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Development of a magnetic catheter with rotating multi-magnets to achieve unclogging motions with enhanced steering capability

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We developed a novel magnetic catheter structure that can selectively generate steering and unclogging motions. The proposed magnetic catheter is composed of a flexible tube and two modules with ring magnets that can axially rotate in a way that enables the catheter to independently steer and unclog blood clots by controlling external magnetic fields. We mathematically modeled the deflection of the catheter using the large deflection Euler-Bernoulli beam model and developed a design method to determine the optimal distance between magnets in order to maximize steering performance. Finally, we prototyped the proposed magnetic catheter and conducted several experiments to verify the theoretical model and assess its steering and unclogging capabilities. https://doi.org/10.1063/1.5005981

I. INTRODUCTION

A catheter is a long flexible tube that is inserted into the body to treat diseases by delivering drugs or performing a surgical procedure. Medical doctors manipulate catheters using mainly their senses and experience because conventional catheters do not have active steering capability. Moreover, since they should continuously track the location and operations of the catheter inside the body using imaging devices such as X-ray or computerized tomography (CT), the doctors are exposed to radiation, which can have side effects on the human body.[1]

Magnetic catheters have been widely investigated to overcome the limitations of conventional catheters because it is possible to control the position and orientation of their tips using the magnets in the catheter and an external magnetic navigation system. However, conventional magnetic catheters with axially magnetized magnets cannot generate the rotational unclogging motion needed to penetrate clogged vessels.[2] Jeon and Jang proposed a magnetic catheter with a diametrically magnetized magnet to generate a drilling motion, but their catheter could cause structural problems due to the twisting between the magnet and tube and has limited steering capability because the magnet is simply fixed to the end of a tube.[3]

We propose a novel structure and design method for a magnetic catheter that can selectively generate steering and unclogging motions. The proposed magnetic catheter has two diametrically magnetized ring magnets, allowing the tip of the catheter to be either deflected for a steering motion or rotated for an unclogging motion by controlling the external magnetic field (EMF). We analyzed the deflection of the catheter using the large deflection Euler-Bernoulli beam model and developed a design method to determine the optimal distance between magnets in order to maximize the steering performance. Then, we prototyped the proposed magnetic catheter and measured the deflection of the catheter as a function of EMF to verify the theoretical model. Finally, the steering and unclogging motions of the proposed catheter were verified in a bifurcated watery glass tube with a pseudo blood clot.

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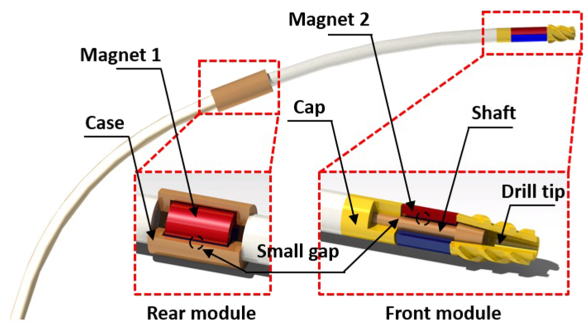

FIG. 1. Structure of the proposed magnetic catheter.

II. PRINCIPLES OF MANIPULATION

Figure 1 shows the structure of the proposed magnetic catheter, consisting of silicone tubes and two modules with diametrically magnetized ring magnets. The rear module is composed of a case and Magnet 1, with a small gap between them so that Magnet 1 can freely rotate relative to the case without damaging blood vessels. The front module is composed of a drill tip, Magnet 2, a shaft, and a cap and is connected to the rear module by a silicone tube. Magnet 2 can freely rotate relative to the shaft, and its axial motion is constrained by the protruding shaft tip and the cap. The drill tip fixed to Magnet 2 rotates as the EMF rotates Magnet 2. Since Magnets 1 and 2 can freely rotate axially, they do not twist the silicone tube during rotation.

The magnetic torque exerted on the magnets can be expressed using the following equation when an EMF is applied to the magnetic catheter:[3]

$$\mathbf{T} = \mathbf{m} \times \mathbf{B} \tag{1}$$

where **m** and **B** are the magnetic moment of the magnets and the magnetic flux density of the EMF, respectively. Since the magnetic torque aligns the magnet in the EMF direction, the magnetic catheter can be steered by manipulating the EMF direction. The magnet can also be rotated using a rotating EMF, which can be expressed as follows:[4]

$$\mathbf{B}_R(t) = B_0(\cos 2\pi ft\mathbf{U} + \sin 2\pi ft\mathbf{N} \times \mathbf{U}) \tag{2}$$

where f, **N**, and **U** are the rotating frequency of the EMF, the unit vector of the rotating axis, and the unit vector normal to **N**, respectively. Using the magnetic torque and the rotating EMF, the drill tip fixed to Magnet 2 can generate the unclogging motion necessary to widen narrowed vessels.

III. DEFLECTION MODEL FOR MAGNET ARRANGEMENT

Since the diameter of a catheter is restricted by the size of blood vessels, we could not include a magnet of sufficient volume to increase the magnetic torque and the resulting steering performance. Instead, we developed a design method to determine the optimal distance between magnets to maximize steering performance. Because the thickness of the catheter was very small compared to its length, the catheter was modeled as an Euler-Bernoulli beam, with the applied magnetic forces and torques modeled as shown in Fig. 2(a). $\mathbf{T}_1$ and $\mathbf{T}_2$ represent the magnetic torque exerted on Magnets 1 and 2 by the EMF, respectively, and $\mathbf{F}_{12}$, $\mathbf{F}_{21}$, $\mathbf{T}_{12}$, and $\mathbf{T}_{21}$ represent the magnetic force and torque generated by the interaction between Magnets 1 and 2. L_1, L_2, φ_1, and φ_2 represent the distance from the fixed end to Magnets 1 and 2 and the deflected angles of Magnets 1 and 2, respectively. Large deflections of an Euler-Bernoulli beam can be modeled as follows:

$$EI\frac{d\varphi}{ds} = M(s) \tag{3}$$

where EI, φ, and s are the bending stiffness of the flexible tube, the deflected angle at an arbitrary point, and the arc length from the fixed end to the arbitrary point, respectively.[5] The above governing equation is nonlinear because of the magnetic forces and torques between the magnets and can be

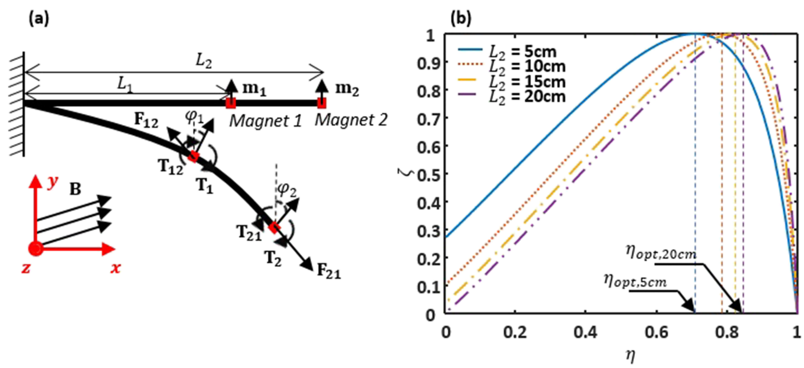

FIG. 2. (a) Deflected magnetic catheter and the applied magnetic forces and torques. (b) Vertical displacement of the tip (y) according to changes in η and L_2.

solved using an iterative numerical method. To find a relation between the vertical displacement at the tip of the catheter (y) and the distance between the magnets, we calculated the deflection by changing L_1 from 0 to L_2 (L_2 is fixed because Magnet 2 is located at the tip of the catheter). The calculated results were compared by introducing the dimensionless parameters ζ and η, as shown in Fig. 2(b). The magnetic moment, bending stiffness, and size of magnets and EMF used to determine the curves in Fig. 2(b) are explained in Section IV. ζ represents the ratio of the difference between current and minimum vertical displacement ($y - y_{min}$) to the difference between maximum and minimum vertical displacement ($y_{max} - y_{min}$), and η represents the ratio of the displacement between the magnets (L_2–L_1) to L_2.

$$\zeta = \frac{y - y_{min}}{y_{max} - y_{min}} \quad \text{and} \quad \eta = \frac{L_2 - L_1}{L_2} \tag{4}$$

According to the above relations, the optimal distance between the magnets can be calculated by ηL_2, and ζ is equal to 1 in this case. Figure 2(b) also shows that η_{opt} becomes large as L_2 becomes long. This relation can be expressed using the following interpolation formula, where L_2 is measured in mm.

$$\eta_{opt} = -1.444 \times L_2^{-0.3891} + 1.024 \tag{5}$$

Using this relation, we can design the distance between magnets using L_2 such that the steering performance is maximized.

IV. RESULTS AND DISCUSSION

We first prototyped the proposed catheter as shown in Fig. 3(a). The parts making up the rear and front modules were fabricated with an ultraviolet-curable acrylic plastic using a 3-dimensional printing technology. Silicone tubes with diameter of 2 mm and a bending stiffness (EI) of 4.418 N·mm^2 were used. Diametrically magnetized NdFeB ring magnets were used for Magnets 1 and 2, and the outer diameter, inner diameter, length, and magnetic moment were 2 mm, 1 mm, 5 mm, and

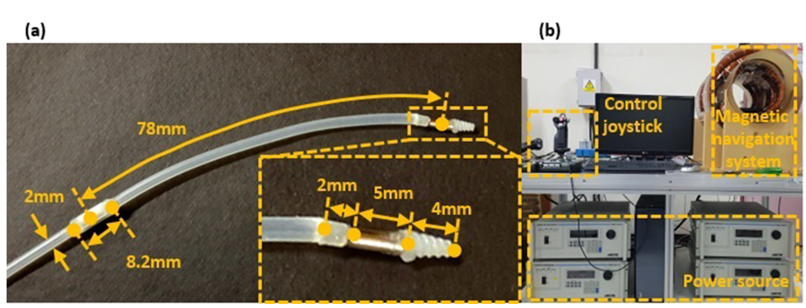

FIG. 3. (a) Prototyped magnetic catheter. (b) Constructed magnetic navigation system.

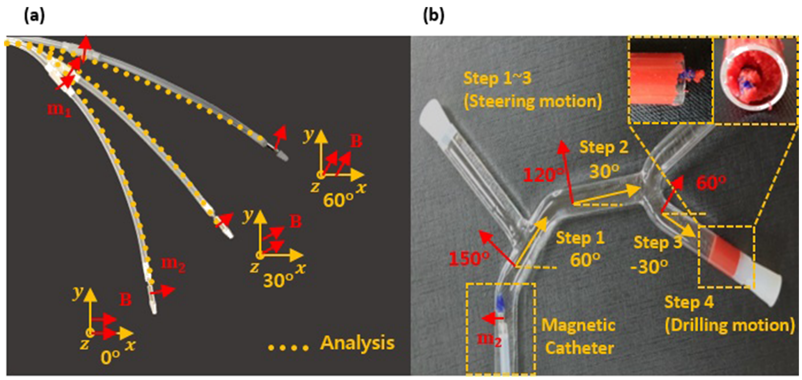

FIG. 4. (a) Comparison between simulated and measured deflection. Background pictures of catheters are experiment results. (b) *In vitro* experiment to verify the selective steering and unclogging motions.

1.36×10^4 A·mm^2, respectively. L_2 was set to 100 mm, and we calculated $\eta_{opt} = 0.78$ and $L_1 = 22$ mm using (4) and (5).

To verify the deflection model of the design method, we applied an EMF to the prototyped magnetic catheter using the magnetic navigation system in Fig. 3(b).[6] An EMF of 14 mT was applied by changing the direction of the EMF by 30° between 0° and 60° relative to the x-axis, where the magnetization of the magnet was set to 90° relative to the axial direction of the catheter. The deflections of the prototyped catheter were compared with those of the theoretical model, as shown in Fig. 4(a), and the maximum error in the position of Magnet 2 (at the tip of the catheter) was 1.51% and 0.61% in the x- and y-direction, respectively. This shows that the deflection model accurately predicts the optimal distance between the magnets and the resulting deflection of the proposed magnetic catheter.

Finally, we conducted an *in vitro* experiment in a bifurcated glass tube with an inner diameter of 5 mm to observe the steering and unclogging motions of the proposed magnetic catheter, as shown in Fig. 4(b). The tube was filled with water, and its lower right branch was completely blocked by a pseudo blood clot made of 5% agar. First, the catheter was inserted at 5 mm/s, and EMFs with a magnitude of 14 mT and directions of 150°, 120°, and 60° were sequentially applied in Steps 1, 2, and 3, respectively, to smoothly align the magnetic catheter with the glass tube. The magnet was diametrically magnetized so that the EMF direction was 90° greater than the declined angle of the glass tube, as shown in Fig. 4(b). When the catheter reached the clogged region, a rotating EMF with a frequency of 18 Hz was applied to generate unclogging motions (Step 4). In the unclogging motion, the magnet of the rear module tends to rotate with the rotating EMF. However, only a component of the rotating EMF perpendicular to the magnetization of the magnet in the rear module play a role in rotating the magnet in the rear module when the magnetic catheter is deflected as shown in Fig. 1. Also, the rotating motion of the magnet is not entirely transmitted to the module and catheter because there is small gap between the case and magnet of the rear module in the proposed structure. When we observed the motion of the rear module in the unclogging motion, the vibration of the rear module was not noticeable. As shown in Fig. 4(b), the proposed magnetic catheter smoothly navigated to the target region and successfully unclogged the pseudo blood clot.

V. CONCLUSION

We propose a novel magnetic catheter structure that can selectively generate steering and unclogging motions. The proposed magnetic catheter can directionally steer and unclog the blood clot using two modules with rotating ring magnets and controlling the EMF. We modeled the deflection of the catheter using the large deflection Euler-Bernoulli beam model and developed a design method to determine the optimal distance between magnets in order to maximize steering performance. We prototyped a magnetic catheter with the model-determined optimal distance and conducted several experiments to verify the theoretical model and assess the steering and unclogging capabilities of the proposed magnetic catheter. The proposed theoretical model well represents the deflection of the catheter, and the prototyped magnetic catheter successfully generated steering and unclogging motions. This research could help expand the medical applications of magnetic catheters for unclogging and drug or stent delivery.

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