A HYDROGEL-BASED INTRAVASCULAR MICROGRIPPER MANIPULATED USING MAGNETIC FIELDS

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ABSTRACT

This work presents a magnetic hydrogel-based microgripper which can be wirelessly manipulated by using magnetic fields. The proposed device made of biocompatible hydrogel material can be employed for the intravascular applications. The actuation mechanism for gripping motions was realized by controlling the exposure doses on the hydrogel composite in lithography process. We also successfully demonstrated the device manipulations in a PVC tube and a PDMS microfluidic channel, such as gripping motion, translational motion, and rotational motion.

KEYWORDS

Microgripper, magnetic nanoparticle, intravascular device, hydrogel.

INTRODUCTION

Cardiovascular diseases have become increasingly common worldwide. The coronary arteries are important vessels for supplying the heart with nutrients, and coronary artery anomaly often causes cardioplegia and even death [1]. Therapy in blood vessels has become a popular medical practice recently. Moreover, intravascular surgery requires assistance from microdevices to deliver diagnostic and therapeutic modalities [2]. Several types of untethered microdevices have been developed for different purposes.

Typically, untethered microdevices scavenge energy from the environment, and convert the energy into mechanical energy for inducing the locomotion through certain principle [3]. Erdem et al. proposed a microrobot that is propelled by cilialike thermal bimorph actuator arrays. Groups of Cilia are controlled independently for generating planar motion with three degrees of freedom [4]. Hu et al. proposed a hydrogel-based microrobot which is optothermally actuated by laser-induced bubbles. The proposed device does not consist of solid materials, while employs a gas bubble in a liquid medium for physically manipulating objects [5].

Recently, magnetic-driven microdevices have attracted attention because they can be wirelessly driven and can provide relatively large actuation force [6]. In general, they can be operated in magnetically-transparent media, such as air, vacuum, conducting and non-conducting liquids. Leong et al. proposed a mass-producible, tetherless microgripper. The locomotion of the device can be manipulated magnetically, and the gripping motion can be triggered by temperature [7]. Jiang et al. proposed a ball-shaped microrobot with rolling capability. Driven by magnetic fields, the device can freely roll on three dimensional surfaces in air, water or silicon oil [8]. Tottori et al. proposed a magnetic helical microswimmer fabricated by 3-D direct laser writing. The device is capable of performing steerable corkscrew motion in water [9].

For intravascular surgery, it is desirable to carry micro devices to perform clinical actions, such as drug delivery, sensing, and surgery. Some researches employed soft materials which require simple fabrication process, and demonstrated the reversibility of shape changing in response to stimuli [10]-[12]. However, due to challenges in fabrication and manipulation, most microdevices can only be operated as either a freely movable unit or an end effector. In this work, we propose a hydrogel-based microgripper which can be wirelessly actuated for translational and rotation motions as well as gripping motions by using uniform and alternating magnetic fields. The proposed device which is made of biocompatible hydrogel material is suitable for the intravascular applications. In addition, the microgripper is fabricated using a simple lithography technique, which realizes the actuation mechanism for gripping motions by two different exposure doses in hydrogel.

DESIGN

Figure 1 shows the schematic of the proposed device moving and gripping an object such as a blood clot in blood vessel for intravascular therapy. Figure 2(a) shows the operation principle of the device locomotion. Fe_3O_4 nanoparticles (NPs) and multiwall carbon nanotubes (MWCNTs) were dispersed in the thermoresponsive hydrogel. Due to the dispersed Fe_3O_4 NPs in the hydrogel, the capabilities of moving can be wirelessly controlled by applying the uniform magnetic fields. As shown in Figure 2(a), the magnetization for aligning Fe_3O_4 NPs is used to fabricate the magnetic microgripper with a specific magnetic axis, which is expected to enable more precise manipulation.

Figure 2(b) shows that the gripping motion can be realized by the bimetallic hydrogel composite with layers of different cross-linkings. Hydrogel polymers contain pendent benzophenone units that allow cross-linking to be tuned by irradiation dose [10]. By controlling the exposure doses on the hydrogel composite in lithography process, the fabricated hydrogel with different cross-linkings can induce different shrinking responses at lower critical solution temperatures (LCST). By applying alternating magnetic fields, the Fe_3O_4 NPs are heated due to Néel and Brownian relaxations, which in turn induces the internal temperature elevation of the hydrogel matrix [11]. Because of the non-homogeneous shrinking responses at LCST in the hydrogel structure, the temperature elevation creates internal stress gradient, gives rise to the deformation of the structure, and induces the gripping motion.

In addition, by dispersing MWCNT molecules in the

hydrogel, the composite exhibits shorter thermal response time due to the enhancement of mass transport of water molecules [12].

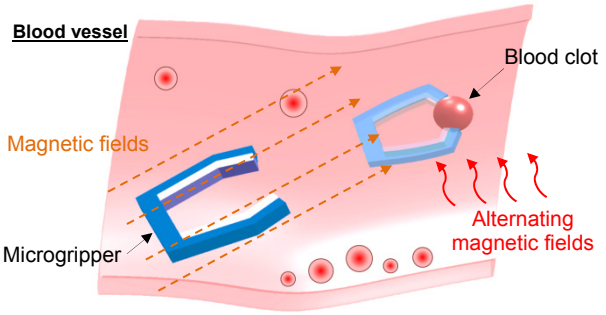

Figure 1: The schematic of the magnetic hydrogel-based microgripper moving and gripping in blood vessel for intravascular therapy.

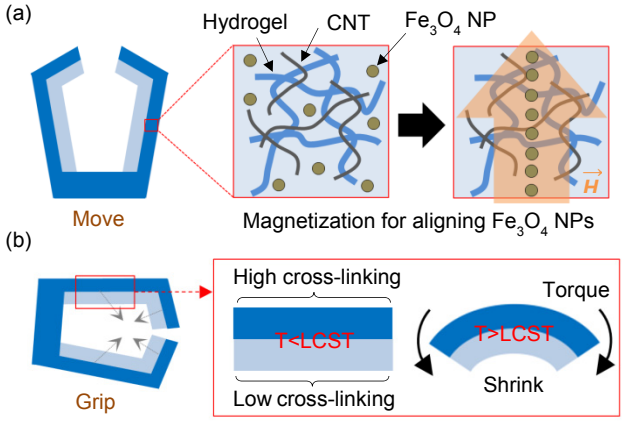

Figure 2: The operational principles of (a) moving and (b) gripping motions.

FABRICATION

The proposed microgripper was fabricated with thermoresponsive hydrogel dispersed with Fe_3O_4 NPs (PVP coated, Nanostructured & Amorphous) and MWCNTs (Golden Innovation Business Company, Ltd; average diameter: 30 nm). The diameter of Fe_3O_4 NPs is about 20 nm to 30 nm, so that the fabricated magnetic structures possess the characteristic of superparamagnetism. For optimal dispersion of MWCNTs in hydrogel, an aqueous 2 wt% sodium deoxycholate (DOC) solution was used as the surfactant to disperse MWCNTs at concentration of 0.5 mg/ml [12]. Subsequently, the aqueous DOC-MWCNTs solution and Fe_3O_4 NPs (1mg/ml) were completely mixed using an ultrasonic agitator at 40 kHz for 3 hours. The pre-gel mixture was composed of 1.5 g N-isopropylacrylamide (NIPAm), 266.5 mg benzophenone acrylamide (BPAm), 57.1 µL Acrylic acid (AAc), 20.2 mg rhodamine B methacrylate (RhBMA), and 2.5 mg azobisisobutyronitrile as an initiator [10], all in the prepared aqueous DOC-MWCNTs-Fe_3O_4 solution. By exposing the pre-gel solution to ultraviolet (UV) light, cross-linking was achieved.

Figure 3 shows the fabrication process of the proposed magnetic hydrogel-based microgripper. Figure 3(a) shows the pre-gel solution drops onto a glass substrate. A trench was formed on a glass substrate by using hydrofluoric acid (HF) etching process. Figure 3(b) and 3(c) shows the first UV exposure for patterning the primary structure of the microgripper with the first photomask. The UV exposure dose is 2 J/cm^2.

In order to avoid the adhesion of the fabricated hydrogel to the photomask, the surface of the mask was treated with octadecyltrichlorosilane (OTS) molecules, so that its surface properties become more hydrophobic with a low surface energy. The mask was thoroughly rinsed with DI water and dried with nitrogen gas. Then, it was placed in a 1mM OTS solution in toluene for 15 min at room temperature.

Figure 3(d) and 3(e) shows the second UV exposure for creating higher cross-linking area with the second photomask. The UV exposure dose was 3 J/cm^2. Figure 3(f) shows the fabricated device after washing with DI water. During the lithography process, a magnetic field is applied across the pre-gel mixture of the magnetic hydrogel, which causes the superparamagnetic NPs in the pre-gel mixture to form chains along the direction of the applied magnetic field. The pre-gel mixture was then photo-polymerized with the UV exposure, which freezes the alignments of superparamagnetic NPs in the polymerized region.

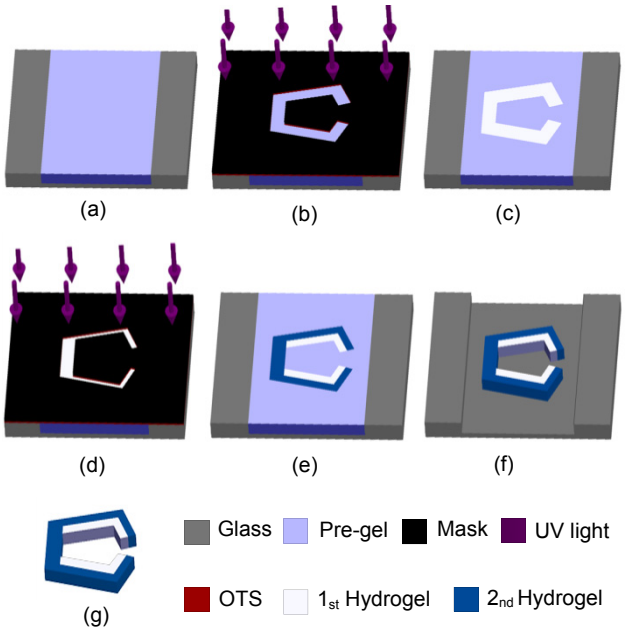

Figure 3: The fabrication processes of the proposed magnetic hydrogel-based microgripper.

The fabricated results of the microgripper are shown in Figure 4. Figure 4(a) is the top view of the microgripper. The length of the fabricated microgripper is about 700 µm. The width of the gripper tip is about 100 µm. The closer view of the microgripper top surface is shown in Figure 4(b). The dispersed Fe_3O_4 NPs and MWCNTs were also shown. The thickness of the fabricated device is about 100 µm.

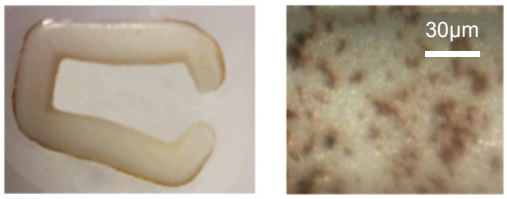

Figure 4: The CCD images of the fabricated result of the microgripper: (a) the top view, and (b) the top surface closer view.

MEASUREMENT AND DISCUSSION

In order to characterize the magnetic polymer structures, we used a vibrating sample magnetometer (VSM) for measuring the hydrogel sample dispersed with magnetic NPs. Figure 5 shows magnetization measurement of the fabricated structure dispersed with Fe_3O_4 NPs. The remanent magnetization at zero applied fields is very small, which indicates that the superparamagnetic characteristic of the NPs as the particle size is smaller than the critical size for superparamagnetism.

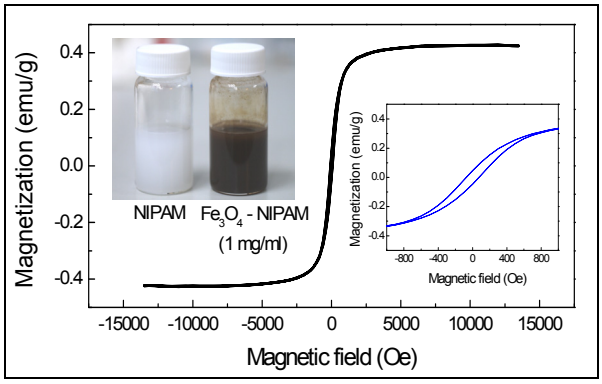

Figure 5: Magnetization measurement of the fabricated structure dispersed with Fe_3O_4 NP.

Experimental setup for operating the microgripper is shown in Figure 6(a). Figure 6(b) is the picture of the induction heater (LT-04-250, Lantech Industrial Co., Ltd.) with an induction coil. The PDMS microfluidic channel chip for demonstrating the operations of microgripper is shown in Figure 6(c). Two pairs of Helmholtz coils surrounded the operation area at the center. The coils connected to direct current (DC) sources controlled by a computer. A Gaussmeter (Model 6010, F. W. Bell) was used to measure the magnetic fields. Observation of the microgripper was performed by using an optical tube with a CCD camera. In order to remotely actuate the gripping motion of the microgripper, the microfluidic chip, including the microgripper, was placed on top of the induction coil of the induction heater with an operating frequency of 250 kHz. The temperature of the microgripper was measured by using an infrared thermal imager (Ti55FT, Fluke).

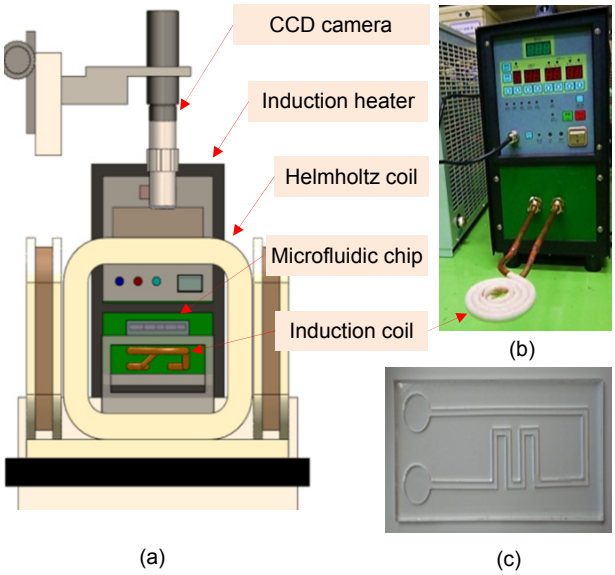

Figure 6: (a) Experimental setup for operating the microgripper: (b) The induction heater with the induction coil and (c) the PDMS microfluidic chip.

The measured moving capabilities of the microgripper with different magnetic fields are shown in Figure 7. The Helmholtz coils generate magnetic fields of 10 mT, 15 mT, and 20 mT. The moving velocities of the microgripper are linearly proportional to the applied magnetic fields by the Helmholtz coils.

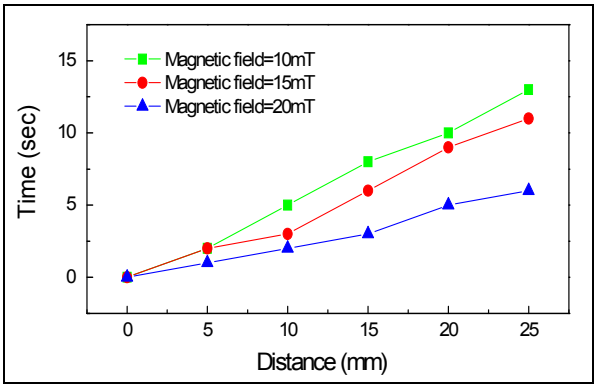

Figure 7: The measured moving distances of the microgripper with different magnetic fields.

Figure 8 presents the measured deformation of the microgripper along different lines of directions as temperature increased. Due to different shrinking responses in the gripper structure, the gripping motion was achieved by the temperature elevation. The gripping motion reaches to a full stroke at approximately 43ºC. Figure 9 shows the overlaid video sequences of manipulation of the proposed microgripper in a PVC tube and a PDMS microfluidic channel controlled by using DC magnetic fields.

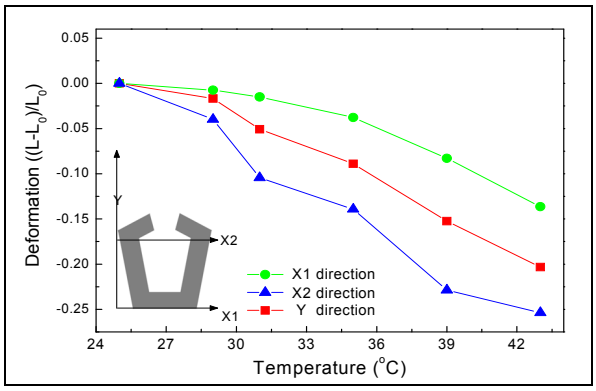

Figure 8: The measured deformations of the microgripper in different directions as temperature increased.

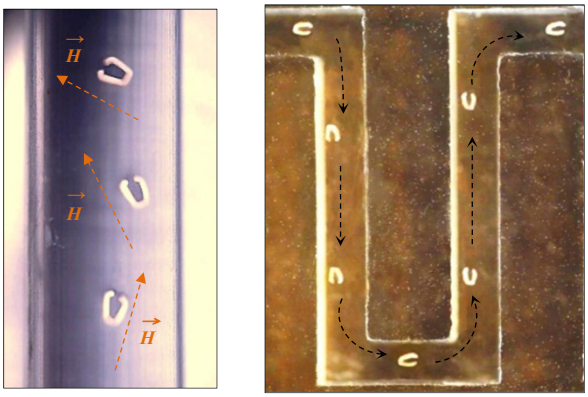

Figure 9: Overlaid video sequences of manipulation of the proposed microgripper in (a) a PVC tube and (b) a PDMS microfluidic channel controlled by using magnetic fields.

CONCLUSION

A magnetic hydrogel-based microgripper was presented in this work. The proposed device can be wirelessly actuated for translational and rotation motions as well as gripping motions by using uniform and alternating magnetic fields. The device is made by biocompatible hydrogel material, and is suitable for intravascular applications or other medical purposes. By controlling the UV exposure doses on the hydrogel composite in lithography processes, the actuation mechanism for gripping motions was realized. The preliminary characterization of the device was also presented. The gripping motion reached to a full stroke at approximately 43ºC. The operation of the device, such as gripping motion, translational motion, and rotational motion, was demonstrated in a PVC tube and a PDMS microfluidic channel.

ACKNOWLEDGMENT

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