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Blister-like Soft Nano-textured Thermo-pneumatic Actuator as an Artificial Muscle

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Abstract

Here, model blister-like soft thermo-pneumatic artificial muscles with the embedded nanofibers impregnated with ethanol are developed. The muscles are essentially blister-like thermo-pneumatic soft actuators (BTSAs), which deflect in response to heat supplied to their bottom. The resulting deflections are on the scale of 1 cm, and the BTSAs are operational for several cycles. They are able to raise the artificial rigid scales, spines or fur/thin fibers attached to them emulating such animals as pangolin, hedgehog and porcupine. They are also capable of removing the stickiest adhesive tapes attached to them, and thus hold great promise for biomedical applications where artificially grown skin patches should be removed from an underlying substrate without being damaged. The theory of the BTSA proposed in this work is in reasonable agreement with the acquired experimental data.

TOC

Blister-like soft thermo-pneumatic soft actuator (BTSA) is developed as a bio-inspired device (the artificial muscle deflecting scales, spines and fur fibers). It is also shown that it holds great promise for biomedical applications where artificially grown skin patches should be removed from an underlying substrate without being damaged. The fabrication process of BTSA is fast, simple, and inexpensive.

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Keywords

soft material; nano-textured thermo-pneumatic actuator

1. Introduction

Soft actuators, which are flexible, stretchable, and deformable are of urgent demand.¹ They hold great promise in a new class of engineering machines for mechanical, environmental, and medical applications because of their softness, light weight, and biocompatibility.^{2–4} In contrast to the existing hard actuators based on motor-driven systems with rigid, heavy, and, high-cost features,⁵ soft actuators, which are currently fabricated from electroactive-polymers (EAPs),^{6, 7} responsive-elastomers,^{8–10} or responsive-gels,^{11, 12} are designed to operate being triggered by external stimuli, such as electricity,^{7, 13} heat,¹⁴ humidity,^{15, 16} *etc.*^{17, 18} Numerous researches on such soft actuators have hitherto revealed remarkable achievements, which demonstrate that soft actuators can perform biomimetic smooth movements akin to natural muscles.^{1, 5, 19–21}

In addition to the above physico-chemically-operated soft actuators, pneumatically-operated soft actuators (the so-called McKibben actuators) have also attracted considerable attention since their development in the 1960's. They are based on pump-driven air being injected into embedded channels in an elastomer system (e.g., PDMS, Ecoflex, *etc.*) and inflating it, which results in the system deformation.^{22, 23} In particular, using passive layers in the elastomer system allows such soft actuators to move in the desired one-dimensional or bidirectional motions (like the agonist/antagonist muscle vibration in animals) with the accompanying twisting, rolling, or turning movements.^{5, 20, 24, 25} Compared to the physico-chemical soft actuators, pneumatic soft actuators not only revealed an outstanding moving performance, but also are based on faster, simpler, and less energy-consuming fabrication techniques, which determines continuous proliferation of pneumatic soft actuators into future applications.

Nevertheless, the fundamental principle of pneumatic soft actuator is still challenging because it involves pump-driven air system, which should be connected an external pump, thus contributing to the cost increase, the difficulties in miniaturization and shaping such actuators, which, in turn, limits their operational area. Here, we propose and demonstrate a soft nano-textured thermo-pneumatic actuator with embedded nanofiber (NF) mat. The NF mat is comprised of three-dimensional inter-connected pores between NFs and even in the NFs. We show that a considerable amount of liquid can be imbibed in the NF mats despite of their few-to-tens of micrometers thickness^{26–28}, which forms the key element of the developed thermo-pneumatic muscle. Specifically, we fabricated a thermo-pneumatically operated soft actuator with the liquid-impregnated NF mat asymmetrically-embedded in a silicone elastomer. The external heat induces the evaporation of the liquid, resulting in the directed deformation of the elastomer. Accordingly, we designed a blister-like soft actuator and showed its potential as artificial muscles that can easily trigger standing scales or fur (as animals can do) or remove a model sticky material, as is required in bio-engineering applications (the artificially grown skin patches, or model scotch tapes, *etc.*; cf. Fig. 1). One

of applications of this inexpensive and straightforward actuator is sought in relation to skin-growing (or skin-culturing) for biomedical purposes, where the grown skin should be removed from an underlying substrate without being damaged. Overall, soft biocompatible actuators, can be used either as implants of their own, or during fabrication of skin implants, *etc.* We also explained the theoretical aspects of the operation of such novel soft actuators.

2. Experimental section

2.1. Materials

Polyacrylonitrile (PAN, $M_w = 150$ kDa) and *N,N*-dimethylformamide (DMF, 99.9%) were obtained from Sigma-Aldrich (USA). Ethanol (200 proof) was obtained from Decon Labs (USA). Fluorescein sodium salt from Sigma-Aldrich (USA) was used to dye the ethanol liquid. Platinum-catalyzed silicon Ecoflex 00–30 and 00–35 were purchased from Smooth-On (USA). Note that circular- and square-shaped petri dishes were used to shape Ecoflex into soft actuators. A paper tower for a passive mat was purchased from the local market. A high adhesive tape (8919MSR) to examine the adhesion energy of a sticker which can be removed by the soft actuator was purchased from 3M (USA).

2.2. Electrospinning

To fabricate a large-area electrospun PAN nanofiber (NF) mat,^{26, 27, 29, 30} an 8 wt% PAN solution in DMF was electrospun onto a rotating drum with a fixed flow rate of 0.3 mL/h and a fixed high DC voltage of 7.5 kV, where an 18-gauge needle (Sigma-Aldrich, USA), a syringe pump (New Era Pump System, USA), and a DC voltage supply (Glassman High Voltage, USA) were used for electrospinning. The distance between the needle and the drum-type collector was 10 cm. The deposited NF mat on the drum was detached and then circular patch was cut from it (cf. Fig. 2). Note that the circular shape of the NF mat resulted in the blister-shaped soft actuator (see Fig. 2). This shape is not only practically important but also admits straightforward modeling and comparison between the experimental data and theoretical predictions (cf. Fig. 4 and Table 1).

2.3. Soft actuator

First, a first volume of un-cured Ecoflex 00–30 liquid was poured into a petri dish and then half-cured there, which allowed us to prevent the NF mat from being wetted by liquid Ecoflex 00–30 (the top layer in Fig. 2a). Second, a circular NF mat and a passive mat on top of it were placed onto the half-cured Ecoflex layer (cf. Fig. 2a). Note that the stiff and inflexible passive mat allows a blister of a soft actuator to swell up only in one direction (Fig. 2c). Third, a second volume of un-cured Ecoflex 00–30 liquid was poured above the mats and the first Ecoflex layer, and then, left until it was completely cured (the bottom layer in Figure 2a). Note that the curing process was completed within a few minutes by applying heat treatment using a hot-plate (Thermo Fisher Scientific, USA). Accordingly, the entire fabrication process of the soft actuator was planar (and thus, appropriate for mass production) and could be completed rapidly, within several minutes. Fourth, the yellow-dyed (for visualization purposes) ethanol was injected into the soft actuator (Figures 2a and 2b) by using a 25-gauge needle-equipped syringe. Then, the injection hole was sealed by the fast-curing Ecoflex 00–35.

2.4. Characterization

The morphology and thickness of NF mats were characterized by a field emission scanning electron microscope (FE-SEM, JSM-6320F, JEOL, USA). A fiber-size distribution was obtained by measuring 100 NFs in SEM images. Uniaxial tensile tests determined stretchability and Young's modulus of the cured Ecoflex 00–30 and blister tests determined the adhesion energy of the adhesives used. Tensile and blister tests were conducted using a universal testing machine (Instron 5492, USA) and a dynamic mechanical analyzer (DMA Q800, TA Instruments, USA). For the blister test, a tip of 0.95 mm in diameter, which was driven by Instron 5492, was used to delaminate an Ecoflex layer from the adhesive tape or (in the reverse setting) to delaminate the adhesive tape from the Ecoflex. The tip speed was 2 mm/min and the entire experiments were recorded to observe the delamination. Images and videos were recorded by using a digital camera (D3200, Nikon, Japan). Infra-red (IR) images were obtained by using an IR camera (FLIR T1030sc, USA).

3. Results and discussion

3.1. Material characterization of soft actuator

Prior to the fabrication of a blister-like thermo-pneumatic soft actuator (BTSA; cf. Fig. 2 and **Section 2**), materials involved in it were characterized as shown in Fig. 3. Figs. 3a and 3b show the stress-strain curves of Ecoflex 00–30. Ecoflex samples were stretched above 800% (Fig. 3a). At such large strains Ecoflex 00–30 exhibits a typical hyperelastic behavior.^{31–33} However, as is shown in Section 3.2 the strains of interest do not exceed $\epsilon = 5.48\%$, which still belongs to the range of purely elastic response for such a material. Note that the value of Young's at the temperature of 80 °C ($E = 54$ KPa) is used below for comparison of the theoretical results of Section 3.2 with the experimental data because the heater temperature $T_h = 80$ °C in most of the experiments. The high stretchability of Ecoflex reflected by its low Young's modulus makes this material appropriate for BTSA fabrication. Fig. 3c reveals that polyacrylonitrile (PAN) nanofiber (NF) mat was perfectly wettable with ethanol, with the static contact angle (CA) being almost nil (the bottom photo in Fig. 3c). On the other hand, PAN NF mat was only partially wettable by uncured Ecoflex 00–30, with $CA = 63^\circ$ (the top photo in Fig. 3c), which prevented the PAN NF mat imbibition by Ecoflex 00–30 (cf. Fig. 2a). The perfect wettability of PAN NF mat by ethanol facilitated its fast imbibition with ethanol, i.e. a short fabrication time (cf. Fig. 2 and **Section 2**). It should be emphasized that PAN NF mats possess several additional highly beneficial features to be used in the present soft actuator. Namely, they have porosity in the 90–95% range, can withstand elevated temperatures, possess high structural integrity unavailable with any particulate material such as carbon nanotubes, activated charcoal, etc., and are one of the easiest materials to be electrospun.²⁶

The rate of the wettability-driven imbibition of ethanol into PAN NF mat can be estimated using the Lucas-Washburn equation,^{27, 34–37} which yields the imbibition velocity as $V = \gamma d / (8\mu H)$, where γ is the surface tension, d and H are the characteristic cross-sectional pore size and length, respectively, and μ is the viscosity. The velocity value for the imbibition of ethanol into PAN NF mats of Figs. 3d–3f is $V \sim 1$ m/s. Note that varying the inter-fiber pore size, pore tortuosity and the NF cross-sectional diameter in electrospun NF mats one can

affect the imbibition velocity of ethanol and its evaporation rate inside the BTSA (cf. Fig. 1d).^{26, 38} The overall shape of the NF mat, e.g. a non-circular shape instead of the current circular one, can produce another offshoots of soft robotics, which are currently under development. With the NF mat thickness of 352 μm (cf. Fig. 3f), ethanol impregnates such mats on the scale of milliseconds, which reveals PAN-ethanol pair as an appropriate choice. PAN, Ecoflex and ethanol are low-cost materials, with the latter two being biocompatible. On the other hand, non-biocompatible PAN is fully encased inside BTSA and has no contact with the surrounding media/tissues.

Figs. 3d and 3e show the SEM images of the electrospun PAN NF mats before and after impregnation of the NF mats with the ethanol. No discernible change was observed after the impregnation, thus demonstrating the compatibility of the PAN NFs with ethanol. The thickness of the NF mat was $h_{\text{NF}} = 352 \mu\text{m}$ (Fig. 3f). The average fiber diameter and the inter-fiber pore size in the NF mat were $292 \pm 42 \text{ nm}$ and $0.306 \pm 0.157 \mu\text{m}^2$, respectively (Fig. 3g). Note that the pore size was measured on the SEM images. The ethanol absorption rate into the porous PAN NF mat (α) was measured by dripping ethanol droplets onto the NF mat until full impregnation without overflow. The value of α was 0.04 mL/cm^2 .

3.2. Theoretical model of blister-like thermo-pneumatic soft actuator

The deformed shape of the upper Ecoflex layer of an activated membrane of a BTSA is described by the following membrane equation:³⁹

$$D \nabla^4 \zeta - \nabla \cdot [h \sigma \cdot \nabla \zeta] = p \quad (1)$$

with

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad (2)$$

where ζ and h are the local membrane elevation and the thickness of the top layer of the actuator, respectively (cf. Fig. 1d). In Eq. (1) σ is the stress tensor in the top layer, and p is the pressure differential acting on of the blister-like membrane (cf. Fig. 1d). It should be emphasized that p is the over-pressure generated by the evaporated ethanol inside the blister above the atmospheric pressure surrounding it. Also, E and ν are Young's modulus and Poisson's ratio of the material of the upper membrane of the soft actuator (Ecoflex in the present study). Note that the maximum stain in the membrane is about $\varepsilon = h/(2R)$, where R is the radius of curvature of the neutral surface related to the membrane deflection at the center ζ_0 as $\zeta_0 = R\{1 - \cos[\arcsin(a/R)]\} \approx a^2/R$, and a is the radius of the resulting blister, which corresponds to the radius of the embedded NF mat (cf. Fig. 1d).⁴⁰ Taking for the estimate $h = 1.44 \text{ mm}$ and $a = 11.0 \text{ mm}$, and finding R using the deflection value of $\zeta_0 = 9.21 \text{ mm}$, which yields $R = a^2/\zeta_0 = 13.14 \text{ mm}$, one obtains $\varepsilon = 5.48\%$ (cf. Table 1). The latter value corresponds to the elastic regime according to Figs. 3a and 3b.

It should be emphasized that the first term on the left in Eq. (1) corresponds to a stiff resistance to bending (the bending stiffness), whereas the second one is associated with the resistance due to stretching of the bending membrane. The entire Eq. (1) is nonlinear, and thus an analytical modeling desirable in the present case would be impossible. Therefore, two asymptotical limits are worth of consideration. The first term in Eq. (1) (the stiffness term) is formally dominant in the limit where $hR/a^2 \sim h/\zeta_0 > 1$. Essentially, this is not the case here, as the data in Table 1 show. However, this formal estimate and conclusion do not account for the effect of the boundary conditions, since in the latter case the order of the equation is reduced and thus two boundary conditions (and the corresponding physical information) should be sacrificed. Therefore, in the limit where the second term in Eq. (1) (the stretching term) is dominant, the agreement of the predictions with the experimental data worsens, as is shown in Fig. 4a. This comparison shows that in the present case rather the second term on the left in Eq. (1) can be neglected [in distinction from ref. ⁴¹ where for soft poly-(dimethylsiloxane) (PDMS) with embedded nanofibers (NFs), the second term of the left in Eq. (1) dominated the first one].

Then, Eq. (1) in cylindrical used for an axisymmetric activated membrane takes the following form:

$$D \frac{1}{r} \frac{d}{dr} \left\{ r \frac{d}{dr} \left[\frac{1}{r} \frac{d}{dr} \left(r \frac{d\zeta}{dr} \right) \right] \right\} = p \quad (3)$$

where r is the radial coordinate centered at the activated membrane axis on its bottom.

The solution of Eq. (3) is subjected to the following initial and boundary conditions:

$$\frac{d\zeta}{dr} = 0 \text{ at } r = 0 \quad (4)$$

$$\zeta = 0, \quad \frac{d^2\zeta}{dr^2} + \frac{\nu}{r} \frac{d\zeta}{dr} = 0 \text{ at } r = a \quad (5)$$

Note that Eq. (5) describes the hinged condition at the blister edge.³⁹

The problem(3)–(5) allows has the following solution describing the blister generatrix of the soft actuator:

$$\zeta(r) = \frac{3pa^4(1-\nu^2)}{8Eh^3} \left[\frac{1}{2} \left(\frac{r}{a} \right)^4 - \frac{3+\nu}{1+\nu} \left(\frac{r}{a} \right)^2 + \frac{3+\nu}{1+\nu} - \frac{1}{2} \right] \quad (6)$$

Fig. 5 depicts the predicted blister shape as a function of Poisson's ratio. Note that Poisson's ratio of Ecoflex is $\nu = 0.4999$.⁴² The blister elevation at the center of the soft actuator $\zeta_0 = \zeta(0)$ is found from Eq. (6) as

$$\zeta_0 = \frac{3pa^4(1-\nu^2)}{8Eh^3} \left(\frac{3+\nu}{1+\nu} - \frac{1}{2} \right) \quad (7)$$

The volume V under the activated membrane is found as

$$V = \pi \int_0^{\zeta_0} r^2 |d\zeta| = \pi \int_0^a r^2 \left| \frac{d\zeta}{dr} \right| dr = \frac{\pi pa^6(1-\nu)(7+\nu)}{16Eh^3} \quad (8)$$

In a steady-state BTSA with a blown upper membrane, the temperature should become equal to that of the heater underneath (T_h) for the heat transfer to BTSA vanish (neglecting the insignificant heat removal to the surrounding air, serving essentially as a thermal insulator, and averaging the surface superheat with the bulk temperature field, i.e. considering a lumped thermal model). Then, the evaporation inside such a BTSA would inevitably stop, which should be the case in steady-state with practically no vapor leakage. In steady-state a part of the embedded ethanol will be evaporated, and a part will stay liquid in equilibrium with it, with the further evaporation suppressed by the inevitable pressure growth in a closed space. The vapor over-pressure inside (in bar) will be equal to:^{43, 44}

$$p = 0.001333224 \exp \left(A_* - \frac{B_*}{T_h + C_*} \right) - 1.01325 \quad (9)$$

where the vapor saturation pressure is given in bar by the first term on the right, which is nothing but the Antoine equation with the values of the parameters for ethanol known as $A_* = 18.9919$, $B_* = 3803.98$, and $C_* = -41.68$ and T_h , B_* and C_* being in °K.^{43, 44} The second term on the right in Eq. (9) is the surrounding atmospheric pressure p_{atm} in bar.

Then, using the ideal gas law, one finds from Eqs. (8) and (9) the evaporated mass of ethanol m_{vap} inside a steady-state BTSA

$$m_{\text{vap}} = \frac{\pi p(p + p_{\text{atm}})a^6 M(1-\nu)(7+\nu)}{16Eh^3 RT_h} \quad (10)$$

where the molar mass of ethanol is $M = 46.07 \text{ g mol}^{-1}$, R is the universal gas constant, and $p + p_{\text{atm}}$ in Eq. (10) stands for the total vapor pressure inside BTSA.

3.3. Adhesion energy

The adhesion energy of a model sticker to BTSA is required to evaluate the capability of the latter to remove film stuck to a surface, e.g. artificially grown skin patches from a substrate. The adhesion energy can be measured using blister tests. If a sticker possesses bending stiffness, the adhesion energy of such a sticker to a hard substrate U_{stiff} is found as^{41, 45}

$$U_{\text{stiff}} = \frac{3F^2(1 - \nu_b^2)}{8\pi^2 E_b h_b^3} \quad (11)$$

where F is the force at which a blister appears, h_b is the thickness of the sticker and E_b and ν_b are its Young's modulus and Poisson's ratio.

On the other hand, if a sticker is soft and does not possess the adhesion energy, while resisting mostly by its stretching in the course of bending, the adhesion energy of such a sticker to a soft substrate U_{soft} is found as⁴¹

$$U_{\text{soft}} = \frac{3}{8} \left(\frac{1}{\pi^4 E_b h_b} \right)^{1/3} \left(\frac{F}{a_b} \right)^{4/3} \quad (12)$$

where a_b is the blister radius.

3.4. Performance of soft actuator

In Fig. 4, the experimental and theoretical results are presented, with the parameters listed in Table 1. When the heater temperature T_h was fixed at 80 °C, the elevation of the top layer of the soft actuator ζ_0 decreased from 9.12 to 5.55 mm as the thickness of the top layer h increased from 1.62 to 4.61 mm [(a)–(d) cases in Fig. 4 and in Table 1]. The over-pressure p corresponding to these values of ζ_0 found from Eq. (7) increased from 231 to 2725 Pa, respectively. According to Eq. (9), these values of the over-pressure p correspond to the temperature T_h increasing from 76.4 °C to 77.0 °C, respectively. These values of the temperature are slightly lower than the heater temperature of 80 °C due to the heat losses to the surrounding air as revealed by the experimental result in Fig. 4g.

Note also that the saturated vapor pressure lowering due to the presence of the yellow pigment (fluorescein sodium salt, cf. **Section 2**) in ethanol, can be evaluated using Raoult's law as $p_{\text{sat, with pigment}} = (1 - x_s)p_{\text{sat, without pigment}}$, with x_s being the mole fraction of the pigment. In the present case $x_s \sim 10^{-4}$, and the effect of the presence of the pigment on the first term on the right-hand side in Eq. (9), and thus on the over-pressure p , is negligibly small.

The theoretically predicted blister-like membrane shapes of the activated BTSA is in reasonable agreement with the experimental ones, especially for the thickest membrane (cf. Fig. 4d). The visible discrepancies at the other thicknesses (cf. Figs. 5a–5f) are attributed to the inaccuracy potentially introduced by the assumed hinged boundary condition at Eq. (5),

whereas the actual boundary condition at the membrane edge could differ from it being more relaxed.

The predicted evaporated mass of ethanol m_{vap} [cf. Eq. (10)] range from about 2.8 to 4.1 mg, i.e., can reach about 1–10% of the total ethanol mass in the actuator $m_e \approx 0.118$ g (cf. Table 1). This prediction is substantiated by the experimental observation in Fig. 4h, where a significant amount of the yellow-dyed ethanol still remains in liquid state in the activated steady-state BTSA. It should be emphasized that a further evaporation of ethanol in a fully hermetic BTSA is inevitably stopped due to the Clapeyron effect (an increase of the boiling temperature with the surrounding pressure).

To explore the potential vapor/liquid losses in the current model BTSA, the cyclability experiments were conducted (the sample of the thickness of $h = 1.62$ mm was tested). Fig. 4i shows that the blister height decreased to 80% and 57% after the second and the third cycles, respectively, presumably due to some vapor or even liquid ethanol losses. It should be emphasized that cyclability of soft actuators can be significantly improved (to 10 cycles on the scale of 1 day without visible deterioration) with the top Ecoflex layer thickness being around $h = 2.5$ mm, because its permeability decreases which reduces the ethanol vapor losses. An improved Ecoflex cast could also be helpful. Potentially, cyclability can be improved in future by a refined fabrication process.

To explore the effect of the heater temperature, the cases of $T_h = 90$ °C and 100 °C were studied (respectively, the **e** and **f** cases in Fig. 4 and Table 1). The comparison of the **a** and **e** cases, with the other parameters being practically the same, shows that the value of the maximum deflection in the **e** case ($\zeta_0 = 9.21$ mm) slightly increased compared to that of the **a** case ($\zeta_0 = 9.12$ mm), as T_h increased from $T_h = 80$ °C to 90 °C. The comparison between the **b** and **f** cases, revealed that maximum deflection in the **f** case ($\zeta_0 = 11.13$ mm) was considerably higher than that of the corresponding **b** case ($\zeta_0 = 8.57$ mm), as T_h increased from $T_h = 80$ °C to 100 °C.

3.5. Prototype modules based on soft actuator

Rigid scales, spines or furs (thin fibers) covering animals (e.g., pangolin, hedgehog and porcupine) contribute to the protection of inner skin from the external threats and environmental changes. Such plates, spines or fibers are moved by the inner skin muscle. To illustrate how the blister-like thermo-pneumatic soft actuator (BTSA) can provide such a muscular-like movement, several prototype moduli of the bio-inspired artificial scales, spines and fur fibers were fabricated (see Figs 6a and 6b, cf. Movie S1 and Movie S2). Each scale-, spine- and fur-like module consisted of multi BTSAs or a single donut-shaped BTSA, respectively, with the attached rigid plates and spines/fibers (cf. Figs. 1a and 1b). Figs. 6a and 6b reveal that various structures with different operating conditions can be implemented, which holds great promise as the programmable soft actuators for various engineering applications.

The ability of the BTSA to remove the most adhesive tape 8919MSR (according to 3M Packaging Solution Guide) is illustrated in Fig. 1c and shown in Fig. 6c and Movie S3. To characterize the capabilities of the BTSA in this respect, the adhesion energy of the most

adhesive tape 8919MSR was evaluated using two blister tests [cf. Eqs. (11) and (12)]. The conducted blister test is similar to the one described by the present group in Ref. 41 (cf. **Section 2.4**), except that the double-side tape was used as the second layer between the first layer (steel) and the third layer (Ecoflex or the adhesive tape). Accordingly, a superglue was additionally applied to the double-side tape in order to make the first and the third layers completely fixed. Note also that the top three layers were punched to make holes in the middle, which allowed a tip to directly contact the bottom fourth layer as illustrated in Figs. 7a and 7c. In the first blister test, the stiff adhesive tape (fourth layer) was delaminated from the Ecoflex (third layer, see Fig. 7a). In the second blister test, the soft Ecoflex (fourth layer) was delaminated from the tape (third layer, see Fig. 7c). The adhesion energies evaluated in the first test with the stiff blister [cf. Eq. (11)] and in the second test with the soft blister [cf. Eq. (12)] were of the same order of magnitude, 5.4 and 1.3 J/m², respectively. Both values were evaluated at the moment when the blisters were formed and detached (Figs. 7a and 7c). The results show that the BTSA is capable of removing the stickiest materials, for example, as is required in bio-engineering applications with the artificially grown skin patches.

4. Conclusion

The model blister-like soft thermo-pneumatic artificial muscles, i.e., the blister-like nano-textured thermo-pneumatic soft actuators (BTSA), are capable of deflections of the order of 1 cm for several cycles. The fabrication process introduced in the present study is straightforward and fast (the entire fabrication can be finished within a few minutes). Also, fabrication of very thin soft actuators is possible. When several artificial rigid scales, spines or fur/thin fibers were attached to them, these artificial muscles were capable of raise them as animals do to protect themselves. It was also capable of removing the stickiest adhesive tapes attached to it (with the measured adhesive energy in the 5.4 and 1.3 J/m² range), as is required in biomedical applications where artificially grown skin patches should be removed without being damaged from an underlying substrate. It is also shown theoretically that the thermo-pneumatic soft actuators are adequately described by the theory membrane theory pushed by the saturated vapor corresponding to the Antoine equation and described by the ideal gas equation. It is shown that up to 1–10% of the imbibed ethanol evaporates and deflects the actuator membrane, whereas 90% stays liquid, since the boiling point moves up at the increased pressure due to the Clapeyron effect.

The size of the actuator in the present study was $2.5 \times 2.5 \text{ cm}^2$. This size was determined by the petri dish size that was used as a mold. Since the size of both the NF mat and the mold can be reduced to a few millimeter scale, we believe that a few-millimeter-scale actuator could be fabricated. Also, the existing microfabrication methods could reduce the size even further.

The present soft actuator does not require external pumping system, as pneumatic soft actuators do, but it still requires an external heater. It should be emphasized that in many cases heaters are more reliable than pneumatic systems. Also, one can imagine operation of the present soft actuator driven by the surrounding conditions, for example, by the difference between the day and night temperature.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1. Potential applications and working mechanism of the blister-like thermos-pneumatic soft actuator (BTSA). Bio-inspired artificial pangolin-like scales (a), animal fur (b). Removing of adhesives (c) Schematic of the working mechanism of the BTSA (d), where p denotes the pressure differential, i.e., the over-pressure inside the blister.

Fig. 2.

Structure of the BTSA. (a) Schematic of the fabrication process of the BTSA. Each inset is the cross-sectional view at the corresponding fabrication step. (b) Images of the as-fabricated samples before and after ethanol injection; ethanol is colored by yellow dye. (c) The soft actuator before and after heating.

Fig. 3.

Material characterization of the BTSA. **(a)** Stress-strain curves of Ecoflex 00-30 in different trials (repeatability), where the strain rate was 25%/min and **(b)** at different temperatures, where the strain rate was 12%/min. **(c)** Images illustrating wettability of PAN NF mats by Ecoflex 00-30 (top) and ethanol (bottom). The blue lines were used to measure the contact angle values. Top-view SEM images of PAN NF mats: **(d)** before and **(e)** after contact with ethanol. **(f)** SEM image of PAN NF mat before contact with ethanol. **(g)** Fiber-size distribution in PAN NF mats.

Fig. 4.

Performance of the BTSA. (a)–(f) Comparison of the experimental and theoretically predicted BTSA shapes (red lines) of the BTSA for different thicknesses of the top layer h and the heater surface temperature T_h . Note that all the red lines correspond to the stiffness dominated limit of Eq. (1), whereas the blue line in panel (a) corresponds to the stretching-dominant one. Scales in are in millimeters. The values of the parameters are listed in Table 1. The theoretically predicted red lines were plotted using Eq. (6). (g) IR image and (h) a photographic image of the BTSA in steady-state with heat supply. (i) Cycling test and the corresponding photographic images in the case of the top Ecoflex layer thickness being $h = 1.62$ mm. The data presented in red correspond to the results obtained at 80°C in any of the cycles; the data presented in blue correspond to the results obtained after cooling to 25°C in-between the cycles.

Fig. 5.
Blister shape predicted using Equation (6) for Poisson's ratio ν in the 0.1 to 0.4999 range.

Fig. 6. Prototype modules based on the BTSA. (a) Bio-inspired artificial scales and (b) spines/furs. (c) Removing a sticker tape.

Fig. 7. Two blister tests used to measure the adhesion energy. (a) and (c) Photographic images; (b) and (d) the corresponding load-extension dependences. Panels (a) and (b) illustrate the case with the stiff blister; panels (c) and (d) illustrate the case with the soft blister.

Table 1.

Experimental and theoretical results for different soft actuators.

Case in Fig. 4	Experimental value					Theoretical value		
	h (mm)	a (mm)	m_e (g)	T_h (°C)	ζ_0 (mm)	P [Pa, cf. Eq. (7)]	T_h [°C, cf. Eq. (9)]	m_{vap} [mg, cf. Eq. (10)]
A	1.62	11.5	0.118	80	9.12	231	76.39	2.78
B	2.40	12.5			8.57	514	76.46	3.07
C	3.24	12.1			8.23	1366	76.66	2.81
D	4.61	12.0			5.55	2725	76.99	1.89
E	1.44	11.0		90	9.21	200	76.38	2.56
F	2.71	12.5		100	11.13	936	76.56	4.05