Thermoresponsive Wrinkles on Hydrogels for Soft Actuators

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Soft microactuators with stimuli-responsive tunable chemistries are highly demanded in complex multifunctional and biocompatible microdevice platforms including microelectromechanical systems and lab-on-a-chip. Developing multifunctional hydrogel actuators is especially of significance for the nano/micro artificial anatomies, which perform functions such as transportation, selection, recognition, and others. Here we demonstrate adaptive surface wrinkles, which exhibit a peristaltic motion and a size selective transportation of micro-objects on bilayered soft materials under thermal stimulus. The bilayered materials made of thermoresponsive poly(N-iso-propylacrylamide) (PNIPAM) and hybrid silica form responsive wrinkles of submillimeter dimensions with temperature variation. This hydrogel-based actuation works at a quasi-physiological environment, which meets the critical requirement for artificial alternatives in bioapplications. Rational design of autonomous actuators is possible through the present strategy because the formation of microarchitectures is driven through a versatile physical process, buckling.

Complex multifunctional microdevice platforms are required for several areas of engineering and sciences, for example to provide biological insights into cells and tissues. Soft microactuators that drive and regulate micropumps and microvalves are crucial components for achieving these advanced platforms. Thin-film piezoelectric actuators promise reliable operation and high throughput, however complex motions and flexible deformations, observed in natural systems, are hard to achieve. For example, aortic valves, one of the most frequently diseased tissues, are repaired by transplanting a synthetic mechanical device or an allograft tissue alternative. These artificial ones are far from the original organs whose specialized motions are achieved by flexible hierarchically structured tissues with complex architectures. On the other hand, hydrogel-based soft actuators are promising due to the large extent to which they can be deformed in aqueous media, thereby conforming to an architecture that mimics natural systems. Large complex 3D architectures can be fabricated with ease, if spontaneous chemical reactions are involved in their fabrication method. Moreover, 3D inkjet printing is reportedly applicable to the production of these polymer-based actuation systems.

We here demonstrate adaptive microarchitectures that exhibit a special peristaltic motion by employing hydrogel actuation on bilayered materials. The surface architectures were designed by mimicking wrinkles in nature. The organ, skin, is a good example of wrinkles with an adaptive response, where wrinkles appear and disappear depending on the movement of the muscles underneath. Here, greatly simplifying, these surface wrinkles form on a bilayered material of a crust top layer (skin) and an elastic bottom layer (muscles). As the bottom layer contracts (or the top layer swells), stress-driven instabilities are generated at the interface of the layers. The accumulated stress is then released through the formation of wrinkles on the crust layer. Such stimuli-responsive wrinkles were reported on artificial bilayered materials prepared from elastomers or resins. Nevertheless, artificial wrinkles, which exhibit large deformations and undergo reversible adaptive response in liquids, are still challenging and are highly required to exploit applications in biological systems. In the present study, we designed and fabricated a bilayered structure made of PNIPAM and hybrid silica (Figure 1a). 3-(Methacryloxy)propyl triethoxysilane was used as a silica source to allow copolymerization with NIPAM and a crosslinker (N,N′-methylenebis(acrylamide), MBA) at the interface of the heterogeneous two layers. The thickness of the hybrid silica layer was tuned from 680 nm to 1.5 µm by using Pluronic F127 as a viscosity improver. This approach allows the strong adhesion at the interface and, most importantly, the complex actuation in liquid phase. PNIPAM undergoes shape change at the lower critical solution temperature (LCST), and thereby wrinkles of submillimeter dimensions appear and disappear as a function of the changing environmental temperature. Significantly large deformations (>40%), due to the flexibility of NIPAM hydrogel, could be attained to achieve biomimicking microstructures,
such as folding (different from creasing that takes place on soft materials without hard skins[8]) and nested wrinkling structures (Figure 1a). Anisotropic ordering of the responsive wrinkles (Figure 1b) is possible by applying a simple patterning process to the hybrid silica coating. Figure 1c and Video S1 (Supporting Information) show nested wrinkles, aligned wrinkles of the periodicity of 350 µm, and dimple-shaped wrinkles of ≈50 µm size, fabricated on a patterned hybrid silica crust layer. The aligned wrinkles were found to show a peristaltic motion on cooling. The motion can be observed transiently on cooling from 36 °C to room temperature. On the other hand, the dimple-shaped wrinkles stay at their original position. In order to assess the capability of the hierarchical wrinkled structure in transporting micro-objects with a size-dependent selectivity, we have deposited microparticles of different sizes onto that structure. The aligned wrinkles convey the microparticle whose dimension is comparable to the periodicity of the wrinkles (red particle in Figure 1c), whereas the smaller particle (yellow particle in Figure 1c) stays at its original position. In short, the wrinkle recognizes and selects particles by size and transfers them from one place to another. The present approach, in principle, can provide stimuli-responsive architectures covering a wide range of sizes, over five orders of magnitude in length scales, and spanning from a few nanometers to a few millimeters.[9] The size diversity and the solution-/environment-mediated responsiveness will open up versatile nano/micro hydrogel actuation at physiological conditions.

The hybrid silica/PNIPAM bilayered hydrogel was prepared via a solution process (Supporting Information Scheme S1). The surface crust layer is composed of a hybrid silica containing polymerizable methacrylate groups. The soft bottom layer is PNIPAM gel network crosslinked with MBA. The bilayered material was found to form various 3D corrugated architectures on its surface depending on the external temperature. Figure 2a shows the typical surface morphologies of the bilayered hydrogels at three different temperatures. The hydrogel surface is flat at 34 °C. Upon cooling to ambient temperature, the surface becomes corrugated at 28 °C (periodic length, λ = 207 µm, amplitude of wrinkle, A = 133 µm), and then folded at 20 °C (λ = 253 µm, A = 159 µm). Cross-sectional observation also confirms the formation of both wrinkling and folding structures (Supporting Information Figure S1). The transition among these structures occurs reversibly and rapidly on a time scale of seconds to minutes. The responsive wrinkles capture particles on folding (see Supporting Information Figure S2) and release them on unfolding. The result demonstrated here is the first example of taking advantage of a reversible wrinkling-to-folding transition, different from the irreversible transition reported on a bilayered photocurable resin.[10] The present adaptive and foldable material has higher throughput of capturing target objects than conventional self-folding capsules,[11] as a result of numerous folds that are able to capture a great number of properly sized objects at one time. This property has also been confirmed by performing X-ray micro-computed tomography of the sample (Supporting Information Video S2).

The thermal response of the hybrid silica layer (crust) and the PNIPAM gel layer (bottom) was separately examined to elucidate the mechanism of wrinkling and folding. Figure 2b shows...
Figure 2. Formation mechanism of surface microstructures. a) Optical microscope images of surface microstructures at different temperatures: no visible wrinkles at 34 °C; microwrinkles at 28 °C; folded structure at 20 °C. Inset illustrations depict cross-sectional surface morphologies. λ: periodicity of wrinkle (folding); A: amplitude of wrinkle. b) Degree of swelling versus time upon cooling at 20 °C. Samples, which had been kept at 36 °C, were immersed in water of 20 °C and observed, independently. A dimension at t min (Rt) is normalized by initial dimension (R0). c) Illustration showing the mechanism of wrinkle formation. Preferential swelling of surface hybrid layer induces stress accumulation at the interface of layers. Wrinkles spontaneously form on the surface to release the accumulated stress.

degree of swelling of the two layers on cooling at 20 °C. The thermal response of the hybrid silica layer is explained by the presence of PNIPAM copolymerized with methacrylate groups in the silica networks.\(^1\)\(^2\) The copolymerization of PNIPAM with the crust hybrid silica layer was evidenced by Fourier Transform Infrared Spectroscopy (FTIR) analysis and the NIPAM concentration in the hybrid silica layer was estimated as 60 mol% (Supporting Information Figure S3). By cooling the film below the LCST of PNIPAM in water (32 °C),\(^7\) hydrogen bonding between the copolymer and water is strengthened, and water is absorbed into the polymer matrix, resulting in swelling of the copolymer hydrogel. Although the bottom PNIPAM layer can also swell on cooling, the swelling was found to be smaller and slower compared to that of crust hybrid silica layer. The hybrid silica showed 44% of swelling in 0.5 min, whereas the PNIPAM gel layer exhibited 14% of swelling in 180 s. The time constants of swelling are 8.6 s and 4.5 × 10^2 s for hybrid silica and PNIPAM gel layers, respectively. The thermal responses of the two layers were further assessed by the setup shown in Supporting Information Figure S4. A film clamped and submerged in water showed curling in response to the temperature variation. The curling behavior confirms that the crust hybrid silica layer shows the larger and faster deformation compared to PNIPAM layer; on heating, the hybrid silica layer rapidly shrinks in a few minutes, whereas PNIPAM gel slowly shrinks in more than 1 h. The hybrid silica layer of 1.3 μm (coating at 1000 rpm) is thin enough to rapidly include water into (or exclude water from) the polymer matrix, which allows the faster deformation on cooling (or heating) compared to the bulk PNIPAM gel layer. The formation mechanism of wrinkling and folding is illustrated in Figure 2c. During cooling, the predominant swelling of crust hybrid silica layer accumulates stress in the out-of-plane direction of the film, thus inducing a stress release by wrinkling and folding on the surface.

The periodic length of wrinkles, \(\lambda\), becomes large with the thickness of the crust layer, \(t\), as shown in Figure 3a. The relationship between \(\lambda\) and \(t\) follows the scaling law reported by Cerda et al., \(\lambda \propto t(E_1/E_2)^{1/3}\), where \(E_1\) and \(E_2\) are Young’s moduli of crust and substrate layers, respectively.\(^3\)\(^4\) The increment of \(\lambda\) as a function of \(t\) gives a \((E_1/E_2)^{1/3}\) of 1.7 × 10^2 which is in good agreement with the estimated value \((E_1/E_2)^{1/3}\approx10^2\) using reported Young’s moduli for hybrid silicas\(^1\)\(^4\) and PNIPAM,\(^1\)\(^5\) where \(E_1\) and \(E_2\) are in GPa and kPa orders, respectively. The theoretical description indicates that \(\lambda\) can be controlled by changing \(t\) over diverse size range. The ratio of NIPAM/MBA also influences the resultant wrinkle structures. PNIPAM was polymerized at NIPAM/MBA = 1000/3 to achieve a highly deformable hydrogel network. At NIPAM/MBA = 1000/3, a nested wrinkle structure which has hierarchical wrinkles in discrete size scales forms on cooling. Figure 3b shows optical microscope images showing structure evolution on cooling. Typical isotropic wrinkles form in 3 min. Additional structures of smaller wrinkles and folding start to form at 5 min. Importantly, these hierarchical structures reversibly appear/disappear as temperature changes in minutes scale. The present nested wrinkles are suitable as storages/separators of colloidal particles of discrete size due to their adaptive response in solvents.\(^1\)\(^6\) The shape of wrinkles was reported to depend on over-stress, a physical parameter at the interfaces on buckling.\(^7\)\(^8\) Accordingly, the wrinkles of a labyrinth shape (1000 rpm of Figure 3a), a ridge shape (3000 rpm of Figure 3a), and a nested shape (Figure 3b) were observed in the present case. The shape diversity of wrinkles is definitely important for controlling some properties of the surface, such as friction and wettability.\(^1\)\(^9\) In summary, the periodicity and the shape of the wrinkles are controllable by tuning the coating condition and the NIPAM/MBA ratio.

The adaptive stimuli-responsive wrinkles appeared on cooling, disappeared on heating, and exactly restored on
subsequent cooling (Supporting Information Figure S5). Such shape-memory effect is a characteristic of surface wrinkles on bilayered films. On the other hand, very interestingly, we have found that the present materials are also capable of “sliding” wrinkles and driving the peristaltic motion as shown in Figure 1c. The peristaltic motion was achieved on a patterned hybrid silica layer (triangle-shaped patterning) placed on the top of PNIPAM (Figure 3c(1)). Oriented anisotropic wrinkles form on cooling (Figure 3c(2)), because the patterning can induce anisotropic stress accumulation. Stress relaxation takes place in the $x$-direction, and the stress is uniaxially accumulated in the $y$-direction to form anisotropic parallel wrinkles. On the other hand, continuous large swelling of crust hybrid silica exceeds the critical expansion of the $x$-direction. The stress which is accumulated in the $x$-direction is released by forming 2D wrinkles (green part of Figure 3c(3)). Another domain of hybrid silica (red part of Figure 3c(3)) keeps the anisotropic geometry of wrinkles, whereas wrinkles move to $-y$ direction in the course of stabilization of the accumulated stress (Supporting Information Video S1). The motion size-selectively conveys the particle whose size is comparable with the periodicity of the wrinkles (Figure 1c). The speed of the peristaltic motion was $5 \mu m \cdot s^{-1}$ at the cooling rate of $1.8 ^\circ C \cdot min^{-1}$. The occurrence of the peristaltic motion and the direction of the propagated wave (anisotropic wrinkles) are simply controlled by the shape of the applied pattern. This leads to the conclusion that by designing bilayered architectures and employing the properties of the PNIPAM-based hydrogel it is possible to successfully generate unique peristaltic motion of the wrinkled surfaces.

In summary, by manipulating the stress accumulation at the interfaces of bilayered materials that deform at different stimuli-responsive rates, hydrogel-based actuation with complex architectures featuring specific motion capabilities is achieved. In particular, various wrinkling and folding architectures can be reversibly controlled by mimicking biological systems. The simple patterning of hybrid silica gives rise to motion of the microarchitecture on changing the external temperature. This hydrogel-based actuation works at a near-physiological environment, thus meeting the critical requirement for artificial alternatives in bioapplications. Moreover, the working temperature
Experimental Section

Sample Synthesis: N-iso-propylacrylamide (NIPAM: 98%), MBA (97%), N, N, N′, N′-tetramethyl ethylenediamine (TEMED: 98%), ethanol (EtOH: 99.5%), tetraethylorthosilicate (TEOS: 95%), hydrochloric acid (HCl: 36 wt% in water), ammonium persulfate (APS: 98%), Pluronic F127 (F127: Mw = 12 000), and 3-(methacyloyloxy)propyl trimethoxysilane (MPTES) were used as received. The synthesis procedure of hybrid composites is summarized in Supporting Information Scheme S1. Briefly, a mixture of TEOS, MPTES, ETOH, F127, HCl, and H2O was stirred for 1 h at room temperature. The mixture was spin-coated on a precleaned Cu foil (30 µm thick, #CU-113243, Nilaco Corp.) with a spinning rate of 1000 rpm for 30 s. The film was dried in an ambient atmosphere for 15 min. Then, the film was placed in a container into which a mixture of NIPAM, MBA, TEMED, APS, and H2O was poured, placed in N2 atmosphere for 3 h at a temperature of 10–15 °C. Polymerization took place and bulk gel formed in the container. A hybrid gel with a bilayer structure (silica surface layer and PNIPAM bottom layer) was obtained by taking out the gel from the container and exfoliating the Cu foil.

Characterization: A laser scanning confocal microscope (SFT-3500, Shimadzu Corp.) was used to evaluate thickness of the films. Optical microscopes (BX51, OLYMPUS Corp. and 2.4 GHz wireless digital microscope, 3R SYSTEMS Corp.) were employed to observe surface wrinkled structures. Periodic length was estimated by optical microscope images. More than ten locations on each sample were measured and averaged.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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[1] C. L. van Oosten, C. W. M. Bastiaansen, D. J. Broer, Nat. Mater. 2009, 8, 677.
[2] J. El-Ali, P. K. Sorger, K. F. Jensen, Nature 2006, 442, 403.
[3] a) N. T. Nguyen, X. Y. Huang, T. K. Chuan, J. Fluids Eng. Trans. ASME 2002, 124, 384; b) B. D. Iverson, S. V. Carrimella, Microfluid Nanofluid 2008, 5, 145.
[4] F. J. Schoen, R. J. Levy, J. Biomed. Mater. Res. 1999, 47, 439.
[5] a) D. T. Eddington, D. J. Beebe, Adv. Drug Delivery Rev. 2004, 56, 199; b) A. Siderenko, T. Krupenkin, A. Taylor, P. Fratzi, J. Aizenberg, Science 2007, 315, 487.
[6] a) H. S. Kim, A. J. Crosby, Adv. Mater. 2011, 23, 4188; b) M. Takahashi, M. Inoue, R. Ihara, T. Yoko, T. Nemoto, S. Isoda, L. Malfatti, S. Costacurta, P. Innocenzi, Adv. Mater. 2010, 22, 3303; c) A. Agrawal, P. Luchette, P. Palffy-Muhoray, S. L. Biswal, W. G. Chapman, R. Verduzco, Soft Matter 2012, 8, 7138.
[7] H. Ringsdor, J. Venzmer, F. M. Winnik, Macromolecules 1991, 24, 1678.
[8] B. Li, Y. P. Cao, X. Q. Feng, H. J. Gao, Soft Matter 2012, 8, 5728.
[9] K. Efimenko, M. Rackaitis, E. Manias, A. Vaziri, L. Mahadevan, J. Genzer, Nat. Mater. 2005, 4, 293.
[10] P. Kim, M. Abbkarian, H. A. Stone, Nat. Mater. 2011, 10, 952.
[11] G. Stoychev, N. Purotiski, L. Ionov, Soft Matter 2011, 7, 3277.
[12] J. H. Park, Y. H. Lee, S. G. Oh, Macromol. Chem. Phys. 2007, 208, 2419.
[13] a) E. Cerda, K. Ravi-Chandar, L. Mahadevan, Nature 2002, 419, 579; b) E. Cerda, L. Mahadevan, Phys. Rev. Lett. 2003, 90, 074302.
[14] a) T. Takimura, N. Hata, S. Takada, T. Yshino, Jpn. J. Appl. Phys. 2008, 47, 5400; b) W. D. Wang, D. Grozea, A. Kim, D. D. Perovic, G. A. Ozin, Adv. Mater. 2010, 22, 99.
[15] a) P. A. L. Fernandes, S. Schmidt, M. Zeiser, A. Fery, T. Hellweg, Soft Matter 2010, 6, 3455; b) T. R. Matzelle, G. A. Ozin, Adv. Drug Delivery Rev. 2003, 36, 2926.
[16] Y. Tokudome, K. Suzuki, T. Kitanaga, M. Takahashi, Sci. Rep. 2012, 2, 683.
[17] S. Cai, D. Breid, A. J. Crosby, Z. Suo, J. W. Hutchinson, J. Mech. Phys. Solids 2011, 59, 1094.
[18] J. Y. Chung, A. J. Nolte, C. M. Stafford, Adv. Mater. 2011, 23, 349.
[19] N. Bowden, S. Brittain, A. G. Evans, J. W. Hutchinson, G. M. Whitesides, Nature 1998, 393, 146.
[20] M. M. Teymoori, E. Abbaspour-Sani, Sens. Actuators A: Phys. 2005, 117, 222.
[21] A. Terray, J. Oakley, D. W. M. Marr, Science 2002, 296, 1841.