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Spring-shaped stimuli-responsive hydrogel actuator with large deformation

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ABSTRACT

This study describes a novel microfluidics-based method for compressive/expanding actuation of stimuli-responsive hydrogel microsprings with large deformations. A continuous flow of mixed alginate and poly(*N*-isopropylacrylamide-*co*-acrylic acid) pre-gel solution can spontaneously form a hydrogel microspring with a wide range of gradient pitches via buoyancy force. This technique enables fabrication of hydrogel microsprings using only simple capillaries and syringe pumps. The resulting microsprings can be patterned via laminar flow inside the capillary, which can contribute to large deformation. Single-layered hydrogel microsprings shrunk isotropically while maintaining the shape of the spring. Compressing stimuli-responsive microsprings can be done by patterning the shrinking part of the spring. Here, the degree of compression in the double-layered spring depends on the initial pitch. Furthermore, large axial expansion of microsprings can be achieved by shrinking part of a microspring. Our large compression/expansion stimuli-responsive hydrogel microsprings have immense potential to be applied in various microengineering products including soft actuators, chemical sensors, and medical applications.

1. Introduction

Stimuli-responsive polymer hydrogels swell and shrink corresponding to external stimuli such as temperature [1], pH [2], light [3], and chemical compounds [4]. Generally, such hydrogels are soft, flexible, and highly biocompatible, rendering them ideal for medical applications [5,6]. Furthermore, because of their high efficiency in energy conversion during swelling and shrinking [7], these hydrogels may be used for stimuli-driven soft actuators such as artificial muscle [8,9], biomimetic robotics [10,11], and microfluidic device components [12,13]. Current challenges of these hydrogel actuators are improvements to their displacement and kinetic heterogeneity [14], since bulk stimuli-responsive hydrogels only swell/shrink isotropically, as determined by the nature of the hydrogel materials. In addition to improving polymeric structures in hydrogels [3,15], microfabrication technology has also contributed to solving these problems by enabling micro-scale hydrogel structures such as bilayer [16], multi-layer [17], and micro patterning [18] to realize various complex movements with large displacements, including bending [19], twisting [20], and folding motions [21].

Among the various microstructures for stimuli-responsive hydrogel actuators, we have focused on a spring-shaped structure. A spring is formed by coiling a straight fibre, and can achieve large deformation via its pitch change. In nature, a microorganism like *Vorticella* moves its oral cavity with large, quick motions using their spring-shaped body (stalk) with patterned inner muscles (100–200 μm in length and 2–3 μm in diameter, Fig. 1a) [22,23]. In addition, spring-shaped structures have been widely used in engineering actuators with a long-stroke and high stress, including shape memory alloy spring actuators [24] and polymer spring actuators [25]. Therefore, patterning stimuli-responsive hydrogel in a micro-scale spring could be a promising approach to improve the displacement of stimuli-responsive hydrogel actuators. Several methods of forming hydrogel microsprings have been proposed, including two-photon stereo-lithography [26], liquid rope coiling [27], and asymmetric gelation with a bevel-tip capillary [28]. However, these hydrogel microsprings have not been applied to soft actuators because of difficulties in patterning stimuli-responsive hydrogel materials in micro-scale springs with variable pitch.

In this paper, we propose a stimuli-responsive hydrogel microspring actuator with a large displacement by patterning in the cross-sectional direction. The main component of our microsprings is poly(*N*-isopropylacrylamide-*co*-acrylic acid) (p(NIPAM-co-AAc)), which responds to temperature changes [29]. To form a p(NIPAM-co-AAc)-based hydrogel microspring, we apply an anisotropic gelation method, as has been previously reported [28], to p(NIPAM-co-AAc). Specifically, a mixed pre-gel solution of p(NIPAM-co-AAc) and sodium alginate

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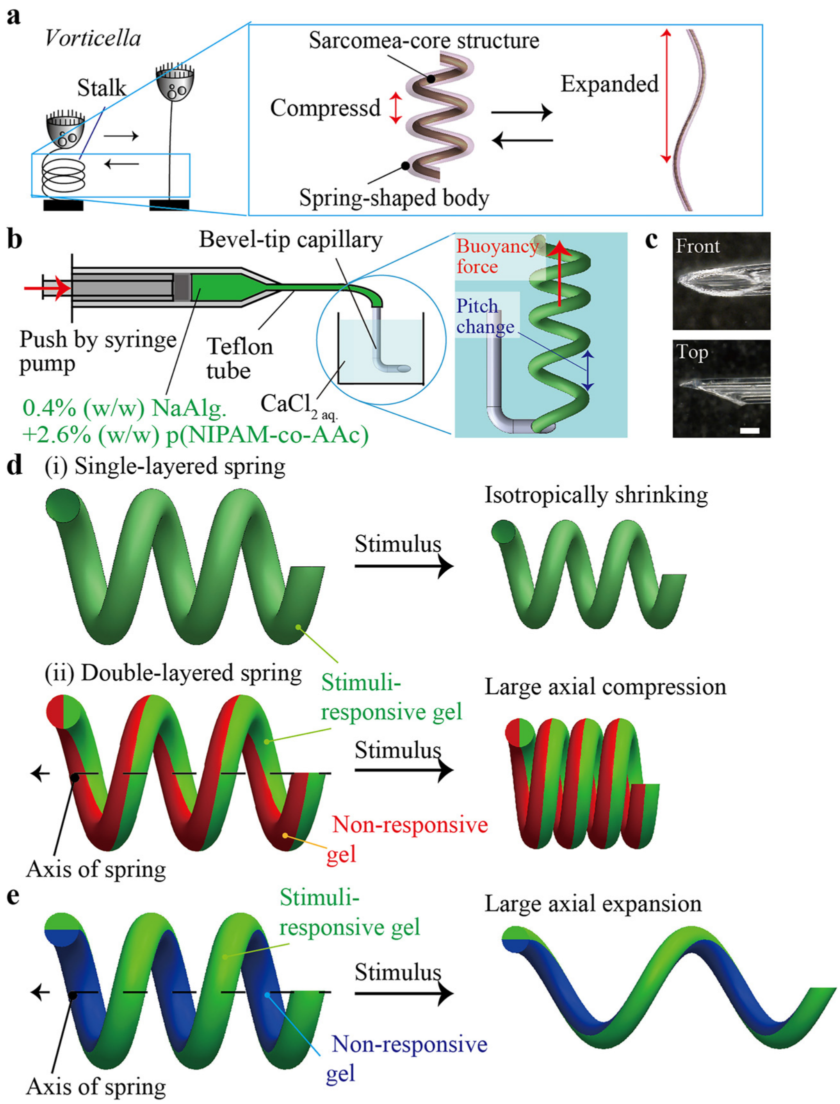

Fig. 1. Formation of a stimuli-responsive hydrogel microsprings with a bevel-tip capillary. (a) A microorganism such as *Vorticella* moves its oral cavity with large and rapid motions by using its spring-shaped body (stalk) with patterned inner muscle (100–200 µm in length and 2–3 µm in diameter) (b) Fabrication set up. The pitch of hydrogel microsprings was enlarged via buoyancy force. (c) Microscopic image of a bevel-tip capillary. (d) Deformation of stimuli-responsive hydrogel microsprings. (i) Single-layered stimuli-responsive hydrogel microsprings shrink isotropically. (ii) By patterning stimuli-responsive hydrogel microsprings, a parallel pattern spring had large axial compression. (e) An outside pattern spring with large axial expansion. A scale bar: 300 µm in (c).

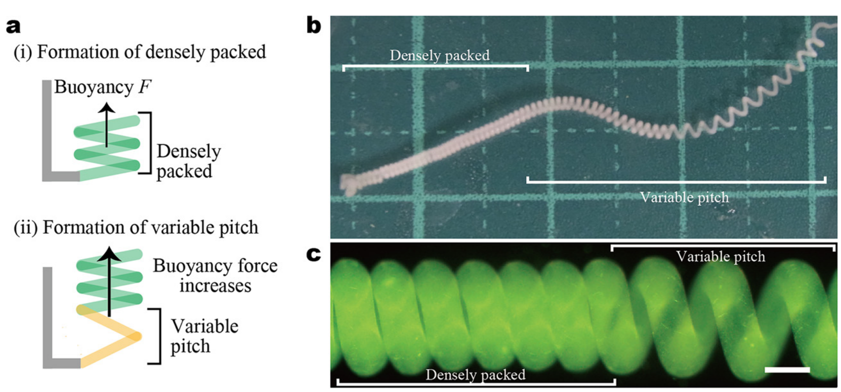

Fig. 2. Fabrication of single-layered stimuli-responsive hydrogel microsprings. (a) Fabricated stimuli-responsive hydrogel microsprings had a densely packed part and variable pitch part. (b) An image of the fabricated hydrogel microspring. (c) A magnified fluorescent image of the hydrogel microspring. A scale bar: 500 µm in (c).

(NaAlg) is extruded into a calcium chloride solution via a bevel-tip capillary (Fig. 1b, c). Because the mixed pre-gel solution rapidly gelates due to calcium ions [16], a stimuli-responsive hydrogel microspring is continuously formed. Through the process of forming the spring, the pitch of the spring, which is an important factor for obtaining large deformation, can be controlled by a buoyancy force (Fig. 1b). To pattern stimuli-responsive p(NIPAM-co-AAc) in a hydrogel microspring, double-layered laminar flow is used to form a bi-layered hydrogel microspring composed of a stimuli-responsive part (blend of p(NIPAM-co-AAc) and calcium alginate hydrogel) and a non-stimuli-responsive part (only calcium alginate hydrogel) (Fig. 1d). To expand the entire spring by compressing a part of the spring, we pattern the stimuli-responsive hydrogel outside part of the spring (Fig. 1e). In this work, we evaluate the shape and responsiveness of p(NIPAM-co-AAc)-based hydrogel microsprings, and demonstrate the large deformation of patterned stimuli-responsive hydrogel microsprings.