Thermoresponsive Semi-IPN Hydrogel Microfibers from Continuous Fluidic Processing with High Elasticity and Fast Actuation

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ABSTRACT: Hydrogels with rapid and strong response to external stimuli and possessing high elasticity and strength have been considered as platform materials for numerous applications, e.g., in biomaterials engineering. Thermoresponsive hydrogels based on semi-interpenetrating polymer networks (semi-IPN) featuring N-isopropylacrylamide with copolymers of poly(N-isopropylacrylamide-co-hydroxyethyl methacrylate) p(NIPAM-HEMA) chains are prepared and described. The copolymer was characterized by FTIR, NMR, and GPC. The semi-IPN structured hydrogel and its responsive properties were evaluated by dynamic mechanical measurements, SEM, DSC, equilibrium swelling ratio, and dynamic deswelling tests. The results illustrate that the semi-IPN structured hydrogels possess rapid response and high elasticity compared to conventional pNIPAM hydrogels. By using a microfluidic device with double coaxial laminar flow, we succeeded in fabricating temperature responsive (“smart”) hydrogel microfibers with core–shell structures that exhibit typical diameters on the order of 100 μm. The diameter of the fibers can be tuned by changing the flow conditions. Such hydrogel fibers can be used to fabricate “smart” devices, and the core layer can be potentially loaded with cargos to incorporate biological function in the constructs. The platforms obtained by this approach hold promise as artificial “muscles”, and also “smart” hydrogel carriers providing a unique biophysical and bioactive environment for regenerative medicine and tissue engineering.

KEYWORDS: core–shell hydrogel microfibers, thermoresponsive polymers, p(NIPAM-HEMA), microfluidics

INTRODUCTION

Stimulus responsive (or as often called, “smart”) hydrogels that exhibit rapid response to environmental stimuli, including temperature, pH, ionic strength, light, pressure, and redox have been used in many fields, such as drug delivery, tissue engineering, and soft machines. However, conventional pNIPAM hydrogels, cross-linked by small molecules such as N,N-methylenebis(acrylamide) (MBA) and poly(ethylene glycol) diacrylate are rather brittle under ambient conditions. This feature constitutes drawbacks for further development and applications. In order to improve the mechanical properties, a series of methods have been proposed, including forming interpenetrating polymer networks (IPN), preparation of copolymers to introduce different types of side chains, grafting side chains onto the networks to generate comb-type grafted hydrogels, and combination with nanostructured composites. In IPN hydrogels, one component is a cross-linked network, which is interwoven with another network held together, e.g., by polymer chain entanglements or physical interactions such as ionic forces, hydrogen bonds, or hydrophobic interactions. IPN structures provide materials with novel architectures that possess clear advantages in a variety of applications. For example, for temperature responsive IPNs, in order to retain LCST behavior and to retain biocompatibility, natural polymers as one of the network components have been used to obtain pNIPAM-based IPN hydrogels including alginate, chitosan, and gelatin.

Recently, responsive hydrogels have attracted great interest as platform materials in the biomedical field especially in tissue engineering, drug delivery carriers, and extracellular matrices. 3D cellular constructs in vivo, such as blood vessels, muscle fibers, and nerve networks, have been prepared by weaving fiber-shaped materials. Fiber-shaped materials are long, thin, and flexible, which means they can be easily weaved...
to 3D complex constructs.\textsuperscript{36} Thus, a fiber-shaped core–shell responsive hydrogel, with, e.g., encapsulated cells and extracellular matrix proteins, would be an ideal model as a carrier in biomedical applications. Some researchers have already explored fiber-shaped core–shell structures to apply on the culture of cells to mimic biological systems and fabrication of multifunctional carriers.\textsuperscript{39–41}

In this study, we describe the preparation of “smart” hydrogels with fast response, and high elastic properties using a simple method by constructing semi-IPN architectures. Water-soluble, high molar mass, linear copolymers of N-isopropylacrylamide (NIPAM) and hydroxyethyl methacrylate (HEMA) were first synthesized by radical polymerization, and then NIPAM monomer and cross-linker MBA were added to the linear copolymers to form the interpenetrating network. By using this approach, p(NIPAM-HEMA)/pNIPAM semi-IPN hydrogels (hereinafter referred to as PNH hydrogels) were formed. Compared to conventional pNIPAM hydrogels, the semi-IPN hydrogel reported here not only possesses covalent cross-linking, but also forms a network of hydrogen bonded structures\textsuperscript{\textsuperscript{\textsuperscript{42}}} and enhanced entanglements within the hydrogel, which can significantly improve the mechanical properties of the hydrogel.\textsuperscript{\textsuperscript{35}} Furthermore, the flexible segments of linear p(NIPAM-HEMA) chains between network junctions can adapt their length fast upon thermal stimuli (>LCST) because limited cross-linking restrictions exist (Figure 1).

\section{Experimental Section}

\textbf{Materials.} N-isopropylacrylamide (NIPAM, Aldrich, 97\%) was purified by recrystallization twice from toluene/hexane, and dried under vacuum for 48 h at room temperature. 2-Hydroxyethyl methacrylate (HEMA, Aldrich, 97\%) was purified by distillation under reduced pressure. N,N,N,N′,N′-tetramethylethylenediamine (TEMED), sodium alginate, calcium chloride and poly(vinyl alcohol) (PVA, M₉ = 89 000–98 000, 99+ % hydrolyzed) were purchased from Aldrich. Water was purified with a Milli-Q Advantage A10 purification system (Millipore, Billerica, MA, U.S.A.).

\textbf{Synthesis of Linear p(NIPAM-HEMA).} Linear p(NIPAM-HEMA) polymers were prepared by free radical polymerization using standard procedures, employing KPS as initiator.\textsuperscript{\textsuperscript{44–46}} A typical procedure for the preparation of the copolymer is described as follows.\textsuperscript{\textsuperscript{44–46}} 1 g NIPAM and 0.05 g HEMA were mixed together in 10 mL of Milli-Q water by continuous stirring under an argon atmosphere in a 50 mL three-necked flask, and placed into an ice–water bath. Then 0.02 g KPS (in 0.5 mL water) and 10 μL TEMED were added to initiate the polymerization. After the polymerization in ice–water bath for 2 h, the solution temperature was raised to 40 °C (>LCST). As a result, the reaction medium turned turbid, confirming the phase transition and successful synthesis of the polymers. After immersion in an ice–water bath, the precipitation was completely dissolved and ready for subsequent use. One mL of solution was dialyzed against Milli-Q water using dialysis hose (molecular weight cutoff: 8000–14 000 g/mol) for 1 week. Dry copolymers were characterized by FTIR spectroscopy ( Nicolet 6700, Thermo Fisher) and 1H NMR (in DMSO-d₆). The copolymer was also analyzed by GPC (PL-GPC 50 Agilent, in hexafluoro-2-propanol) and DLS (Zetasizer Nano ZS, Malvern). Linear pNIPAM and pHEMA polymers were prepared by a similar procedure as described above.

\textbf{Preparation of PNH Hydrogel with Semi-IPN Structure.} PNH hydrogels were prepared by mixing linear p(NIPAM-HEMA) solutions (100 mg/mL) and NIPAM solutions (100 mg/mL, containing 1.5 mol % MBA) in a vial at required ratios (0:10, 1:9, 2:8, 3:7, 4:6, and 5:5, v/v). The mixture was purged with argon for 15 min and 4 mg/mL KPS and 1 μL/mL TEMED were added to the final reaction medium. The solution was mixed thoroughly and then quickly transferred into a cylindrical mold and kept at room temperature for 10 h to prepare the PNH hydrogels (in which 0:10 presents the conventional pNIPAM hydrogel). The samples were analyzed by differential scanning calorimetry (DSC, 204 F1 Phoenix, Netzsch) and dynamic oscillation rheometry (Physica UDS 200, Anton Paar GmbH). Additionally, the PNH hydrogel samples (0:10 and 3:7) were washed and equilibrated in pure water at 20 °C for 24 h and then were freeze-dried in liquid nitrogen for SEM analysis (S-3000N/H, Hitachi).

\textbf{Thermoresponsive Properties of Hydrogels.} To illustrate the thermoresponsive property of the hydrogels, the equilibrium swelling ratio (SR) and water retention (WR) as a function of temperature and time were studied gravimetrically. The hydrogel samples were

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**Figure 1.** Schematic diagram of semi-IPN hydrogel preparation. (a) NIPAM and HEMA monomer. (b) Linear p(NIPAM-HEMA) copolymer. (c–e) Schematics of hydrogel with semi-IPN structure in the swollen state (<LCST). In the PNH gel, the second network was formed by covalent cross-linking (green square) and networks are held together by hydrogen bonding (black rectangle) and the entanglement. The gray spheres represent dense cross-linked regions within hydrogel. (f) PNH hydrogel in the shrunken state (>LCST).
equilibrated in water over a temperature ranging from 20 to 45 °C. After wiping away surface water with filter paper, the weight was measured \( (W_i) \). Then the weight of corresponding dried gels \( (W_d) \) were measured following an oven-drying step. The value of the SWR is defined as \( SWR = (W_i - W_d)/W_i \times 100\% \).

The deswelling kinetics of the hydrogels was evaluated gravimetrically at 37 °C. The hydrogel samples were first allowed to swell to reach equilibrium at room temperature before the measurement, and then were transferred to a water bath at 37 °C. The weight of hydrogels was measured at a given time as \( W_d(t) \).

**p(NIPAM-HEMA) Copolymers.** Polymeric microfibers were produced by a microfluidic device, which was assembled by using three injection pumps (PHD ULTRA, Harvard apparatus) and a double coaxial PDMS chip. The core solution consisted of sodium alginate \( (3 \text{ mg/mL}) \) and black marker \( (\text{carbon black dispersion}, 1 \text{ mg/mL}) \) as a representative payload substitute. The shell consisted of linear p(NIPAM-HEMA) copolymer solution, NIPAM monomer aqueous solution \( (3:7 \text{ v/v}) \) and the initiator \( (\text{KPS}) \). The solution contained CaCl\(_2\) as an ionic cross-linker and TEMED as accelerator. By controlling flow rate of the three layers, core–shell microstructures with different diameter can be prepared. Finally, the microfibers were embedded into the PVA solution \( (5\% \text{ w/w in water}) \) by using a grooved PDMS substrate to form a “Janus-like” hydrogel film after three freeze–thaw cycles.48

**RESULTS AND DISCUSSION**

Characterization of Linear p(NIPAM-HEMA) Copolymer. p(NIPAM-HEMA) copolymer was synthesized by free radical polymerization. In order to verify the formation of the copolymers, linear pNIPAM and pHEMA homopolymers were prepared in a similar manner.49 FTIR spectra of linear pNIPAM, pHEMA, and copolymer p(NIPAM-HEMA) are shown in Figure 2. The spectrum of p(NIPAM-HEMA) exhibits main peaks at 1645 and 1540 cm\(^{-1}\) corresponding to the characteristic peaks for amide I and amide II, respectively.50 The linear p(NIPAM-HEMA) copolymers also have a distinct characteristic peak at 1713 cm\(^{-1}\) with a relatively low absorbance which corresponds to a carbonyl group in pHEMA indicating the successful formation of the copolymer p(NIPAM-HEMA).42,50

Integration of the amide and hydroxyl protons, protons on the secondary carbon of NIPAM and methylene bridge connected to the hydroxyl of HEMA in the \(^1\text{H NMR spectrum (Figure S1 of the Supporting Information, SI)} \) confirmed the presence of copolymerized p(NIPAM-HEMA) with quantitative conversion (molar ratio 23:1, NIPAM/HEMA). We note here that only 1.2% (in molar ratio) HEMA monomer was introduced to a typical semi-IPN hydrogel sample (3:7).

**Formation of PNH Hydrogels.** The schematic process of preparing PNH hydrogels and the as-formed semi-IPN structures are shown in Figure 1A. As mentioned, the linear, long p(NIPAM-HEMA) copolymer chains (Figure 1b) were synthesized by free radical polymerization of NIPAM and HEMA monomers (Figure 1a) initiated by KPS in ice–water bath. After polymerization, the solution medium turned turbid after elevating the temperature to 40 °C (>LCST), confirming the phase transition and successful synthesis of the polymers. After immersing the turbid solution in ice–water bath, the linear polymer was completely dissolved (<LCST). A corresponding heating–cooling treatment gave a redistribution of polymer chains in aqueous solution and enhanced physical entanglement and heterogeneity. The PNH hydrogel was prepared by adding NIPAM monomer, MBA, KPS and TEMED into the linear p(NIPAM-HEMA) copolymer solution (Figure 1e). The linear p(NIPAM-HEMA) copolymer chains are interpenetrated within the hydrogel matrix and connect new formed pNIPAM chains together by hydrogen bonding. The weight-average molar mass for p(NIPAM-HEMA) was determined to be \( 1.5 \times 10^6 \text{ g mol}^{-1} \) by GPC (Figure S2b) and a relatively large hydrodynamic radius \( R_H \) (Figure S2a shows the hydrodynamic size as a diameter) could be extracted from DLS measurement in water. These values are consistent with as-synthesized long linear copolymer compared to conventional pNIPAM synthesized by one-step radical polymerization.51 The free segments of the chains between dense cross-linked regions which meander among network provide good deformability at the molecular scale for the semi-IPN structured hydrogel. When the temperature is below the LCST, the relaxed p(NIPAM-HEMA) chains allow the hydrogel to swell. Once the temperature was raised above LCST, pNIPAM chains pass through the coil-to-globule transition and the network shrinks (Figure 1f). Hydrogen bonds and entanglement interaction between polymer chains and networks can significantly enhance the mechanical properties of the hydrogel, which is exploited here to obtain enhanced gel elasticity and reduced brittleness. Furthermore, the flexible part of long linear p(NIPAM-HEMA) chains between dense network regions can shrink relatively fast as there is limited cross-linking restriction (Figure 1f).52 These features make the PNH hydrogel to possess a rapid response and higher elasticity compared to conventional pNIPAM hydrogel.

**Elastic Characteristics of Hydrogels.** To illustrate gel stiffness, and elastic recovery, single manual compression was carried out as shown in Figure 3. The optical images clearly indicate that conventional pNIPAM hydrogels are too brittle to endure compression (Figure 3f–h) but PNH hydrogels were very elastic to sustain higher compression strains (Figure 3c–e, and Movie S1). The height of PNH hydrogels was 5 mm before compression (Figure 3c) which became 1 mm under load (Figure 3d). As the load was removed, the hydrogel returned to its initial height without rupture (Figure 3e). The PNH hydrogel samples are highly elastic, as is capable of withstanding high levels of deformations such as knotting and stretching (Figure 3a,b).

By using an oscillatory rheometer with a parallel plate geometry, we tested the storage modulus \( G' \) and loss modulus \( G'' \) of the conventional pNIPAM hydrogel, as well as PNH hydrogels with different mixing ratios at 1 Hz as a function of
time. Frequency-sweeps were also carried out over the range of 0.06−20 rad/s at 20 °C. As shown in Figure 4a, the value of the storage modulus of the PNH hydrogel sample is lower than the conventional pNIPAM hydrogel. According to the polymer rubber elasticity theory, the effective cross-link density ($\nu_e$) can be estimated from the experimentally determined shear storage modulus ($G'$) and the polymer volume fraction ($\theta$):

$$G' = \nu_e RT \theta^{1/3}$$

The value of the storage modulus of the PNH hydrogels declined as the decrease of the chemical cross-linking.

Dependencies of storage moduli on angular frequency were also used to characterize the viscoelastic behavior. From the frequency sweep experiments (Figure 4b), it was found that the magnitude of the loss modulus $G''$ was substantially lower than the value of the storage modulus $G'$ for both the pNIPAM hydrogels and the PNH hydrogels (1:9, 2:8, and 3:7), respectively; and the value of the storage modulus did not depend on the frequency in the employed frequency range, indicating successful network formation and a characteristic viscoelastic behavior of the hydrogel. When the content of linear copolymer is above 30%, the value of the storage modulus will significantly decrease (Figure 4). Therefore, the preferred ratio for PNH hydrogel will be in the range of 3:7 in applications, due to the moderate solution viscosity and storage modulus of the as-formed hydrogel.

Morphology of Hydrogels. SEM images show that the microstructures of freeze-dried PNH hydrogels (3:7) are significantly different from the microstructure of the freeze-dried conventional pNIPAM hydrogel (Figure 5). The conventional pNIPAM hydrogel shows typical microporous morphology with dense walls (Figure 5a). However, the PNH hydrogel with lower covalent cross-linking density shows smaller pore sizes (Figure 5b). Although the average pore size of the PNH hydrogels is much smaller than that of "conventional" pNIPAM hydrogels, the micropores inside the PNH hydrogels are all interconnected. We note that such channels connect adjacent cells, which should provide more rapid water transport.

In a typical covalent cross-linked hydrogel sample, the mesh size of the molecular network (which is not to be mixed up by the pore size of the freeze-dried microporous sample) should increase with an decreasing cross-linking density, as well as an increasing swelling ratio of the hydrogels. However, when pores are formed during freeze-drying, the pore sizes are not directly related to the molecular cross-link density as the molecular network structure, the freeze-drying process, and ice crystal formation influence the pore dimensions. The microsized pores within the hydrogel after freeze-drying result from the ice crystals presented in the swollen hydrogel acting as
a template for pore generation. Hydrophilic HEMA monomer, hydrogen bonding between linear p(NIPAM-HEMA) and gel networks, and heterogeneity within the semi-IPN structure (Figure 1e) provide fast water transport, thus rapid cooling and formation of more nuclei of ice crystals within the hydrogel, resulting in smaller-sized pores in the final freeze-dried hydrogel specimens. Additionally, the linear copolymer obtained in the free radical polymerization/cross-linking process provides a second network skeleton to the hydrogel forming the entanglements and hydrogen bonding between the polymers, which makes a further contribution to the hydrogel elasticity.

**Thermoresponsive Properties.** In order to test the LCST behavior, pieces of hydrogels swollen in water (at 20 °C) were gradually heated to 55 °C. Optical images show the conventional pNIPAM and PNH hydrogel samples in swollen states at 20 °C (<LCST) and in shrunken states at 55 °C (>LCST) in Figure 6. At the beginning, there was no visible change after exposing the samples to 55 °C. Then the PNH hydrogel began to turn opaque indicating the beginning of the phase transition but the conventional pNIPAM hydrogel did not change over the same time. Compared to the conventional pNIPAM hydrogel, a significant and fast shrinking of the PNH hydrogel was observed within 5 min (Figure S4). After keeping the temperature at 55 °C for 8 h to ensure that the hydrogel samples have reached the equilibrium state before measurement, the diameter of pNIPAM hydrogel sample changed from 10 to 9 mm, but the diameter of PNH sample (3:7) showed a strong collapse from 15 to 5 mm (Figure 6a). The equilibrium swelling ratios and shrinking kinetics are shown in Figure 6b,c. The results illustrate that PNH hydrogels have a fast response and large deformation compared to the conventional pNIPAM hydrogel.

The hydrogel samples were also tested by DSC. The results show that PNH hydrogel has a slightly lower LCST as
compared with the conventional pNIPAM hydrogel (Figure S5) which is caused by the incorporation of HEMA.

According to the results of the equilibrium swelling ratio experiments and the deswelling kinetics, the addition of the p(NIPAM-HEMA) copolymers into the conventional pNIPAM hydrogel matrix provided less covalent cross-linking and contributed to cause large polymer relaxation and fast water transport, which result in the enhancement of the elasticity of the semi-IPN hydrogels as well as contribute to yielding fast and large response. This phenomenon can be explained by the coil-to-globule transition (of pNIPAM), and the interconnected microporous structure (Figure 5) of the PNH hydrogel. At a given temperature in the vicinity of the LCST, the less cross-linked, long and linear p(NIPAM-HEMA) chains can easily pass the coil-to-globule transition and provide fast relaxation corresponding to the cooperative diffusion of the subchains between two entangled points, which can accelerate the volume-phase transition of the PNH hydrogel. We note that the long copolymer chain with hydrophilic HEMA units will also help the transport of water.

Core–Shell Microfiber Actuators. One application envisaged for the gels prepared in this study includes cell encapsulation and microgel embedding in biomedical coaxial constructs. In order to prepare fiber shaped core–shell gel specimens, a microfluidic chip was designed and constructed as described in ref 59. The basic constituents of the device are shown in Figure 7a. The core–shell microfibers were prepared by a coaxial chip (Movie S2). The coaxial chip was designed by bonding two PDMS modules and capillaries with a tip at the end (Figure S6). By tuning the flow rate, we can control the spinning process to be a stable laminar flow (Figure S7). The core solution was consisted of sodium alginate with black markers as a model payload to substitute cells, microgels, or other payloads. Linear p(NIPAM-HMA) copolymer solution, NIPAM monomer aqueous solution (3:7 v/v), and the initiator (KPS) were introduced as outer layer of the core–shell construct. The addition of the linear p(NIPAM-HMA) increases the viscosity of the shell solution and ensures the formation of a stable laminar flow. Here, we choose the volume ratio to be 3:7 due to the medium viscosity and appropriate injection pressure. The sheath solution contained CaCl2 as ionic cross-linker and TEMED as accelerator. By controlling flow rate of three layers, core–shell microfibers with different diameters were prepared (Figure S8).

The cross-section of the freeze-dried microfiber was observed by SEM (as depicted in Figure 7b). A clear boundary can be seen in the SEM image as essentially no cross-links form between the alginate and the PNH hydrogels. The coaxial microfluidic apparatus we used is capable of creating a microporous structure (Figure 5) of the PNH hydrogel. At a given temperature in the vicinity of the LCST, the less cross-linked, long and linear p(NIPAM-HEMA) chains can easily pass the coil-to-globule transition and provide fast relaxation corresponding to the cooperative diffusion of the subchains between two entangled points, which can accelerate the volume-phase transition of the PNH hydrogel. We note that the long copolymer chain with hydrophilic HEMA units will also help the transport of water.

To further illustrate the thermoresponsive functionality of the as-formed core–shell hydrogel constructs, a bundle of microfibers was collected and stacked together directly after microfluidic processing and in situ cross-linking. Such a simple device can be used as an actuator (artificial “muscle”) to lift weight in response to a thermal stimulus. Figure 7d shows photographs of an experiment conducted on the hydrogel actuator composed of four microfibers (20 mg). The microfiber bundle with a parallel fiber geometry passing through an aluminum ring (5.7 g) was held by a clamp and immersed in a beaker of water. The length of the microfibers was elongated, almost by 150% of its original length, under the load. Considering buoyant forces, the mass of the load (3.6 g) was almost 180 times the mass of the hydrogel actuator. The microfibers turned to opaque immediately after elevating the temperature to above the LCST of pNIPAM (32 °C) and showed fast response to lift the weight up by about 12 mm within a few seconds. The results demonstrate that this microfiber bundle functions also as actuator in response to thermal stimuli, even bearing a high load and at large strain values (150%).

In addition to linear actuation, shape transformations can also be achieved utilizing the difference in swelling and elastic properties of the structural components by using bilayers or gradient architectures along the thickness direction. Figure 7e illustrates a typical design of a hybrid hydrogel made from parallel microfibers embedded on the top layer of a freeze–thawed hydrated PVA hydrogel. The hybrid hydrogel composite is transparent at room temperature due to the similar refractive index values for both components. When the temperature was elevated to above LCST, opaque microfibers can clearly be observed and the hybrid hydrogel exhibited fast bending transformation perpendicularly to the axis of the microfibers, with the microfibers hidden inside (Figure 7f and Movie S3).

CONCLUSIONS

Here we report the preparation of thermoresponsive semi-IPN hydrogels which possess rapid response and high elasticity by introducing less cross-linked long linear p(NIPAM-HEMA) chains to the conventional pNIPAM hydrogels. By using a coaxial microfluidic apparatus, thermoresponsive (“smart”) hydrogel microfibers with high elasticity and fast response were prepared. Due to the enhanced elasticity and reduced brittleness, we expect novel applications of such soft materials in fabrication of 3D complicated constructs with thermoresponsive properties. Two hydrogel microfiber actuators were fabricated to demonstrate linear actuation as artificial “muscles” and also fast shape transformations. The core–shell hydrogel microfibers can also potentially be used for loading with cargos to incorporate biological function in the constructs. The platforms obtained by this approach hold promise as carriers or scaffolds providing a unique biophysical and bioactive environment.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.6b13097.

1H NMR spectra, DLS and GPC measurements, volume-phase transition and DSC traces of hydrogels, elastic compression test, double coaxial chip fabrication, micro-
fibers diameter versus sheath flow rate and optical images of microfibers (PDF).
Simple manual compression of PNH hydrogel (Movie S1).
Microfluidics spinning process of PNH core–shell microfibers (Movie S2).
Thermoresponsive Janus hydrogel film (Movie S3).

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**REFERENCES**


