Encoding Smart Microjoints for Microcrawlers with Enhanced Locomotion

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1. Introduction

Microrobots have potential applications in many realms, e.g., biomedical, industrial, and environmental fields, due to their small scale, high flexibility, and excellent environmental adaptability.[1–4] Similar to traditional motor-driven robots at the macroscale, the microrobots normally require joints as significant components to realize precise operability and efficient mobility. However, there still are a few technical obstacles to fabricating microrobots in practice, let alone microjoints, as it is quite challenging to integrate such sophisticated machinery and control systems into a miniature robot, especially when their feature scale reaches micrometer or even smaller. The combination of smart materials, ingenious structural designs, and precise actuation strategies offers a potential solution to manufacturing fast, agile, and controllable microrobots and their joints for operability and mobility.[2,4,7]

Material is crucial for the design of microrobots, which regulates their mechanical properties and further determines their functions. Smart materials, which can sense and react to external stimuli, such as temperature,[8–11] pH,[12,13] light,[14–18] humidity,[19–22] magnetism,[23–26] and electric fields,[27,28] are indispensable for fabricating untethered soft microrobots. However, almost all stimuli–response materials reported exclusively exhibit a monotonic dependence of swelling deformation with some specific stimulus. For example, a homogeneous block made from pH- or thermal-sensitive gels either swells or shrinks once some external stimulus is imposed on it.[8,13] The monotonic deformation response of the material itself limits the development of soft microrobots with more complicated functions. Meanwhile, structural design is another significant component for microrobots. In the macroscale, structural considerations have already opened a new perspective on designing soft robotics.[29–31]

Based on asymmetric structure arrangements or partial stimuli response, soft actuators have been fabricated to achieve directional migration by sequentially controlling the contact between their bottom and the underlying substrates.[10,19,29,32,33] Moreover, inspired by the concept of self-folding origami, researchers have proposed actuators/robots capable of achieving controllable functions with multiple degrees of freedom.[6,31,34,35] However, it is hard to apply the concepts to fabricate robots at small scales. At millimeter or smaller scales, by prefabricating zigzag substrates, soft walkers have been developed that are capable of realizing successive locomotion with the aid of some external stimulus source,[14,36] while it is difficult to achieve programmable locomotion. Furthermore, the effective precise actuation of each part for specific functions is still an arduous challenge for robots at very minute scales, whereas few researches investigate this aspect.

Using direct laser writing (DLW),[37,38] we demonstrate that the bilayer-based microbeam made of pH-response smart materials can trigger a size-dependent layer-by-layer sequential swelling effect that induces nonmonotonic bending deformations.

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during the swelling process. This inspired us to fabricate 4D-printed microcrawlers with controllable microjoint structures capable of spontaneous deformations in response to ambient pH stimulation. Likewise, we found that structural designs aided by finite-element analysis (FEA) based on a hyperelastic constitutive model can be adopted to implement gait analyses for microcrawlers with smart microjoints (SMJs) in response to spatiotemporal changes in the surrounding pH. This provides an effective means to optimize geometric configurations and fabrication conditions for enhanced locomotion. We further show that the motion of microcrawlers is controllable. We can encode the SMJs by presetting the number and spatial distribution of SMJs on the microcrawlers, as well as their geometric configurations for encodable locomotion ability. This enables microcrawlers to achieve superior migration speed (0.15 body length s⁻¹) and efficiency (1.1 body length per step), as well as controllable locomotion, e.g., migration along/against the stimuli source or along a preplanned path. Our work offers a new strategy for across-scale structural designs, functional assembly, and optimizations of soft microbots with high flexibility and excellent environmental adaptability.

2. Results
2.1. Mechanism of Sequentially pH-Triggered Swelling Microbeam Units

To fabricate the SMJs, we first used pH-responsive gels (as described in Section 4) to fabricate microbeam units utilizing 4D DLW, as shown in Figure 1a. The 3D microbeam units (100 μm × 10 μm × 10 μm in size) were printed by spatially...
polymerizing the gel precursors to form nanoscale crosslink networks, using a pulsed two-photon femtosecond fiber laser with an emission wavelength of 780 nm and a 63× oil-immersion objective. During the printing process, the local crosslink density of the gels could be finely adjusted by presetting different curing parameters, e.g., the laser power (LP) and scan speed (SS). In this way, we fabricated the bilayer beams (BLBs) using two different LPs (22.5 mW for the loose layer with a relatively low crosslink density, and 40.0 mW for the dense layer with a relatively high crosslink density) along the direction of thickness with a thickness ratio of 2:1 between the loose layer and dense layer. For comparison, we also printed the corresponding monolayer beams (MLBs) with LP of 35.0 mW over the whole microstructures. The SS was fixed at 5 mm s⁻¹ for all these microbeams. After polymerization, the remaining gel precursors were completely removed by soaking them in isopropanol (IPA) for 30 min. Before the experiments, these microbeams were immersed in an acidic solution (pH ≈ 4.5) for complete shrinking. Afterward, a certain amount of alkaline solution was slowly injected to neutralize the solution and eventually increase the environmental pH to ≈ 10. Accordingly, both MLBs and BLBs underwent significant swelling in response to the increase in environmental pH. It appears that there was no bending deformation for MLBs during swelling, whereas there was a time-related bending deformation for BLBs whose bending curvatures initially and rapidly increased and subsequently decreased to zero with time, as shown in Figure 1b. This revealed a nonmonotonous time-dependent response of BLBs to environmental pH stimulation (Movie S1, Supporting Information). Furthermore, we found that the response was essentially reversible after adding the acidic solution.

We describe the nonmonotonous response of BLBs to variation from acid to alkali by dividing the time-related periodic bending deformation into three successive phases, namely, the 1) initial phase, 2) intermediate phase, and 3) final phase, as shown in Figure 1c. The initial phase corresponds to when the BLBs are immersed in an acidic solution and their subsequent bending deformation caused by the interface mismatch from the differences in shrinkage capabilities and mechanical properties between the loose and dense layers. The intermediate phase describes the stage where BLBs reach their maximum bending deformations with increasing environmental pH. The final phase characterizes the process during which the bending curvatures of BLBs are reduced to approximately zero with a further increase in pH to ≈ 10. Figure 1d schematically shows the gel networks with low and high crosslink densities, in which the degree of the dissociation of the carboxyl groups fixed on polymer chains is directly associated with the pH of the external solution. The higher the ambient pH, the greater the degree of carboxyl dissociation involved. This implies that the acidic environment inhibits carboxyl dissociation, whereas the alkaline condition promotes it. Once these carboxyl groups in the gel networks are dissociated, the cations in the solution, e.g., Na⁺, will quickly aggregate to the vicinity of the dissociated carboxyl groups to maintain the local electrical neutrality, which inevitably induces an increase in local cation concentration inside the gel network and further results in an osmotic pressure difference.

\[ \Pi = RT(c_+^e - c_+^g) \]  

where \( R \) and \( T \) are the ideal gas constant and absolute temperature, respectively, and \( c_+^g \) and \( c_+^e \) denote the local concentrations of cations in the gel and the external solution, respectively. Generally, \( c_+^g > c_+^e \) leads to a directional migration of water molecules from the external solution to the gel networks, causing the gel to swell. Our experiments further reveal that the critical pH that initially triggers gel swelling is closely related to the extent of the polymerization of the gel network. Figure 1e shows that the critical pH is ≈ 5.3 for the densely crosslinked gel networks and ≈ 5.9 for loose ones. The underlying reason for this is that there are significantly more available carboxyl groups in the dense networks than in the loose networks. Thus, dense networks are capable of recruiting considerably more cations, triggering gel swelling before this happens in loose networks. This implies that it is essentially feasible to develop microstructures with a sequential pH-triggered response by spatiotemporally tuning the crosslinked densities involved in the process of 4D DLW fabrication.

Taking the aforementioned BLB as an example, we here dissect its dynamic response to variations in pH. The swelling kinetics of a specified BLB can be characterized by the following well-adopted logistic sigmoidal equation:

\[ \lambda(t) = \frac{l(t)}{l_0} = \lambda_\infty + \frac{\lambda_0 - \lambda_\infty}{1 + \left(t/t_0\right)^q} \]  

where \( \lambda(t) \) is the stretch ratio at an arbitrary time \( t \); \( l_0 \) and \( l(t) \) denote the nominal length of BLB we predesigned before 4D printing and its length at time \( t \), respectively. Further, \( \lambda_0 \) and \( \lambda_\infty \) are the stretch ratios corresponding to sufficient shrinkage and swelling in the acidic and alkaline solutions, respectively; \( q \) and \( t_0 \) denote the swelling index and the characteristic time, respectively. We can quantify the bending deformations of BLBs driven by ambient pH using Timoshenko’s beam theory. The balance of general forces and moments requires \( P_1 + P_2 = 0 \) and \( Q_1 + Q_2 + P_1 a_1/2 + P_2 (a_1 + a_2/2) = 0 \), respectively, where \( P_1 \) and \( P_2 \) denote the tensile forces acting on the loose layer and the dense one, respectively, \( Q_1 \) and \( Q_2 \) represent the corresponding bending moments, \( a_1 \) and \( a_2 \) denote the thickness of the two layers, and \( E_1 I_1/\rho(1/2) \) with \( E_1, I_1 = a_1^4/12 \) and \( \rho = 1/\kappa \), representing the elastic moduli (Figure S1a, Supporting Information) and moments of inertia and the curvatures, respectively. Furthermore, we take into account the interlayer strain coordination condition, yielding \( \varepsilon_1 + P_1/E_1 a_1 + a_1/2p = \varepsilon_2 + P_2/E_2 a_2 - a_2/2p \) with \( \varepsilon_1(t) = \lambda(t) - 1 \). In this context, the curvature of a specific BLB may be expressed as

\[ \kappa = \frac{1}{h} \times \frac{6(e_2 - e_1)(1 + m)^2}{3(1 + m)^2 + (1 + mm_e)(m^2 + 1/mm_e)} \]  

where \( h \) denotes the total height of the BLB, \( m = a_1/a_2 \), and \( m_e = E_1/E_2 \). All parameters in Equation (3) are functions of time \( t \). Figure 1f shows the theoretical curve of the bending curvature of BLB versus time \( t \), which is in quantitative agreement with the corresponding experimental results (see also Figure S4, Supporting Information).
Furthermore, we found that there is a specific pH-response range for MLBs, as shown in Figure 2a. Our experimental results indicate that the critical pH that triggers gel swelling in acid has a slightly decreasing trend from approximately 6.0 to 5.0 when the LP of DLW is enhanced from 20 to 37.5 mW, after which it remains approximately stable. By contrast, the pH required for sufficient swelling in alkali is always approximately 9.0, indicating that it is less sensitive to variations in LP. Furthermore, we note that the pH response of these microbeams is generally geometrically size dependent, as shown in Figure 2b. It appears that the total time required for gel networks to swell sufficiently is proportional to the square of its length scale \( l \), with total time \( t_{\text{total}} \approx 8.976 \times 10^{-4} \) s in the current work. One may thus envision that, if the length scale of gel-based microbeams is reduced to the order of several tens of micrometers, the total swelling time can be as short as the order of seconds, which is often comparable with the time difference in initial swelling between the dense layer and the loose one. This point is crucial for realizing layer-by-layer sequential deformations of BLBs. We checked the effect of the thickness ratio of the loose layer to the dense one upon BLB bending deformation, as shown in Figure 2c. Both our theoretical analyses and experimental results demonstrate that there is an optimal thickness ratio that enables us to maximize the bending deformation in response to the ambient pH. Figure 2d further shows a simple phase diagram that quantitatively characterizes the dependence of the normalized maximum curvatures \( \kappa_{\text{max}} = \kappa_{\text{max}} / \kappa_0 \) on the LP adopted during the fabrication of the BLBs.

2.2. BLB-Based SMJs as Controllable Actuating Units

Inspired by the layer-by-layer sequential deformation of BLBs, we can seamlessly insert the BLBs into specific structures with larger scales during 4D DLW, as shown in Figure 3a. The embedded BLBs function as controllable SMJs that are capable of actively responding to variations in environmental pH, thereby driving the entire structure to generate folding deformation around the SMJ, as shown in Figure 3b. In this sense, the embedded BLB-based SMJs can be viewed as a series of actuating units capable of being controllably triggered by ambient pH. With encodable SMJs that create time-related active deformations under the stimulation of environmental pH, we can develop soft microactuators with complex functions based on the concept of across-scale structural designs. Inspired by the way an inchworm

![Figure 2. Deformation properties of MLBs and BLBs with different geometric and fabrication parameters. a) Dependence of pH values corresponding to initial and complete swelling with LP that varies from 20 to 50 mW in the experiments. The other fabrication parameters remain unchanged. b) Total swelling time of the gel networks of MLBs as a function of the length scale \( l \), with \( t_{\text{total}} = 8.976 \times 10^{-4} \) s in the current work. One may thus envision that, if the length scale of gel-based microbeams is reduced to the order of several tens of micrometers, the total swelling time can be as short as the order of seconds, which is often comparable with the time difference in initial swelling between the dense layer and the loose one. This point is crucial for realizing layer-by-layer sequential deformations of BLBs. We checked the effect of the thickness ratio of the loose layer to the dense one upon BLB bending deformation, as shown in Figure 2c. Both our theoretical analyses and experimental results demonstrate that there is an optimal thickness ratio that enables us to maximize the bending deformation in response to the ambient pH. Figure 2d further shows a simple phase diagram that quantitatively characterizes the dependence of the normalized maximum curvatures \( \kappa_{\text{max}} = \kappa_{\text{max}} / \kappa_0 \) on the LP adopted during the fabrication of the BLBs.](image-url)
of the microcrawler. Figure 4b shows the curves of locomotion distance versus time within four crawling cycles. The actuation period is \(\approx 8\) s, and the distance is \(\approx 50\,\mu\text{m} (\approx 1.0\) body length, BL) for a specific crawling step with a moving speed up to \(\approx 5\,\mu\text{m}\,\text{s}^{-1}\) (Movie S2, Supporting Information). Figure 4c shows details regarding the locomotion process over time for an entire crawling step, where \(\lambda_{\text{BL}}\) is the relative BL, defined as the ratio of the current BL to the original one preset during printing. We used FEA based on commercial software (ABAQUS) in which the gels were defined as hyperelastic materials\(^{43}\) to simulate the gait of the microcrawler (see Section S4, Supporting Information). This simulation was in excellent agreement with the corresponding experimental results (Figure S17, Supporting Information). The FEA-based technique provides a powerful tool for across-scale structure design and fabrication of 4D-printed soft microrobots.

### 2.3. Programmable Locomotion of Structured Microcrawlers

Generally, the performance of microcrawlers is dependent on the deformation-response characteristics of SMJs, the number and spatial distribution of the SMJs, and the geometric configuration of the microcrawler itself. The FEA-aided across-scale structural design can fully take into account the influence of all the aspects (mentioned earlier) on the performance of microcrawlers. This facilitates the development of soft microrobots and the optimization of their performance. For this kind of microcrawler, our structural simulations indicate that the locomotion efficiency, defined as the ratio of the step distance (SD) to the “BL,” “SD/BL,” takes on a nonlinear dependence on the thickness ratio of the BLB-based SMJs, \(M\), ranging from 0.25 to 4, which is consistent with the corresponding experimental results (Figure 5a,b). By tuning the LP required to fabricate the loose layers and thickness ratios of these BLB-based joints, we acquired maximum efficiency up to \(\approx 1.1\) BL per crawling step. This corresponded to a crawling velocity of \(\approx 0.15\) BL s\(^{-1}\). Figure 5c shows a 2D phase diagram that compares the locomotion performance of the microcrawler to that of existing soft robots and some kinds of animals. It turns out that locomotion efficiency as high as \(\approx 1.1\) BL per step of the microcrawler outweighs that of those soft robots reported recently (\(\approx 10^{-2}–0.4\) BL per step). Moreover, the corresponding velocity is higher than that of most existing soft robots. Indeed, the efficiency and mass are comparable to that of most of the animals shown in Figure S12, Supporting Information.

The BLB-based structures inspired us to design SMJs capable of actively responding to external stimuli, as confirmed in the current work. In essence, the structural arrangements for the SMJs act as hinges together with the corresponding curing parameters during 4D DLW. These play a major role in regulating the locomotion of these microcrawlers. It is feasible to achieve programmable motion under periodic pH stimulation through diverse structural arrangements and functional assembly. In addition, it should be emphasized that the deformation-response characteristics of the BLB-based SMJs themselves can influence the locomotion of the microcrawlers. Generally, there are two typical deformation-response modes for BLBs and SMJs, hereafter referred to as DRM-1 and DRM-2, as shown in...
Figure S13, Supporting Information. DRM-1 corresponds to the case of a normalized maximum curvature for BLBs $\kappa_{\text{max}}$ that is significantly greater than one. DRM-2 denotes the case where $\kappa_{\text{max}}$ is very close to one, as shown in Figure 2d. Our FEA-based analyses demonstrate that the locomotion efficiency of a reptile-like microcrawler has a $//C_{25}$1.75-fold increase from $//C_{25}$0.4 to $//C_{25}$1.1 BL per step when DRM-2-based SMJs are replaced by DRM-1 SMJs, as shown in Figure S14, Supporting Information. This implies that the nonmonotonic layer-by-layer deformation response arising from the DRM-1 SMJs enhances the locomotion efficiency of microactuators.

Subsequently, we demonstrate that this class of microcrawlers can achieve multiple types of locomotion based on programmable structural designs. By spatially arranging the position and direction of SMJs on microcrawlers, we can regulate their direction, as shown in Figure 6a,b. The newly designed microcrawler can move upstream in response to environmental pH (Figure S18 and Movie S3, Supporting Information). Unlike an inchworm-like microcrawler shown in Figure 3, this microcrawler includes two back-to-back joint structures in its rear leg, generating a differential deformation response to pH compared with the front leg. Moreover, inspired by the locomotion of starfish, we further developed a starfish-like soft microcrawler similar to the inchworm-like microcrawler in Figure 3 but with two side legs (Figure 6c). Under the same acid–alkali stimulation cycle, we found that the starfish-like microcrawler could realize 2D planar motion by tuning the diffusion direction of alkali. The specific arrangement of these SMJs regulates the locomotion efficiency, velocity, and spatial trajectory of the starfish-like microcrawlers, thus achieving programmable motion. With a specific structural configuration, for example, the microcrawler can move along an M-shaped route depending on the stimuli direction (Figures 6d,e, Figure S19, and Movie S4, Supporting Information).

3. Discussion and Conclusion

Smart materials effectively integrating with the structural design of SMJs is one of the the key steps to realize functional soft microrobots with high flexibility, controllability, and...
environmental adaptability. In this work, we first showed a sequential swelling effect during swelling caused by BLBs made of smart materials. This effect results in spontaneous bending deformations under the stimuli of ambient pH. Based on the spontaneous swelling/shrinking property and size-dependent layer-by-layer sequential swelling effect, we fabricated a series of bionic multilegged microcrawlers embedded by SMJs of several micrometers using 4D DLW. The microcrawlers had controllable locomotion performance and could reach superior locomotion ability. Moreover, by introducing programmable structural designs and functional assembly of SMJs, we found that these microcrawlers are capable of achieving not only superior crawling performance but also multiple types of motion such as migration along/against the source of the pH stimuli and locomotion along a specific route. Likewise, we showed an FEA-aided structural design based on a hyperelastic constitutive model. This is a powerful tool for optimizing the geometric configurations and fabrication conditions of microcrawlers. This work provides a novel way of manufacturing 4D-printed microrobots which have potential applications in multiple engineering fields such as biomedicine.

This work reveals that the sequential swelling effect is size dependent. Our analysis indicates that there is almost no sequence swelling effect on the macroscale. The smaller the length scale of BLBs, the faster their response to changes in environmental pH. This will help develop soft micro- and nanorobots, with fundamentally different design concepts from those adopted for macrorobots. In principle, it is feasible to develop soft actuators/robots with feature scales ranging from micrometers to submillimeters by assembling a large number of BLB-based SMJs that can undergo the sequential swelling effect, with which they can realize much more complicated functions. The sequential swelling effect is directly associated with the geometric configuration and the local crosslink density of BLBs. Our investigations demonstrated that both the amplitudes of spontaneous bending deformations of BLBs and the response sensitivity to environmental changes can be quantitatively predicted with the help of the FEA-based numerical simulations in the framework of a hyperelastic constitution in combination with the traditional bilayer beam theory.

Structural design-based programmability offers a new solution for microrobots to implement a controllable and predictable
movement. Following this concept, we believe it should be practicable to develop microrobots/actuators with more complicated geometric configurations that can exhibit much stronger environmental adaptability and thus more complex functions. It should be pointed out that the FEA-based mechanical analysis and computer-aided design can be powerful tools for across-scale structural design, fabrication, and performance optimization for microrobots. This allows us to quantitatively capture the dynamics of local deformations and the motion of the microstructures involved.

4. Experimental Section

**Synthesis of pH-Responsive Materials:** The prepolymer of pH-responsive gel material used in this work was a mixture of several functional monomers, including NIPAAm (N-isopropyl acrylamide, Aladdin, China) and AAc (acrylic acid, Aladdin, China), DPEPA (dipentaerythritol pentaacrylate, Aladdin, China) as the crosslinker, EMK (4,4'-Bis(diethylamino)benzophenone, Red chemical, China), DMF (N,N-dimethylformamide, Aladdin, China), TEOA (triethanolamine, Aladdin, China) dissolved in EL (ethyl lactate, Aladdin, China), and PVP (polyvinylpyrrolidone, Mw ≈1 300 000, Aladdin, China).

**Fabrication of Microstructures:** The microstructures studied in this work were fabricated using 4D DLW with the “Galvo” scanning mode (Photonic Professional GT, Nanoscribe GmbH, Germany) with a 63× oil-immersion objective (numerical aperture = 1.4). Square borosilicate glass coverslips (22 mm × 22 mm × 0.15 mm, Thermo Fisher Scientific, USA) were used as substrates during fabrication. Before 4D DLW, the coverslips were first cleaned up by IPA (Aladdin, China) and dried in nitrogen at room temperature. Then, the prepolymer was dropped on the coverslip substrate for printing. Microstructures were fabricated at steady temperature (≈22 °C) and humidity (≈40 %). The slicing and hatching distances were set to 0.5 and 0.3 μm, respectively. After printing, the coverslip substrates containing the microstructures and redundant prepolymer were developed in IPA three times for 30 min.

**Characterizations of Swelling and Mechanical Properties of Gel Materials:** The glass substrate with printing microstructures was inserted in a

Figure 6. Programmable multimodal locomotion of soft microcrawlers based on structural arrangements. a) The structural diagram of a microcrawler that can move upstream in response to environmental pH. b) Top and side views of locomotion with six typical moments in an entire crawling step. c) Diagram of a starfish-like microcrawler. d) Locomotion distance of four legs and head of the starfish crawler with time t. The skyblue areas in the background denote the shrinking phase of the microstructures, and the beige areas represent the swelling phase. e) M-shaped locomotion trajectory of the starfish-like microcrawler in six steps. Scale bar: 30 μm.
channel of a self-designed glass holder, which was fabricated by a multi-material 3D printer (Objet 350 Connex 3, Stratasys Ltd., USA) based on the photosensitive “Veroclear” that was a kind of transparent PolyJet photopolymer provided by the same company. Meanwhile, a solution-injecting channel (printed by the same 3D printer and photore sist as mentioned earlier) was placed on the glass holder, as shown in Figure S24, Supporting Information. The solution-injecting channel had two inlets and two outlets. The inlets were connected with syringe pumps (LSP02–18, Longer Precision Pump, China) for solution injecting, whereas the outlets faced the microstructures with the outlet direction parallel to the underlying substrate. In experiment, these microstructures were first allowed to fully shrink in an acidic solution (pH ≈4.5). Subsequently, the microstructures were stimulated by slowly injecting an alkaline solution (pH ≈12.5) in a microfluidic chamber using a syringe pump with a flow rate of \( v = 1.8 \times 10^{-6} \text{Ls}^{-1} \) to induce an increase in environmental pH. The resultant swelling process of these microstructures was observed and recorded with a digital microscope (RH-2000, Hirox, Japan). A micro-mechanical testing system (FT-NMT03, FemtoTools, Switzerland) was used to quantify the mechanical properties of gel materials. Briefly, a series of cylindrical gel blocks (printing diameter: 30 μm, height: 30 μm) were first fabricated based on the fixed SS of 5 mm s⁻¹ with LP ranging from 20 to 50 mW. Before the experiments, the gel blocks were immersed in either an acidic solution with pH ≈4.5 (hydrochloric acid, Aladdin, China) or an alkaline solution with pH ≈12.5 (sodium hydroxide, Aladdin, China) such that they fully shrank or swelled. Then, an FT20000 sensing probe with a force range of 1–20 mN was adopted to compress the cylindrical blocks in situ and measure their mechanical properties. All mechanical tests were conducted in the “step” mode with a compression speed of 0.075 μm s⁻¹.

Characterizations of the Locomotion Properties of Microcrawlers: The microcrawlers were first required to fully shrink in an acidic solution (pH ≈4.5). Then, they were stimulated by slowly injecting an alkaline solution (pH ≈12.5) in a microfluidic chamber using the syringe pump with a flow rate of \( v = 1.8 \times 10^{-6} \text{Ls}^{-1} \) to induce an increase in environmental pH. Then, the microcrawlers took a step forward with the aid of these SMJs that were sequentially triggered when the environmental solution varied from acid to alkaline. Next, the microcrawlers were immersed in the acidic solution once again by turning off the inlet of the alkaline solution and simultaneously turning on the injection inlet of the acidic solution. In this way, the microcrawler achieved continuous locomotion, which was observed and recorded with a digital microscope as mentioned earlier.

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

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Conflict of Interest
The authors declare no conflict of interest.

Keywords
enhanced locomotion, microcrawlers, sequential swelling, smart microjoints

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