

## SOFT ROBOTS

# Hygrobot: A self-locomotive ratcheted actuator powered by environmental humidity

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Microrobots that are light and agile yet require no artificial power input can be widely used in medical, military, and industrial applications. As an actuation system to drive such robots, here we report a biologically inspired bilayer structure that harnesses the environmental humidity energy, with ratchets to rectify the motion. We named this actuator-ratchet system the hygrobot. The actuator uses a hygroscopically responsive film consisting of aligned nanofibers produced by directional electrospinning, which quickly swells and shrinks in lengthwise direction in response to the change of humidity. The ratchets based on asymmetric friction coefficients rectify oscillatory bending motion in a directional locomotion. We mathematically analyzed the mechanical response of the hygrobot, which allowed not only prediction of its performance but also the optimal design to maximize the locomotion speed given geometric and environmental constraints. The hygrobot sterilized a trail across an agar plate without any artificial energy supply.

## INTRODUCTION

Microrobots can perform various functions by interacting with the surroundings for medical, military, industrial, or environmental purposes. One of the major challenges faced by microrobotic engineering is a lack of power sources to drive robots without needing artificial intervention. Among many attempts to address this issue, we pay special attention to plants because they generate motions and deformations with a very simple structure, unlike animals relying on the complex of motor proteins, or muscles. Most botanical movements are hydraulic in nature; that is, simple transport of fluid (mostly water) in and out of the plant tissue generates motions. In particular, hygroexpansive properties of plant cells, leading to volumetric change in response to moisture content, are exploited by many plants, as seen in opening and closing of pine cones (1); self-digging of seeds of wild wheat (2), *Erodium* (3), and *Pelargonium* (4); self-sealing of pollen grains (5); and opening of seed pods (6) and ice plant capsules (7).

Various soft materials are responsive to external stimuli—such as heat (8, 9), light (10–12), and chemical substances (13–17)—and interest in actuators using hygroexpansive materials either artificial or natural is growing recently thanks to the potential to harness energy from environmental humidity change. Paper is probably the most easily accessible example of such actuators, which bends due to strain gradient in thickness-wise direction when placed near a wet substrate (18–20). Artificially synthesized polymers (21) and biological materials like *Bacillus* spores (22) have been used to achieve similar hygroscopic actuation, which can be used for electrical power generation and locomotion.

However, there are challenges with implementing hygroscopic actuation mechanisms to power microrobots. First, the response of the overall actuation system should be agile enough for practical use. A thin hygroscopic layer can hasten the response but may result in the sacrifice of actuation magnitude. Second, the actuation should be

possible without artificial control of atmospheric humidity condition. Many previously demonstrated hygroscopic actuators move when humidity is raised either by external supply of water vapor or by placement near a water source. For repeated motion, humidity levels should be periodically decreased as well, which has required human intervention or complicated and bulky mechanical mechanisms (23). Third, the movement should be regulated to achieve locomotion in a desired direction. Thin sheets of paper (20) and polymers (21) were shown to flip repeatedly on a moist surface owing to natural drying of a part far from a vapor source, but their tumbling hardly gives any directional locomotion. Fourth, a mathematical understanding of the dynamic response of the hygroscopic actuation has been rarely attempted, which should play a pivotal role in obtaining the optimal design.

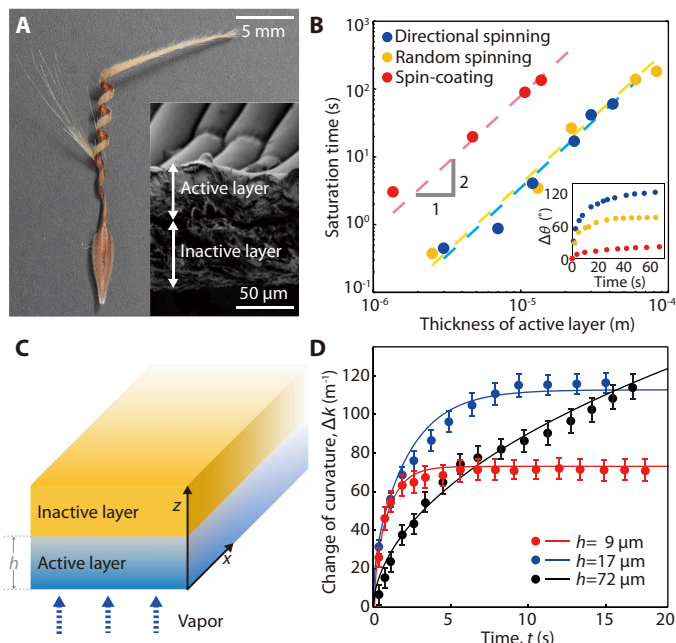
To meet the foregoing challenges, here we report a hygroscopically powered robot, named hygrobot, that locomotes spontaneously in a ratcheted fashion on a moist surface at a speed high enough to enable practical applications. Also, we mathematically analyzed the motion of the hygrobot, which allows us to obtain optimal geometric design to maximize the locomotion speed. The mathematical model couples the moisture diffusion and elastic bending of the actuator plate. We used an inexpensive, commercially available hygroscopic material instead of specially prepared polymers or biomaterials that are not easily accessible to most robotic engineers. A manufacturing process is described to increase the actuation speed and strain of the material in response to humidity change. A simple mechanism is attached to the actuator to enable autonomous yet directional locomotion. Last, we demonstrate a possible application of the hygrobot for biomedical treatments on a wet skin.

## RESULTS

### Hygroscopic response of the bending actuator

Tissues of many motile plants, such as pine cone (1), awns of wild wheat (2), and *Erodium* (24), use a bilayer structure, one layer of which is hygroscopically active, whereas the other layer is hygroscopically inactive. Although such bilayer configuration has been mimicked frequently (10, 18, 21, 22), aligned microstructures of the plant tissues have drawn relatively little attention, despite their critical role in effective

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**Fig. 1. Hygroscopically responsive bilayer structures.** (A) Optical image of a seed of *P. carnosum* and the SEM image of the cross-section of its awn. (B) Time for saturation of deflection angle versus thickness of active layers fabricated via spin-coating (red circles), random electrospinning (yellow circles), and directional electrospinning (blue circles). The thickness of the inactive layer is 55 μm for all the cases. The trend lines for all the types of active layer follow  $t_s \sim h^2$ , implying the diffusive transport of moisture in the layers. Inset: Temporal evolution of the deflection angle at the free end of the bilayers, 25 mm in length, whose active layers are fabricated by spin-coating (red circles), random electrospinning (yellow circles), and directional electrospinning (blue circles). The active layer thickness is 35 μm. (C) Coordinate system for the bilayer. (D) Temporal evolution of the bilayer curvature when the environmental humidity abruptly increases to 0.8 from 0.2 at  $t = 0$ . Circles and lines correspond to experiment and theory, respectively. Error bars represent SD.

generation of movements. Figure 1A shows the cross-section of an awn of *Pelargonium carnosum* seed, consisting of hygroscopically active cells aligned on a hygroscopically inactive layer. The awn is responsible for the propulsion of the seed into the soil by stretching when wet but helically coiling when dry. The deformation mode of the awn is determined by both the cell alignment direction and the arrangement of cellulose microfibrils winding up the cell walls. Such alignment of hygroresponsive cells—found in *Selaginella lepidophylla* (25), awns of Stork’s bill (24), as well as *Pelargonium* species—inspired us to adopt the structure to facilitate and to magnify deformation of the actuator in a desired direction.

We fabricated an aligned structure of hygroscopic PEO (polyethylene oxide) nanofibers via the directional electrospinning. To test the effectiveness of the nanofiber alignment in hygroscopic actuation, we compared the bending characteristics of the bilayers with aligned PEO fibers, randomly spun PEO fibers, and spin-coated PEO film of the same dimensions. Their length and inactive layer thickness are 25 mm and 55 μm, respectively. We abruptly raised the relative humidity of the air surrounding the actuators from 20 to 80% at 25°C within a closed chamber; the actuator bent toward the inactive layer due to hygroscopic expansion of the active layer.

The deflection angle at the free end versus time is plotted in the inset of Fig. 1B. Defining the time when the deflection angle reaches

90% of its maximum value as the saturation time,  $t_s$ , we plotted  $t_s$  of the hygroscopic actuators versus the thickness of the active layer,  $h$  (Fig. 1B). The response time of the electrospun layers is only 20% of the spin-coated structure. In addition to the fast response of the electrospun aligned structure, its maximum deflection angle is 5.6 and 1.7 times greater than those of the spin-coated and the randomly electrospun actuators, respectively. Furthermore, the bending of the aligned structure occurs in a single direction due to the uniform longitudinal swelling of fiber arrays, unlike the spin-coated and randomly electrospun ones that bend and twist in a random fashion. The irregular directions of bending and twisting of previous hygroscopic actuators make it nearly impossible to control their wriggling trajectory, severely limiting their use as a robotic actuator (20, 21).

In Fig. 1B,  $t_s$  increases with  $h^2$ , implying that the hygroexpansion occurs as water molecules diffuse into the active layer (26). The plot also allows us to obtain the effective diffusivity,  $D$ , defined as  $D = h^2/t_s$ , of the water molecules in the active layers:  $0.9 \times 10^{-10}$  m<sup>2</sup>/s for the electrospun fiber layers and  $1.2 \times 10^{-12}$  m<sup>2</sup>/s for the spin-coated layers.

We attribute the orders-of-magnitude improvement of the diffusivity in the aligned fiber structure primarily to its high porosity. The pores between nanofibers provide gaseous paths of water molecules instead of a solid barrier as experienced in the spin-coated layer. The effective diffusivity,  $D_e$ , for a binary medium can be estimated by the following relation (27):  $(D_e - D_s)/(D_e + 2D_s) \sim \eta(D_a - D_s)/(D_a + 2D_s)$ , where  $\eta$  is the porosity of the electrospun layer, and  $D_a$  and  $D_s$  are the water vapor diffusivity in the air and the solid polymer, respectively. Substituting  $\eta = 0.7$  as obtained by comparing the densities of the porous and dense PEO layers, we calculated  $D_a$  to be  $2.82 \times 10^{-5}$  m<sup>2</sup>/s (28).  $D_s = 1.2 \times 10^{-12}$  m<sup>2</sup>/s as obtained from Fig. 1B, so we write  $D_e \sim 1 \times 10^{-11}$  m<sup>2</sup>/s, which agrees with the foregoing estimate.

The diffusive transport of moisture in the hygroscopically active layer allows us to compute the transient bending response of the bilayer actuator using the theory of elasticity. The one-dimensional diffusion of the water molecules follows  $\partial\phi/\partial t = D\partial^2\phi/\partial z^2$ , where  $\phi(z, t)$  is the water concentration,  $t$  is time, and  $z$  designates the thickness direction as shown in Fig. 1C. With the initial concentration  $\phi(z, 0) = \phi_0$ , the concentration distribution in the active layer ( $0 < z < h$ ), which is subjected to the boundary conditions of  $\phi(0, t) = \phi_\infty$  on the outer surface and  $\partial\phi(h, t)/\partial z = 0$  on the interface of the active and inactive layers, is given by

$$\phi(z, t) = \sum_{n=0}^{\infty} \left[ \frac{-2(\phi_0 - \phi_\infty)}{(n + 1/2)\pi} e^{-\lambda_n^2 t} \sin\left(\frac{(n + 1/2)\pi z}{h}\right) \right] + \phi_\infty$$

Here,  $\lambda_n = D^{1/2}(n + 1/2)\pi/h$ , and  $\phi_\infty$  is the environmental humidity.

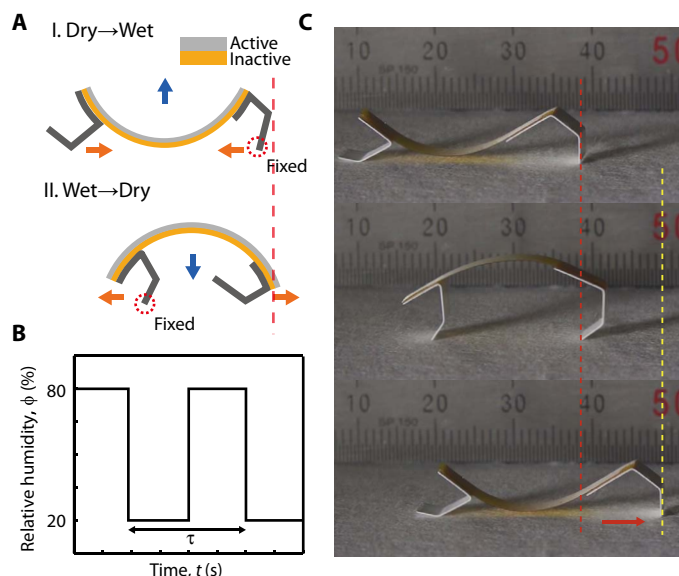
The local moisture concentration induces the hygroscopic strain  $\epsilon_h = \alpha\phi$ , where  $\alpha$  is the hygroscopic expansion coefficient, 0.05, as empirically measured for the active layer with aligned nanofibers. The total strain in the active layer is given by  $\epsilon(z, t) = \epsilon_0 - \kappa\zeta - \epsilon_h$ , where  $\epsilon_0$  is the reference strain at the reference plane,  $\zeta$  is the distance from the reference plane, and  $\kappa$  is the bending curvature. The local stress,  $\sigma$ , equals  $E\epsilon$ , with  $E$  being Young’s modulus.  $E$  of the active layer was measured as a function of  $\phi$  in a constant humidity chamber separately to give  $E = -77.4\phi + 169.2$  MPa. The absence of any external loads led us to write the force  $F = \int\sigma d\zeta = 0$  and the moment  $M = \int\sigma\zeta d\zeta = 0$  throughout the active and inactive layers. The change of curvature of the bilayer from the base (dry) state, obtained by numerical integration of the force and moment, is plotted in Fig. 1D. The initial change

of the bending curvature with the diffusion influx of water molecules and the later saturation of the curvature due to concentration equilibrium with the environments were predicted well by our theory. It not only validated the diffusion-coupled elastic bending model but also indicated that our estimation of diffusivity based on the saturation time in Fig. 1B is reasonable. The time for curvature saturation increased with the thickness of the active layer, whereas the thickness of the inactive layer  $h_i$  was fixed at 55  $\mu\text{m}$ . Upon exposing a hygroscopic actuator to  $10^4$  cycles of relative humidity variation between 0.2 and 0.8 at 25°C, we found the amount of curvature change to decrease by 17% from the initial value.

### Locomotion under temporal humidity variation

The temporal variation of the environmental humidity caused the actuator to alternate the bending directions, enabling its use as a simple energy-harvesting device (21, 22). However, here we transformed symmetric oscillations into a directional motion for locomotive applications. Inspired by the creeping, crawling, and slithering animals like worms, snails, and snakes, which rectify their motion by breaking the symmetry of friction (29), we attached legs of very simple geometry at the ends of actuator, as schematically shown in Fig. 2A. Without complicated surface texturing of the footpads (30), the motion can be rectified by only folding the legs in the middle, providing an advantage of simplifying the microrobot design. In the following, we describe the strategy of motion rectification.

With the hygroscopically inactive layer beneath the active layer, the dry bilayer is initially bent convex downward. In this configuration, the end tip of the foreleg and the knee (the folded part) of the hind leg is in contact with the substrate. The static friction coefficients of the end tip and knee of the legs made of PET (polyethylene terephthalate) with the substrate, filter paper (GB005 Blotting Paper, Whatman), were respectively measured to be about 1 and 0.5 (see section S3). As the environmental humidity increases, the bilayer bends upward with



**Fig. 2. Ratcheted locomotion of hygrobots.** (A) Ratcheting of two legs attached to a bilayer actuator. The difference in the static friction coefficients of the end tip and knee of the legs rectifies the motion. (B) Artificially controlled temporal variation of the environmental humidity. (C) Advance of the hygrobot for a single period of humidity variation. The corresponding movie is shown in movie S1.

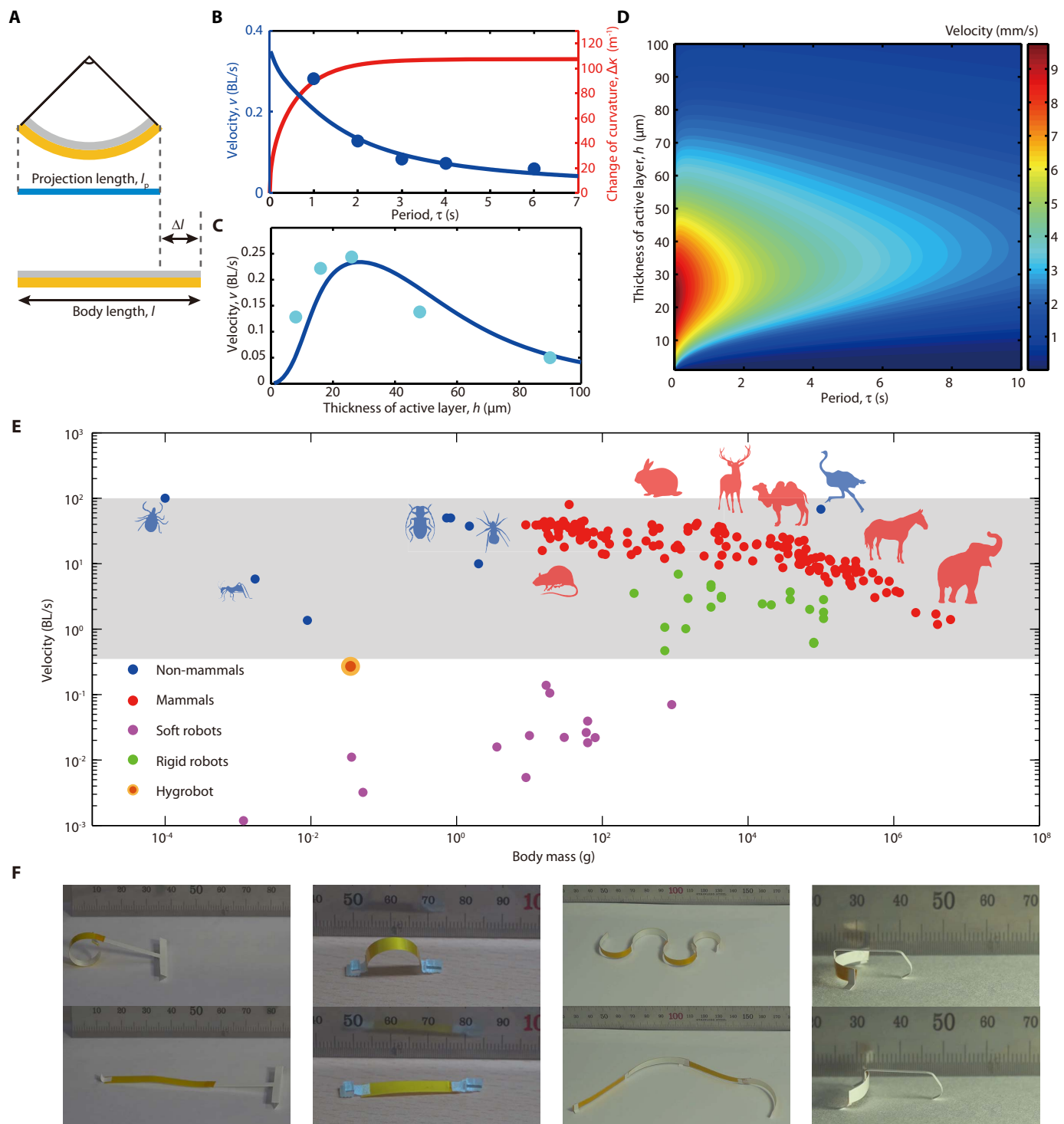
the swelling of the active layer, thereby bringing the legs closer (Fig. 2A). Because of the difference in the static friction coefficient, the knee of the hind leg slides forward while the foreleg is stationary. When the bilayer reaches the upward convex, the foreleg touches its knee on the substrate while the hind leg stands on its tip. Then, we let the bilayer dry, causing it to return to the initial downward convex, spreading the two legs. The foreleg that kneels slides forward while the hind leg is fixed. By repeating the humidity cycle (Fig. 2B) with alternating supply of water-saturated air and dry nitrogen gas, the directional locomotion of the hygrobot was achieved, which resembled that of inchworms (31). The corresponding images and movie are shown in Fig. 2C and movie S1.

Now, we theoretically predict its speed and optimize the design. The distance the hygrobot travels in a period ( $\tau$ ) of humidity cycle is  $\Delta l = l - l_p$ , where  $l$  is the length of the straightened actuator and  $l_p$  is the projected length of its arc with the maximum curvature  $\kappa_m$  reached during a period, as illustrated in Fig. 3A. For  $l_p = 2\kappa_m^{-1}\sin(\kappa_m/2)$ , one can obtain the locomotion speed  $v = \Delta l/\tau$  by calculating  $\kappa_m$ . Our theory to compute  $\phi(t, z)$  and subsequently  $\kappa(t)$ , as delineated above, allows us to find the locomotion speed as a function of various design and environmental parameters, including the bending stiffness of the active and inactive layers, length of the actuator, hygroscopic expansion coefficient of the active layer, and the amplitude and frequency of humidity change.

We plot the theoretical speed  $v$  of a hygrobot with  $h = 13 \mu\text{m}$ ,  $h_i = 55 \mu\text{m}$ , and  $l = 25 \text{ mm}$  under the relative humidity oscillation between 0.2 and 0.8 at 25°C as a function of the period  $\tau$  (Fig. 3B). The decrease in humidity period corresponds to the increase in actuation frequency but shortens the time of moisture diffusion into the active layer. The maximum curvature increased with  $\tau$  when  $\tau$  was small. However, the effect of actuation frequency dominated that of the curvature, and thus,  $v$  monotonically decreased as  $\tau$  increased, which agrees well with the experimental results.

Figure 3C plots the dependence of  $v$  on  $h$ , the thickness of the active layer, when  $h_i = 55 \mu\text{m}$ ,  $l = 25 \text{ mm}$ , and  $\tau = 2 \text{ s}$  under the swing of humidity between 0.2 and 0.8. The velocity  $v$  increased with the active layer thickness until  $h$  reached about 30  $\mu\text{m}$ , but  $v$  decreased afterward. The penetration thickness of moisture through diffusion is scaled as  $(D\tau)^{1/2} \sim 10 \mu\text{m}$ . When the active layer was excessively thick, causing only a fraction of the layer to swell, the remaining region only resisted the bending, leading to a decrease of  $v$  with  $h$ . These experimental results match favorably the theoretical prediction.

We plot  $v$  as a function of  $h$  and  $\tau$  with  $h_i = 55 \mu\text{m}$  and  $l = 25 \text{ mm}$  (Fig. 3D). Using this contour map, one can find the optimal thickness of the active layer to maximize the locomotion speed when the period of humidity variation is set by the external condition. We compared the performance of the hygrobot with other robots and terrestrial animals on a two-dimensional space constructed with the velocity measured in body length (BL) per second and body mass (Fig. 3E). The robot optimized in Fig. 3C, which has an active layer thickness of 30  $\mu\text{m}$  and a mass of 0.035 g, achieved linear locomotion at a speed of 6 mm/s, or 0.24 BL/s when  $\tau = 2 \text{ s}$ . Owing to the hygrobot's superior velocity despite small mass, it is located well above the trend line of the previously reported soft robots, where the locomotion velocity increases with the body mass. The speeds of the terrestrial animals and most of the conventional robots with rigid parts are above  $10^0 \text{ BL/s}$  regardless of the body mass. The speed of the hygrobot is close to the lower speed limit of the rigid robots. By attaching an additional weight, the hygrobot was found to be able to carry 50 times its weight at half



**Fig. 3. Velocity of hygrobots.** (A) The difference between  $l$  and  $l_p$  corresponds to a distance that a hygrobot advances a period. (B) Velocity of hygrobots as a function of the period of humidity variation. Circles correspond to the experimentally measured velocity. Blue and red lines are theoretically calculated velocity and maximum change of curvature, respectively. (C) Velocity of hygrobots as a function of the active layer thickness. Circles and lines correspond to experiment and theory, respectively. (D) Contour map of the hygrobot velocity as a function of active layer thickness and period. (E) Velocity of various animals and robots measured in body length (BL) per second versus body mass. For data, see tables S1 to S3. (F) Hygroscopic actuation systems of different designs from Fig. 2C, which can also propel themselves under temporal variation of environmental humidity. The corresponding movie and details are in movie S2 and section S2.

of the speed under free load and to cease to move when the weight increased to 80 times its original value.

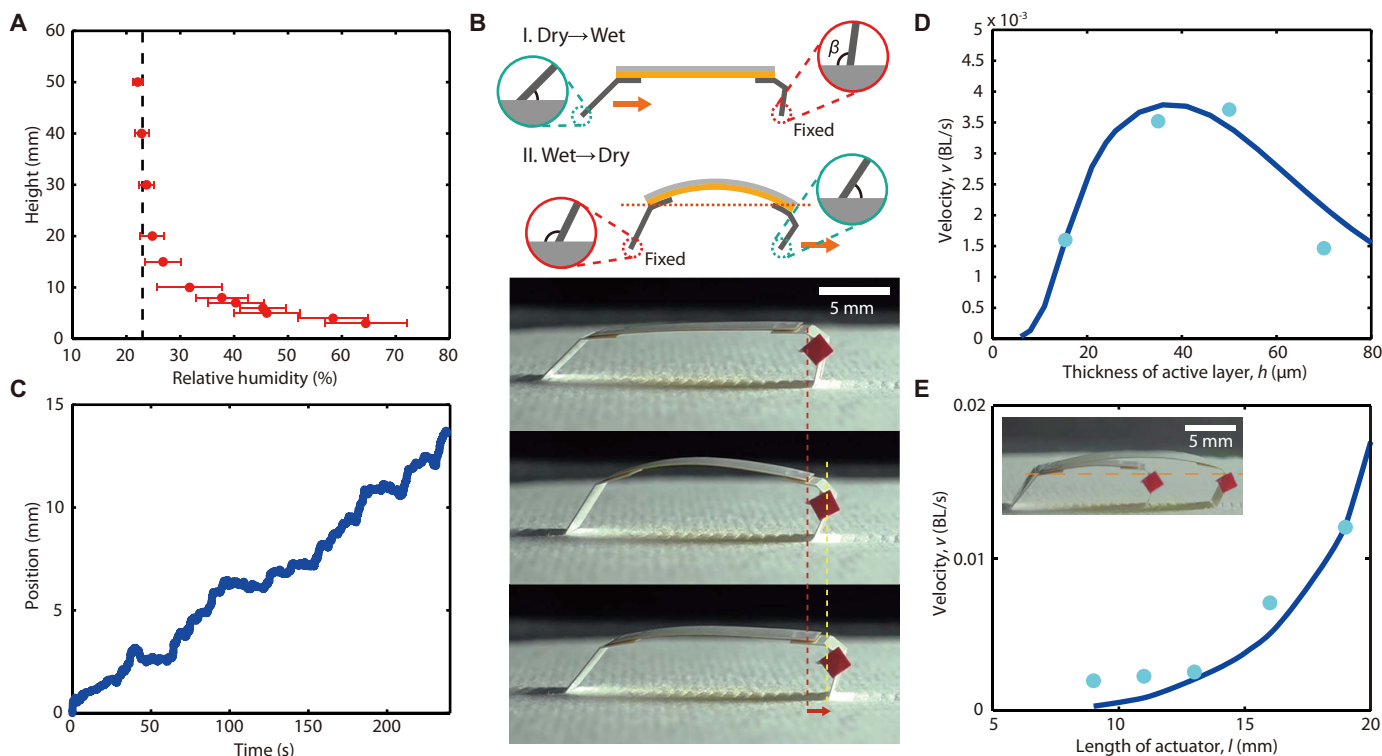
A number of different designs in addition to that shown in Fig. 2C can be developed to achieve linear locomotion of the hygroscopic actuator in response to temporal change of environmental humidity. Bending can occur in a plane perpendicular or parallel to the substrate, and ratchets of various types can be devised, as shown in Fig. 3F (details in section S2). Samples of those actuation systems creeping or crawling under varying humidity are shown in movie S2.

### Spontaneous locomotion in spatial humidity gradient

Although temporal variation of humidity around the hygrobot can occur naturally via human breathing or day-night humidity cycle (3), here we show that it can propel itself spontaneously when placed on a moist surface. Figure 4A displays the experimentally measured humidity distribution of quiescent air near a moist surface using a humidity sensor (Sensirion EK-H5) at 23°C. The relative humidity decreases with distance from a damp filter paper, a significant change occurring within 10 mm. The hygrobot exploits this spatial gradient of humidity by oscillating between the regions of high and low humidity. The shape change is similar to what is shown in Fig. 2A. Being convex toward the hygroscopically active layer when dry, the initially dry bilayer placed on the moist surface turns convex upward (or toward the inactive layer) because the active layer swells due to a high humidity near the substrate. When convex upward, the hygrobot dries by losing moisture to the local environment of low humidity and returns to the downward convex.

Because the motion strategy similar to that under the temporal oscillation of humidity is adopted, we use a similar ratchet system having the asymmetric friction coefficient. However, in this case, the ratchet has been designed to maximize the displacement of the hygrobot in the vertical direction to fully exploit the humidity difference (section S4). When the humidity around the bilayer is high (mode I in Fig. 4B), the legs are pulled together because of bilayer bending, but only the hind leg moves because its friction coefficient is less than that of the foreleg. When the bilayer is dried (mode II in Fig. 4B), the legs are pushed apart as the bilayer is stretched out, causing only the foreleg to move because of its lower friction coefficient than that of the hind leg. The experimental images of the hygrobot that propels itself using the spatial humidity gradient are shown in Fig. 4B. The distance that a hygrobot (where the thickness of the active and inactive layers is 35 and 55  $\mu\text{m}$ , respectively, and the length is 15 mm) travels with time is shown in Fig. 4C.

We estimate the locomotion speed of the hygrobot driven by the spatial gradient of humidity in the following. The theoretical model built for the speed of the hygrobot under temporal variation of humidity can be used once the period ( $\tau$ ) and magnitude ( $\Delta\phi$ ) of humidity oscillation are specified. Because the humidity variation is caused by bending of the hygrobot, the time scale of the moisture diffusion into the active layer, which determines the bending time, gives  $\tau$ . For a cycle of moisture transfer in and out of the active layer,  $\tau \sim 2h^2/D \sim 2$  s, which is consistent with the experimental observation. The magnitude of humidity oscillation is determined by the humidity



**Fig. 4. Spontaneous locomotion of hygrobots under spatial gradient of humidity.** (A) Spatial distribution of relative humidity at 23°C near a moist filter paper. Error bars indicate SD. (B) Schematics and experimental images of a hygrobot crawling spontaneously on a moist surface. The angle that the leg makes with the substrate,  $\beta$ , determines the friction coefficient (section S3). (C) Temporal evolution of the position of the hygrobot. Velocity of hygrobots powered by the spatial gradient of humidity as a function of (D) the active layer thickness and (E) the actuator length. Circles and lines correspond to the results of experiment and theory, respectively. Inset of (E) shows the overlapped images of hygrobots of different lengths.

at the closest and farthest positions of the hygrobot from the moist surface. Thus, it depends on the bending curvature of the bilayer and the ratchet deformation. We plot the speed of hygrobots as a function of thickness of the active layer and length in Fig. 4, D and E, respectively.

With the increase of the thickness of a thin active layer, the bending moment and thus the curvature of the bilayer increased, which helped the hygrobot to use the greater humidity variation, resulting in an improved locomotion speed (see Fig. 4D). But when the thickness further increased, the bending was completed before the moisture fully diffuses in the active layer. Then, the unsaturated layer restricted bending, leading to the decrease of locomotion speed for the active layer thickness over about 40  $\mu\text{m}$ . Our theoretical prediction correctly captures this trend. The balance between the bending speed and the diffusion rate allows us to find the optimal active layer thickness. The locomotion speed increases with the actuator length (Fig. 4E), because a longer actuator can make a larger vertical displacement to experience a greater humidity difference. Our theory shows a good match with the experimental results.

The ability of the hygrobot to propel itself on a moist surface without an artificial supply of energy opens a wide window of practical applications. In particular, a rich variety of biomedical functions can be performed by the hygrobot on moist human skin (32). Small animals, like maggots and leeches, that are capable of autonomous locomotion have already been used on unhealthy skins and tissues for medical therapy over a long period of time (33, 34). In these applications, microrobots have a great potential to replace the living creatures. We have tested the capability of the hygrobot to inhibit bacteria growth from a model skin without any artificial energy supply for locomotion. A hygrobot with antibiotics [cephalosporin (0.8 g/liter) in 67 weight %

(wt %) aqueous glycerine] coated on its legs was placed on an agar plate (Fig. 5A), an enriched medium to cultivate bacteria. The bacteria (*Staphylococcus aureus*) were inoculated over the entire agar surface. Because of the humidity gradient in the air above the moist agar plate, the hygrobot moved spontaneously to traverse the 9-cm-diameter petri dish in 10 min, leaving a trail of antibiotics that was dyed blue (Fig. 5B). Then, the plate was incubated at 37°C at humidity above 95% and CO<sub>2</sub> concentration of 5% for 24 hours. A sterilized lane formed in the middle, whose width broadened compared with the initial trail of antibiotics due to diffusion, whereas the rest of the area was cultured to confluency (Fig. 5C).

## DISCUSSION

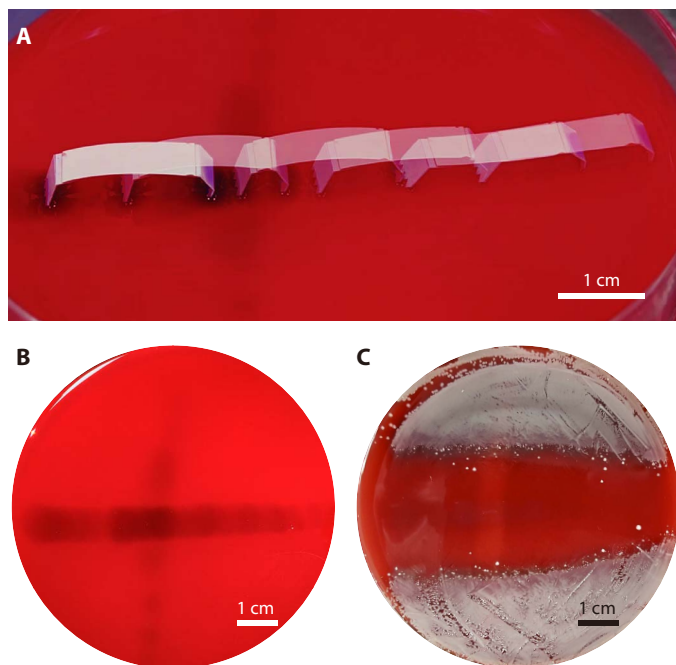
Inspired by the motile awns of some plant seeds with aligned fibrous structure of hygroscopically responsive layer, we have fabricated a bilayer actuator that can bend with great speed and magnitude in response to change in environmental humidity. The oscillatory motion of the actuator with periodic change of humidity has been rectified into directional locomotion by attaching legs with asymmetric friction coefficients. In addition to temporal change of humidity, the spatial gradient of humidity that exists naturally above moist surfaces has been shown to power the hygrobot without requiring any human intervention. We have theoretically modeled the moisture diffusion and consequent swelling and bending of the actuator, which allowed us to predict the speed of the hygrobot and to optimize the actuator design for maximum locomotion speed.

The ability of the hygrobot to propel itself without any artificial energy can be exploited in a variety of applications. Just as with motile seeds, it can actuate military and environmental robots deployed on the ground in response to temporal changes in environmental humidity. On intrinsically moist biological materials, including human skin, it can perform various biomedical treatments while crawling as powered by spatial humidity gradient. By using materials that respond to gases other than water vapor, we may be able to build sensors that produce mechanical responses to the concentration of specific gas molecules.

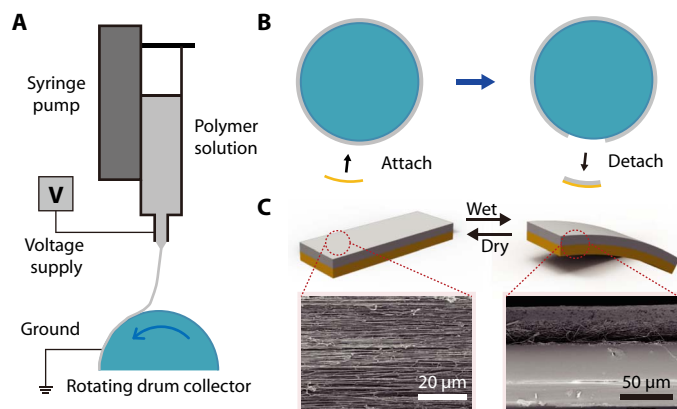
For practical applications, the enhanced speed and magnitude of the mechanical response to humidity change would play a critical role. On the basis of our finding that the directionally deposited nanofibers lead to agile and large-magnitude responses, further development of fabrication processes to print finer nanofibers with sufficient strength is called for. Although we have focused on pure bending actuators to enable linear locomotion by exploiting the spatial humidity gradient formed normal to the moist surface, different modes of mechanical actuation are possible by controlling the fiber alignment angle with respect to the major axis of slender actuators. The simultaneous generation of twisting and bending can lead to various locomotion modes, including rotation, screwing, and tumbling. The actuation system fabricated and mathematically analyzed here serves as a model that senses, responds to, and interacts with microscale environmental conditions while harvesting energy from nature, just as its biological counterparts, motile plant seeds.

## MATERIALS AND METHODS

We used PEO as the hygroscopically active material for its superior hygroexpansivity and biocompatibility. To arrange PEO in thin fibers, we used the electrospinning process, where the 10 wt % aqueous PEO solution was ejected in nanojets from the tip of metal capillary



**Fig. 5. Power-free sterilization of culture plate.** (A) Overlapped images of the hygrobot, with its legs coated with antibiotics, crawling on the agar plate as powered by spatial humidity gradient. (B) Horizontal trail of the antibiotics applied by the hygrobot. (C) Sterilized region after 24-hour incubation coincides with the hygrobot trail.



**Fig. 6. Fabrication of bilayer actuator composed of a hygroscopically active layer with aligned nanofibers and an inactive layer.** (A) Experimental apparatus to directionally electrospin nanofibers of polymer solution. (B) Formation of bilayer structure by detaching the active layer from the collector drum with the adhesive inactive layer. (C) Schematic of the bending deformation of the bilayer and SEM images. Left: Top view of the active layer. Right: Cross-section of the bilayer.

under a strong electrical field, 1.12 kV/mm (35). To circumvent chaotic piling of the electrified nanojets because of the coulombic repulsion, we collected the nanojets on the surface of a metal drum that rotates at the same linear speed as the jet, 3.5 m/s, a process called directional electrospinning (Fig. 6A). The thickness of the deposited layer varies from 1 to 100  $\mu\text{m}$  depending on the jetting duration. The solidified PEO fibers that were aligned along the direction of the drum rotation were detached from the collector surface using a sticky polyimide (PI) tape (Fig. 6B). Because PI is hygroscopically inactive, the bilayer structure consisting of an aligned hygroexpansive fiber layer and an inactive layer was completed. The inactive layer consists of 30- $\mu\text{m}$ -thick PI and 25- $\mu\text{m}$ -thick silicone adhesive of different elastic moduli, which were accounted for in our mechanical model. The fabrication details are given in section S1. Figure 6C shows the scanning electron microscopy (SEM) images of the bilayer, where PEO fibers ( $350 \pm 25$  nm in average diameter) are arranged in a single direction.

## SUPPLEMENTARY MATERIALS

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Section S1. Experimental details of the electrospinning process

Section S2. Various designs of hyrobot

Section S3. Asymmetric friction coefficients of the ratchets

Section S4. Ratchet design to harness spatial gradient of humidity

Section S5. Data of locomotion speed and mass of animals and robots

Fig. S1. Static friction coefficients of ratchets.

Table S1. Locomotion speed and mass data of mammals.

Table S2. Locomotion speed and mass data of non-mammals.

Table S3. Locomotion speed and mass data of walking robots.

Movie S1. Locomotion of a hyrobot under temporal variation of environmental humidity.

Movie S2. Locomotion of various designs of hyrobot.

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## Hygrobot: A self-locomotive ratcheted actuator powered by environmental humidity

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