bladder widths of $w = 25\text{ mm}$ and $w = 15\text{ mm}$, whereas the pleat height h and other structural parameters were kept at their baseline values. These actuators were subjected to the same adhesive-winding performance test described for Figure 3B. The experimental conditions were kept consistent: an acrylic rod diameter of 11 mm, driving pressure range of 30–80 kPa in 10 kPa increments, and axial pulling speed of 50 mm/min. The experimental results are presented in Figure 4B.

The results indicated that the actuator with $\alpha = 50^\circ$ exhibited a slightly lower axial adhesive-winding force than the baseline actuator. This is primarily attributed to the reduction in the helix angle of the winding, which leads to a decrease in the enveloping force and effective adhesive contact area. The actuator with $\alpha =$

40° exhibited a slight increase in the axial adhesive-winding force; however, the discreteness of its winding morphology increased significantly, indicating reduced stability.

The bladder width had a substantial effect on both force output and winding stability. For $w = 25$ mm, the larger inflated cross-section produced a higher force at relatively low pressures, but further pressure increase enlarged the winding radius and reduced the enveloping central angle. This decreased the effective adhesive contact and load sharing. For $w = 15$ mm, the smaller chamber width increased the geometric enclosure but limited the chamber volume and structural stiffness, resulting in a lower overall adhesive-winding force than the baseline actuator. These results suggest that the pressure-dependent force variation is governed by the coupled effects of the bladder width, pressure-driven expansion, winding geometry, and adhesive contact, rather than by the bladder width alone.

In summary, among the tested angle and width configurations, the baseline parameter set showed the best overall balance between adhesive-winding performance and operational stability. Although the actuator with $\alpha = 40^\circ$ produced slightly higher winding forces under some conditions, its winding stability was poorer. The actuator with $w = 25$ mm showed better performance only at relatively low pressures, and this advantage diminished as the pressure increased. Overall, these results support the design rationale in Section “Structural parameter selection of FAWA” and suggest that actuator performance is influenced by the combined effects of the structural geometry, coiling morphology, and load stability, rather than by adhesive material alone.

Adhesive-winding performance limits of FAWA

Figure 5A shows the peak adhesive-winding force of FAWA with baseline parameters for acrylic rods with diameters from 6 to 15 mm under driving pressures from 10 to 80 kPa. FAWA achieved winding and grasping at 10 kPa; however, the adhesive-winding force remained low because of the limited actuator stiffness at this pressure. As the driving pressure increased, the peak adhesive-winding force generally increased, exceeding 20 N at approximately 50 kPa and reaching about 30 N at 80 kPa, corresponding to a load-to-self-weight ratio of more than 1,000 for an actuator mass of about 2 g. The grasping performance also depended strongly on the rod diameter: effective winding and grasping were difficult for diameters of 6–7 mm and remained limited at 8–9 mm, whereas diameters of 10–12 mm provided the best overall balance between peak adhesive-winding force and repeatability. For 13–14 mm rods, the peak force increased further under some pressure conditions, but the larger error margins indicated reduced repeatability and winding stability; at 15 mm, both the force and stability decreased. This decrease in stability can be attributed to the enlarged helical diameter imposed by the thicker rods, which induces torsional deformation in the actuator and reduces the enveloping central angle, thereby decreasing both the effective adhesive contact area and enveloping force.

To validate the actuator’s adaptability, as shown in Figure 5B, we mounted FAWA on a ROKAE ER7 Pro robotic arm for compliant adhesive winding of common objects [Supplementary Video 2]. Targets included adhesive tape rolls, bucket handles, water hoses, and mobile phone holders, with weights ranging from 3.9 to 465 g and equivalent diameters at the grasping location from 8 to 14 mm. The experimental results demonstrated the excellent adaptability of FAWA to rod-like targets of varying diameters.

In summary, FAWA achieved effective adhesive winding and grasping for rod-like objects with diameters approximately in the range of 0.8R to 1.4R, with the best overall balance between load capacity and repeatability observed within 1.0R to 1.2R (where R represents the diameter of the constraining-layer circle of FAWA in its naturally deformed state). Together with the load-to-weight ratio exceeding 1,000 at 50 kPa, these results support the potential of the proposed actuator as a lightweight rod-climbing end-effector that combines low-pressure actuation with relatively high axial load-bearing capacity.

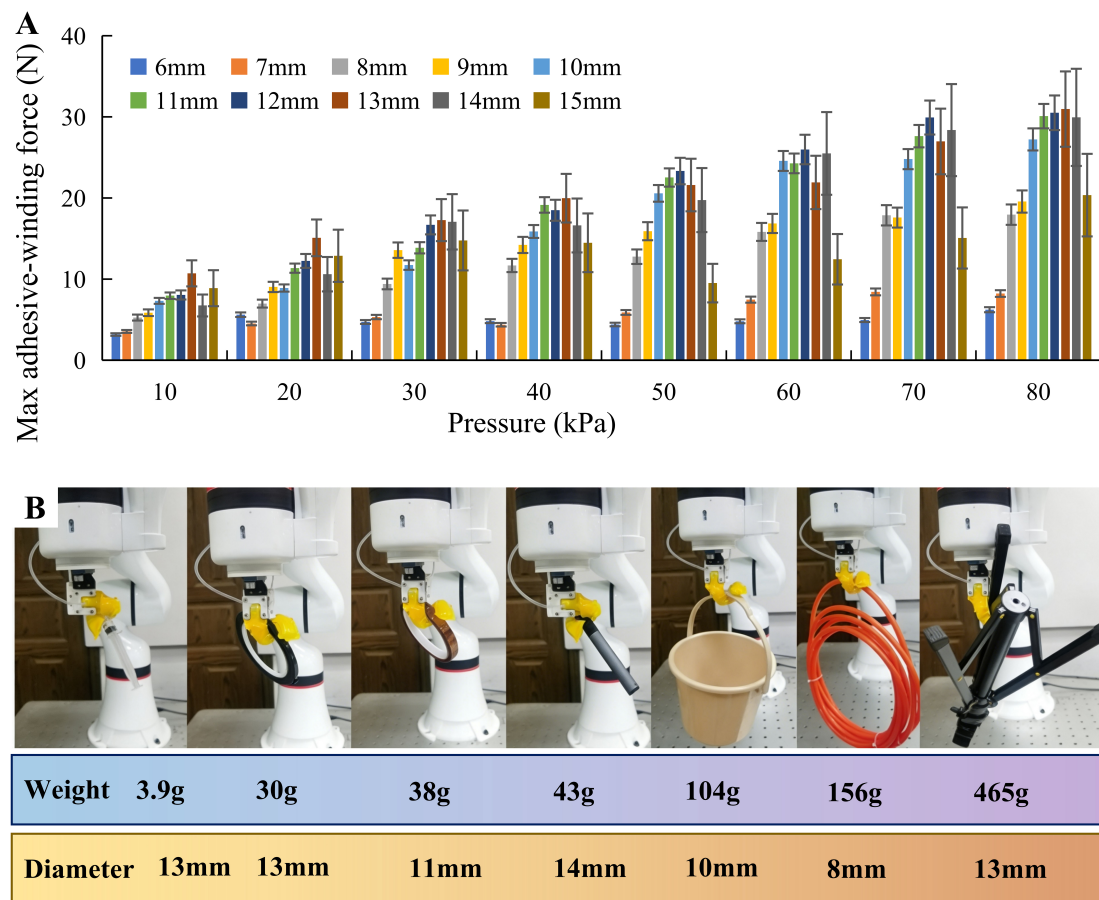


Figure 5. Tests of adhesive-winding performance limits of FAWA. (A) Adhesive-winding performance limits of FAWA on acrylic rods with diameters ranging from 6 to 15 mm. Data are presented as mean $\pm$ standard deviation from five repeated measurements ($N = 5$); (B) Multi-object grasping tests of FAWA with a robotic arm. FAWA: Fabric-based adhesive winding actuator.

A rod-climbing robot based on FAWAs

Coordinated motion of FAWAs

Four actuators with baseline parameters were fabricated to validate the practical feasibility of the attachment device. Among these, two actuators were designed with left-handed helical pleats and two with right-handed pleats, arranged symmetrically. These were integrated onto the distal tibia ends of a highly integrated climbing robot developed by our research group (equipped with a complete locomotion drive and control system), resulting in a biomimetic robot with adhesive winding and climbing capabilities, weighing approximately 430 g [Figure 6A]. Acrylic rods were fixed to aluminum profiles via clamps, enabling the robot's climbing angle to be adjusted by tilting the experimental platform [Figure 6B].

To address these requirements, we devised a phase-synchronized motion control strategy by matching actuator states to limb phases, as illustrated in Figure 6C. During stance, the pleated bladders are pressurized for the actuator to coil firmly around the target and provide a stable adhesive-winding force. During the transition from stance to swing, the pleated bladders are deflated, causing a rapid reduction in structural stiffness and adhesive capacity; the actuator can then be detached with only a small force from the servo motor. During swing, the constraining-layer bladder is pressurized after most residual air in the pleated bladders has been released, thereby extending the actuator and restoring a repeatable initial configuration for

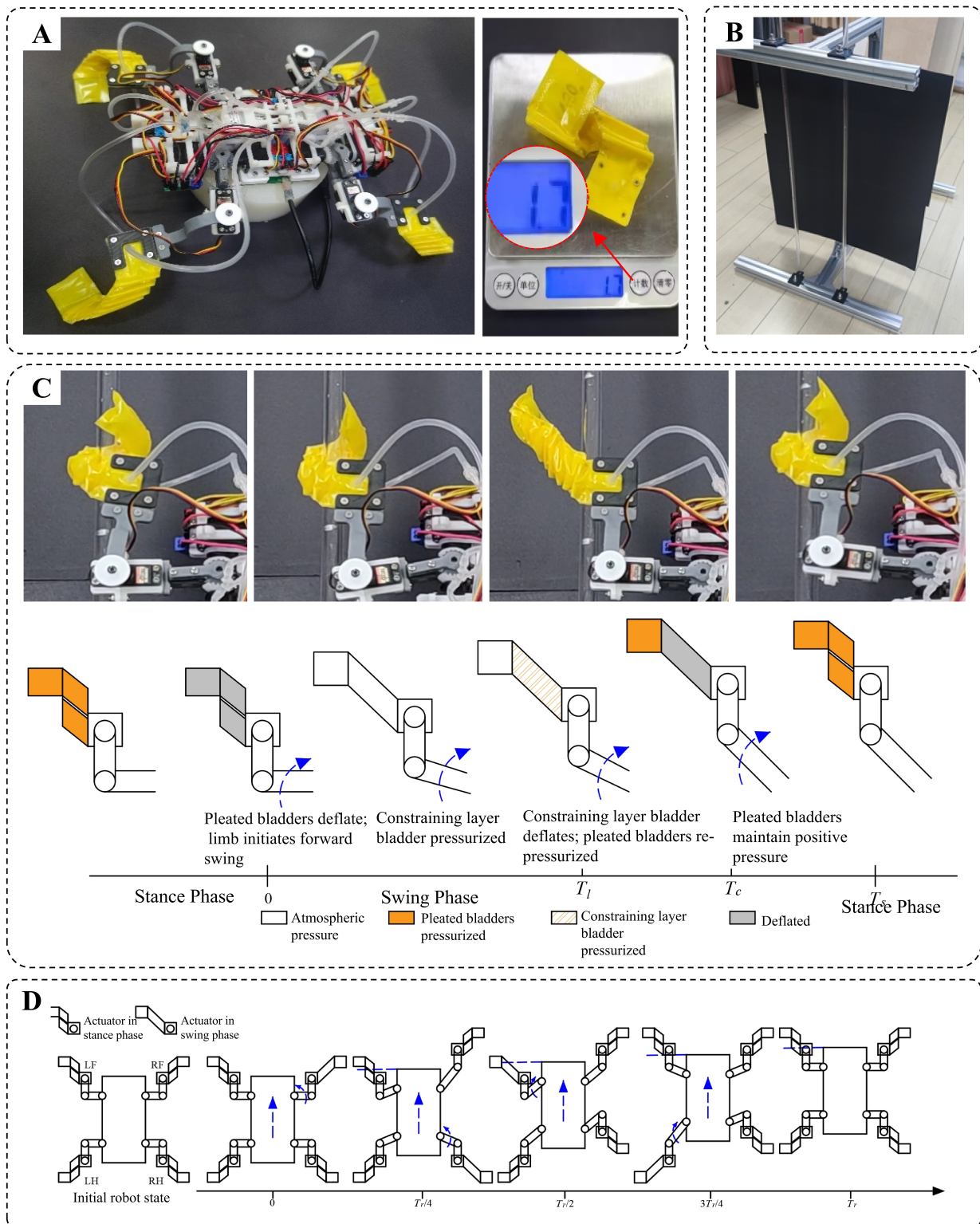


Figure 6. (A) Climbing robot equipped with FAWA; (B) Dual-rod climbing platform with adjustable inclination angle; (C) Coordinated motion mechanism between the robot and FAWAs; (D) Schematic of the robot climbing using a tripod gait. FAWA: Fabric-based adhesive winding actuator; LF: left front; RF: right front; LH: left hind; RH: right hind.

the next winding cycle. This sequence was designed specifically to resolve the attachment, release, and re-extension requirements of cyclic rod climbing.

Table 2. Robot operation timing and corresponding procedures

Timing	Procedure
0-3/16 T_r	RF in swing phase: pleated bladders deflate, actuator detaches; limb swings forward; subsequently, constraining layer bladder inflates to extend actuator, preparing for next grasp. Remaining three limbs provide support
3/16 T_r -4/16 T_r	Quadrupedal stance phase: all limbs move rearward, robot advances; RH prepares for detachment
4/16 T_r -7/16 T_r	RH in swing phase: pleated bladders deflate, actuator detaches; limb swings forward; subsequently, constraining layer bladder inflates to extend actuator, preparing for next grasp. Remaining three limbs provide support
7/16 T_r -8/16 T_r	Quadrupedal stance phase: all limbs move rearward, robot advances; LF prepares for detachment
8/16 T_r -11/16 T_r	LF in swing phase: pleated bladders deflate, actuator detaches; limb swings forward; subsequently, constraining layer bladder inflates to extend actuator, preparing for next grasp. Remaining three limbs provide support
11/16 T_r -12/16 T_r	Quadrupedal stance phase: all limbs move rearward, robot advances; LH prepares for detachment
12/16 T_r -15/16 T_r	LH in swing phase: pleated bladders deflate, actuator detaches; limb swings forward; subsequently, constraining layer bladder inflates to extend actuator, preparing for next grasp. Remaining three limbs provide support
15/16 T_r - T_r	Quadrupedal stance phase: all limbs move rearward, robot advances; RF prepares for detachment

RF: Right front; RH: right hind; LF: left front; LH: left hind.

The deflation of the pleated bladders is synchronized with the limb's forward swing to mitigate impact during detachment/adhesion, enabling the tangential load to be gradually released during motion. Throughout the swing phase, the actuator must recover its initial configuration conducive to the subsequent winding grasp. Due to the limited passive restoring capability of the fabric-based pleated structure, the actuator cannot fully recover to its extended initial configuration after the pleated bladders are deflated. Therefore, after the residual air in the pleated bladders is substantially released, the constraining layer bladder is pressurized, forcibly driving the actuator to extend. This sequence prevents residual air from being trapped within the pleated bladders, ensuring that during the next inflation cycle, deformation and coiling initiate consistently from the proximal end, maintaining a predictable spatial trajectory. Subsequently, while the limb continues its forward swing, the pleated bladders are re-pressurized, enabling the actuator to gradually deform before contacting the target object. The moment the actuator achieves adhesive winding contact, the limb transitions from the swing phase to the stance phase, maintaining pressure in the pleated bladders to provide a sustained, stable adhesive-winding force.

During actual robot climbing, the four limbs must execute coordinated motions according to a specific gait. A tripod gait was adopted as the fundamental climbing gait. In this gait, at any given time, three limbs are typically in the stance phase and one limb in the swing phase, ensuring stability during locomotion. In [Figure 6D](#), the four FAWAs are designated as left front (LF), right front (RF), left hind (LH), and right hind (RH). The complete locomotion cycle of the robot is $T_r = 16$ s, the swing phase duration is $T_s = 3$ s, and the quadrupedal stance phase duration is $T_f = 1$ s. The deflation time for the pleated bladders after detachment is $T_l = 0.26T_s$. The initiation time for constraining layer bladder deflation and pleated bladder re-inflation is $T_c = 0.9T_s$. Therefore, the residual-air release stage lasts approximately 0.78 s in each swing phase. This stage is incorporated into the forward swing of the corresponding limb rather than being treated as an additional stop interval; nevertheless, it limits further shortening of the swing phase and therefore affects the achievable climbing speed. The actuator operating pressure is 50 kPa. The gait sequence is RF, RH, LF, LH. The detailed robot operation timing and corresponding procedures are presented in [Table 2](#).

Rod-climbing experiments of the robot on slopes of varying inclinations

[Figure 7](#) shows the robot climbing on a 20° inclined acrylic rod. In addition to sequential snapshots from the top and side views, the instantaneous velocity and displacement along the rod were quantified. The robot advanced approximately 100 mm within 120 s, corresponding to an average climbing speed of approximately 50 mm/min and an effective step length of about 13.3 mm. [Figure 8](#) shows the corresponding experiment on

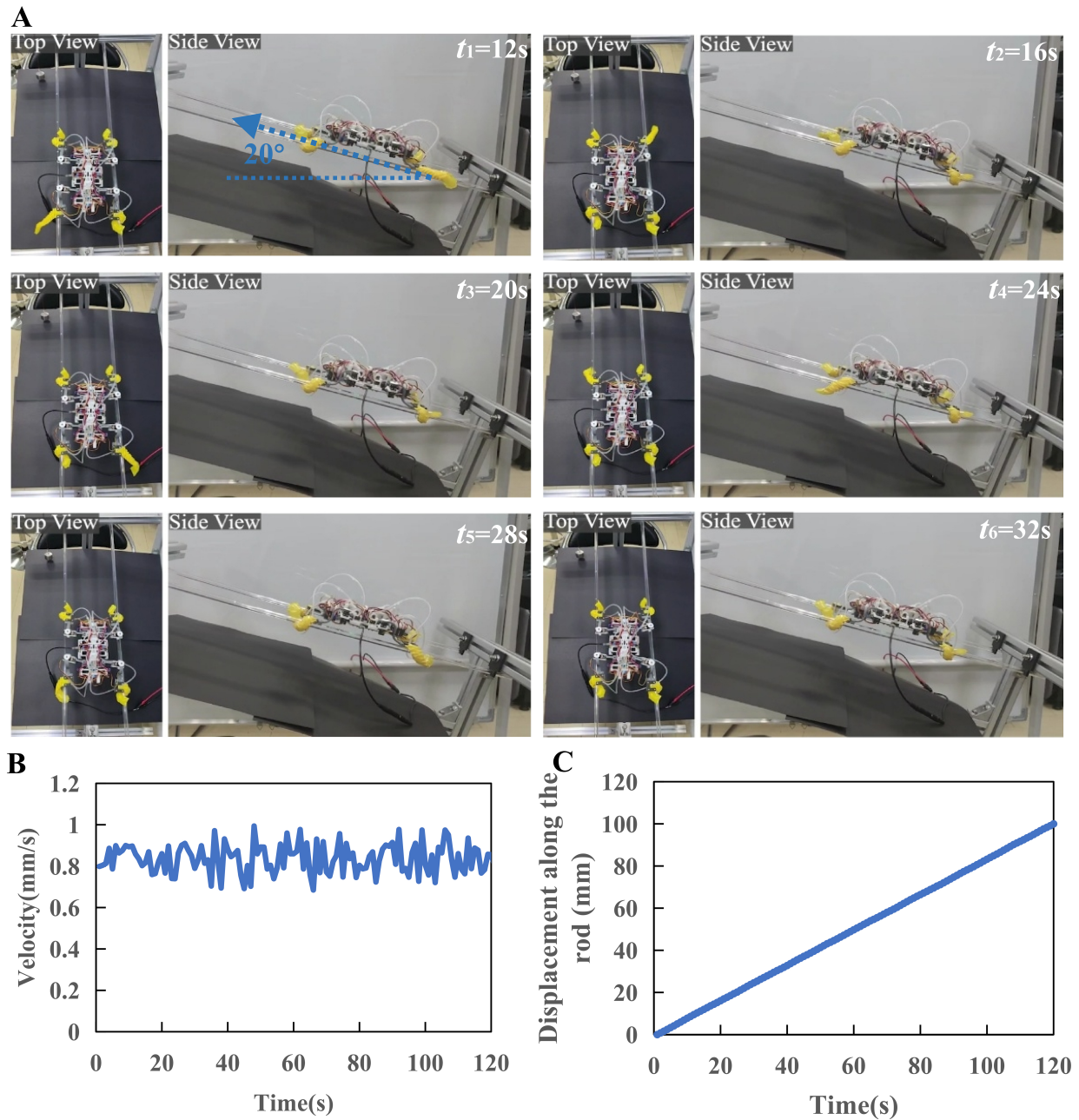


Figure 7. Climbing performance of the FAWA-based robot on a 20° inclined acrylic rod. (A) Sequential snapshots of the robot climbing process recorded from top and side views; (B) Instantaneous climbing velocity along the rod; (C) Displacement of the robot along the rod during climbing. FAWA: Fabric-based adhesive winding actuator.

a 45° inclined acrylic rod. The robot advanced approximately 44 mm within 120 s, corresponding to an average climbing speed of approximately 22 mm/min and an effective step length of about 5.9 mm. In both cases, the displacement increased continuously, indicating stable forward climbing without obvious backward slip [Supplementary Video 3].

An analysis of the robot's climbing process revealed that the passive pressure relief mode of actuator detachment is relatively time-consuming [Figures 7 and 8], which prolongs the climbing cycle and reduces speed. When a limb transitions from the stance phase to the swing phase, the corresponding actuator should detach before the servo motor drives the limb forward. Benefiting from the actuator's structural design,

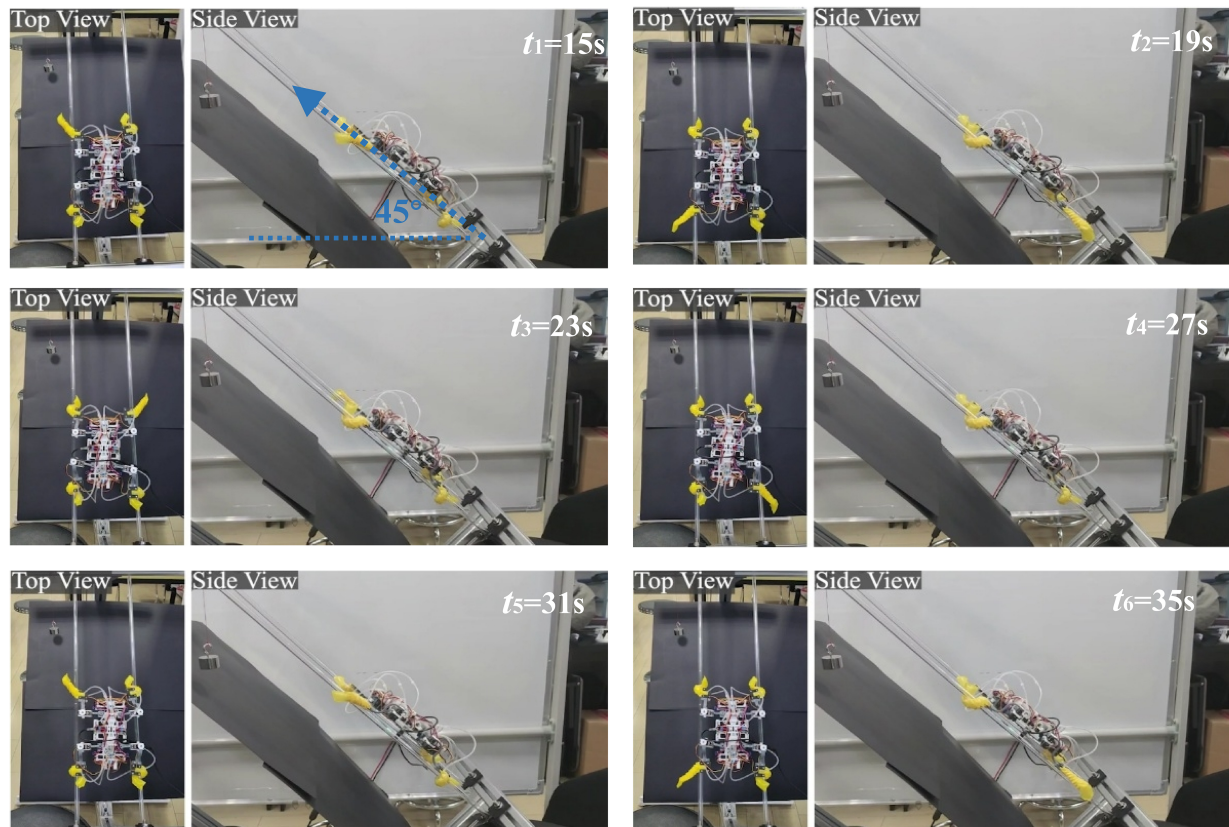
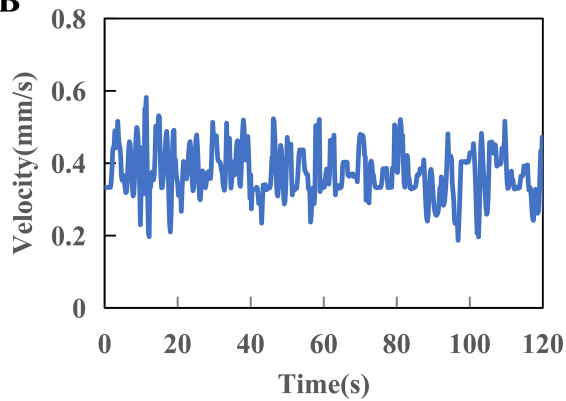
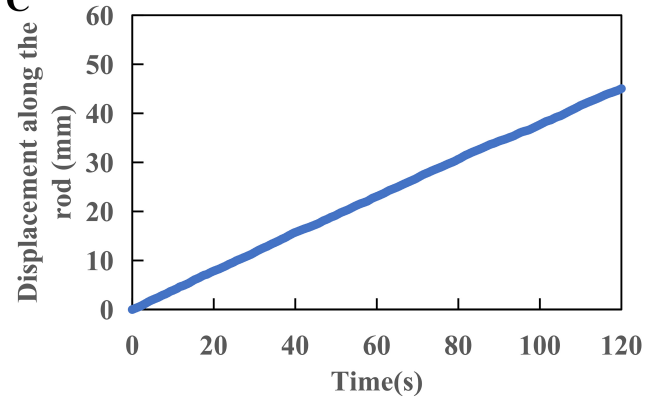
A**B****C**

Figure 8. Climbing performance of the FAWA-based robot on a 45° inclined acrylic rod. (A) Sequential snapshots of the robot climbing process recorded from top and side views; (B) Instantaneous climbing velocity along the rod; (C) Displacement of the robot along the rod during climbing. FAWA: Fabric-based adhesive winding actuator.

inflation of the constraining layer increases the detachment angle of the adhesive material, causing rapid interfacial adhesive failure at the adhesive–substrate interface. Consequently, detachment is swiftly completed with only a minor external force applied by the servo motor as it moves the actuator forward. Shortly after, both the constraining layer and pleated bladders begin deflation. However, after the end-effector detaches from the target object and before the subsequent winding grasp, i.e., during the limb’s swing phase, a specific problem occurs. During the first half of the swing phase, both the pleated and constraining layer bladders are at atmospheric pressure. Because the fabric-based pleated structure has insufficient passive restoring capability after deflation, the actuator cannot automatically recover to its fully extended initial state; instead, it remains partially coiled, and residual air escapes slowly from the pleated

bladders. A waiting period is required for most of this residual air to exit before proceeding to the second half of the swing phase. In the second half, positive pressure is applied to the constraining layer bladder, forcibly extending the actuator to prepare for the subsequent adhesive winding. Throughout this process, the limb continues its forward swing.

If positive pressure were applied to the constraining layer bladder immediately upon deflation, the pleated bladders, although near atmospheric pressure, would still contain a volume of residual air. Subsequent inflation of the pleated bladders would then cause them to expand. The pleats near the proximal end would be forced to fold, and the inflation of the constraining layer bladder could partially obstruct the pleated bladder inlet, sealing the residual air inside. This would prevent the pleated bladders from extending, maintaining the actuator in a coiled state. Similarly, if a certain amount of air remains in the pleated bladders when the constraining layer is pressurized, that air can also become sealed, typically accumulating in the distal end of the bladders and the few pleats nearest the distal end. Because of the small volume and distal location of this trapped air, the actuator can still be extended by the constraining layer. However, after the constraining layer deflates, this residual air can redistribute, establishing interconnections between pleats. Consequently, during the subsequent inflation of the pleated bladders, without the obstructive effect of the pleats on airflow, deformation and coiling may initiate from the distal pleats rather than the proximal ones. This results in a deformation trajectory different from the initial, intended pattern.

Equipping the system with a negative pressure circuit for assisted deflation can significantly reduce the actuator deflation time, thereby increasing the robot's climbing speed. For reliable winding and grasping while maintaining stability, the target climbing object is positioned near the proximal end of the actuator during robot climbing. If coiling deformation initiates from the distal end, by the time the proximal end is reached, the distal portion is already coiled, rendering it unable to perform the desired coiling and grasping action on the target object and leading to subsequent winding failure. Therefore, the residual air in the pleated bladders should be sufficiently minimized before the constraining layer is pressurized. Experimental testing determined that when the deflation waiting time $T_i > 600$ ms, the residual air in the pleated bladders does not adversely affect the actuator's subsequent winding deformation trajectory. Furthermore, experiments confirmed that employing negative pressure for active deflation, rather than relying on passive pressure relief, substantially increases the deflation rate. Under such active deflation conditions, $T_i > 300$ ms is sufficient. The climbing tests were performed using an external regulated power supply; therefore, onboard power feasibility was further estimated based on the selected actuator pressure of 50 kPa and the 16 s tripod-gait period (the detailed calculation process can be found in [Supplementary Section 5](#)). The pneumatic subsystem was estimated to require approximately 1.45 A and 7.25 W on the 5 V bus, with an estimated single-pump heat load of approximately 1.02 W; excessive overheating is not expected if basic thermal paths are provided, although temperature-rise testing is still required. For an 11.1 V/1,000 mAh battery, the estimated endurance is approximately 23.9 min, corresponding to about 90 complete tripod-gait cycles.

DISCUSSION

In this study, we developed a lightweight FAWA for slender rod-climbing robots. The significance of the proposed actuator does not lie in simply combining a fabric coiling structure with an adhesive interface. Rather, it establishes a functionally coupled architecture in which wrinkle-guided pleated chambers generate 3D helical winding, while the constraining-layer bladder regulates geometric enclosure and assists release. This design enables the actuator to achieve stable winding, controllable attachment–detachment switching, and relatively high axial load capacity under low driving pressure. Quantitatively, the 2 g actuator generated stable axial adhesive-winding forces exceeding 20 N at about 50 kPa and approached 30 N at 80 kPa, corresponding to a load-to-weight ratio greater than 1,000. Although direct comparison should be made cautiously because the actuation modes and loading conditions differ among systems, this value is higher

than those reported for several representative high-performance soft systems, such as an entanglement-based soft gripper with a ratio of approximately 770^[33], pneumatic fabric-lattice artificial muscles with a ratio of approximately 250^[34], and SMA- or dielectric-elastomer-based micro/soft actuators with ratios of approximately 155^[35,36]. Importantly, the high ratio of FAWA was achieved under adhesive-winding conditions on slender rods, rather than under simple static lifting or linear actuation^[37]. These results support the feasibility of using fabric pneumatic structures as lightweight robotic end-effectors that combine load-bearing attachment, rod-conformal winding, and controllable release. Another important outcome of this work is the clarification of the influence of structural geometry on winding performance. The experiments showed that adhesive-winding stability depends strongly on the coupling among the helix angle, pitch, enveloping central angle, and effective contact area. During tensile failure, increases in the helix angle and pitch, together with a reduction in enveloping central angle, are associated with a decline in axial force, indicating that load support is governed by coiling morphology as well as by the adhesive interface. Parameter-comparison experiments further showed that the baseline configuration provided the best balance between force output and operational stability, and that rods with diameters of 10–12 mm provided the best overall balance between load capacity and repeatability, whereas the effective range extended approximately from 0.8R to 1.4R. This interpretation is consistent with previous studies showing that the deformation mode and output performance of fabric pneumatic actuators are highly sensitive to structural configuration and geometric constraint design^[14,38]. Recent computational design studies further show that pattern and orientation can directly program bending and twisting in fabric pneumatic actuators^[39]. This corresponds with recent research on integrated textile pneumatic structures, where mechanical response is programmed primarily through architecture rather than large intrinsic material stretch^[40].

Comparison with existing winding and coiling soft actuators further highlights the practical relevance of FAWA for rod-climbing robots. Elastomer-based pneumatic coiling actuators generally provide excellent deformability, but improved load capacity often requires a higher driving pressure or larger structural dimensions^[6,7]. Even when stiffness modulation or patterned constraints are introduced, these systems primarily emphasize deformation programming rather than axial anti-slip support under wrapping conditions^[8]. Textile and fabric actuators are attractive because of their low mass and fast response, but many were originally developed for wearable assistance or general shape morphing rather than for stable high-load attachment on slender rods^[12,13]. Recent soft robotics research further suggests that stiffness-programmed soft actuators can improve grasp robustness in load-bearing tasks^[41]. Other winding and wrapping systems, including cable-driven actuators, thermally actuated tendril-inspired grippers, and inflatable helical grippers, can provide substantial force or versatile deformation; however, they typically rely on bulky external drives, elevated temperatures, or relatively large structures, which limit distal integration into lightweight climbing robots^[15,18,42]. For example, the rubber-bellows actuator reported for a snake-like rod-climbing robot required pressures above 200 kPa, whereas cable-driven and thermally actuated systems reported holding capacities under approximately 35-N cable tension or 90 °C actuation, respectively^[4,15]. Related studies on soft and gecko-inspired adhesive grippers have shown that compliant deformation, enveloping contact, and engineered adhesion can improve grasping adaptability for objects with diverse shapes and surface properties^[43]. Accordingly, the demonstrations in [Figure 5B](#) suggest that FAWA may be extended to manipulation tasks involving smooth, curved, or slender objects. However, this capability should not be overgeneralized: wet, greasy, or heavily contaminated surfaces would be limited by the environmental tolerance of the adhesive material^[44], and soft or easily deformable objects may change the winding geometry, contact distribution, and peeling behavior^[45]. Therefore, the grasping versatility of FAWA beyond the tested objects requires further systematic investigation.

Our robotic experiments further showed that the value of FAWA lies not only in static holding force but also in its compatibility with cyclic locomotion. At the current stage, this cyclic attachment–detachment process is

primarily coordinated by a predefined pneumatic sequence and gait timing, rather than by real-time sensory feedback. In rod-climbing robots, the end-effector must repeatedly alternate between reliable attachment during stance and rapid detachment during swing. The proposed actuator addresses this requirement by coupling coiling deformation with adhesive contact: winding establishes distributed normal loading and geometric enclosure, whereas the adhesive interface helps suppress axial slip and improves attachment stability^[46,47]. A representative repeated-use test under a typical operating condition showing that FAWA retained a peak adhesive-winding force of approximately 17–18 N after 100 cycles on a 10 mm acrylic rod at 50 kPa ([Supplementary Figure 6](#), Representative cyclic reusability test of FAWA is presented in [Supplementary Section 6](#)). This mechanism is consistent with general principles of controllable dry adhesion, in which contact state, load direction, and peeling kinematics strongly affect attachment and release behavior^[25,48]. Recent studies further show that actively deformable adhesive backings can improve conformal contact on curved surfaces while facilitating switchable release^[49,50]. When integrated into a 430 g multi-limb robot, the actuator enabled stable climbing on inclined rods, reaching about 50 mm/min on a 20° slope and about 22 mm/min on a 45° slope without apparent slipping. Continuous climbing along fully vertical rod- or pole-like structures was not examined in the present study and will require further validation of the adhesion safety margin and gait coordination. Additionally, the proposed system reveals a meaningful limitation: the climbing speed is constrained more by actuator recovery and exhaust than by insufficient peak holding force. Residual air in the pleated chambers affects repeatable re-extension and prolongs the swing phase, whereas pressure-failure safety requires further engineering consideration. Although no mechanical backup locking mechanism was integrated in the current prototype, sudden pressure loss would not necessarily cause instantaneous release because the holding effect is also supported by helical winding, compliant conformal contact, and the dry adhesive interface. In addition, the present experiments were conducted indoors on dry acrylic rods. Because the dry adhesive interface is sensitive to surface conditions, rain film, condensation, grease, dust, and temperature-induced changes may reduce interfacial adhesion in outdoor cable environments. Therefore, future research should further optimize the adhesive layer and fabric sealing for contaminated or wet surfaces while retaining the winding-based load-supporting architecture proposed in this study. Overall, the present study has demonstrated a robot-oriented attachment architecture that addresses the coupled requirements of winding generation, axial load support, controllable release, and cyclic reuse in slender rod-climbing robots.

CONCLUSION

This study developed FAWA for slender rod-climbing robots. By functionally coupling a wrinkle-guided pleated chamber with a constraining-layer bladder, the actuator achieves 3D helical winding, axial load-bearing adhesive attachment, and controllable release within a lightweight fabric structure. Experiments showed that FAWA weighs about 2 g, sustains axial loads exceeding 1,000 times its own weight at 50 kPa, adapts to rod-like targets over a practical diameter range, and supports stable climbing when integrated into a multi-limb robot. More importantly, the study shows that a fabric actuator can be designed not only for shape change, but also to resolve the coupled robot-level requirements of attachment, load support, release, and cyclic re-use in slender rod climbing. Future research will focus on the long-term durability of the adhesive interface; broader geometric adaptability; and the integration of real-time sensory feedback, such as pressure, deformation, contact, and slip sensing, to enable closed-loop regulation of FAWA during cyclic winding, attachment, and detachment.

DECLARATIONS

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Authors' contributions

Conceptualized the study and designed the experimental framework: Wang, Z.; Yin, X.; Wang, L.

Carried out the fabrication and the experiments: Yin, X.; Weng, Z.

Carried out the data collection and analysis: Duan, Y.; Xue, C.

Assembled the robot platform: Wang, L.; Yin, X.

Provided guidance on the construction of the robot platform: Xie, J.

Wrote the original draft of the manuscript: Wang, L.; Yin, X.; Wang, Z.

Reviewed and edited the manuscript: Wang, Z.; Dai, Z.

Availability of data and materials

The data supporting the findings of this study are presented in this manuscript and [Supplementary Materials](#).

AI and AI-assisted tools statement

During the preparation of this manuscript, ChatGPT (GPT-5.5, released 2026-04-23; OpenAI) was used for language editing and to generate the chameleon illustration in the upper-left part of [Figure 1](#). Doubao (Seedream 5.0 Lite, released 2026-02-13; ByteDance) was used solely to visually enhance and stylize the graphical abstract based on an original robot image provided by the authors. It was not used to generate the original robot image or any scientific data. These AI-assisted tools did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All AI-assisted content was carefully reviewed and verified by the authors. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Supplementary Materials

[Supplementary Materials](#)

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