Selective separating and assembling motion control for delivery and retrieval of an untethered magnetic robot in human blood vessels

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ABSTRACT
We developed an integrated magnetic robot (IMR) that can selectively separate and assemble tethered and untethered magnetic robots. The proposed IMR is composed of a flexible-legged untethered magnetic robot (FLUMR) and a delivery catheter. Assembled magnets (AMs) with zero net magnetic moment are placed at the distal tip of the catheter and the rear part of the FLUMR. A selective separating and assembling (SSA) mechanism was proposed that can control the separating and assembling motion by an external magnetic field (EMF) to generate relative rotational movements between the catheter and FLUMR by selectively producing the attractive and repulsive forces between AMs. Finally, the IMR was prototyped to verify the SSA mechanism, and the separation, mobility, drilling, and retrieval of the developed IMR using SSA mechanism was verified in in vitro experiments.

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I. INTRODUCTION
Vascular intervention is a popular medical procedure to treat vascular diseases. The intervention is minimally invasive due to the use of a catheter, a thin and flexible tube, to treat vascular diseases through the human vascular system. However, precisely controlling the magnitude and direction of the force and the torque at the distal part of the catheter is almost impossible and the medical staff is constantly exposed to a high-dose radiation from X-ray imaging devices during the vascular intervention. To replace the conventional catheter, untethered medical magnetic robots have been studied and applied to various biomedical fields including the treatment of vascular diseases. Magnetic robots, which have a simple and small structure, are wirelessly manipulated using an external rotating magnetic field (ERMF) generated by a magnetic navigation system (MNS). Ishiyama et al. proposed a spiral wireless micromagnetic robot capable of controlling the swimming direction in liquids. Lee et al. proposed a flexible-legged magnetic robot capable of supporting vascular walls that can enhance stability while moving under pulsatile flow by incorporating flexible legs into a magnetic robot. However, magnetic robots have not been applied to blood vessels with fast blood flow due to insufficient propulsive magnetic force or torque generated by MNS. In the worst case, the magnetic robot may be lost due to disturbance while driving to the lesion or returning after treatment. Development of a mechanism for stable delivery and retrieval of the magnetic robot to be effectively used in vascular treatment is important.

In this paper, an integrated magnetic robot (IMR) composed of a flexible-legged untethered magnetic robot (FLUMR) and a delivery catheter, as shown in Figure 1, is proposed. The robot has a selective separating and assembling (SSA) mechanism to deliver and retrieve the FLUMR using a delivery catheter. First, analyses and experiments were conducted to determine the torque condition for separating and assembling motion. Finally, several experiments in pseudo blood vessels were conducted to verify SSA mechanism.

II. PRINCIPLES OF MANIPULATION
The proposed IMR consists of a FLUMR and a delivery catheter as shown in Figure 1(a). Assembled magnets (AMs) are attached to the rear part of the FLUMR and distal tip of the delivery catheter.
The AM is designed to have zero net magnetic moment by combining two axially magnetized half-ring type magnets to prevent unnecessary movement caused by an external magnetic field (EMF).

The FLUMR is composed of a body magnet, AM, flexible legs, and drill tip as shown in Figure 1(a). Magnetic torque generated by the body magnet of the FLUMR under the ERMF can be expressed as follows:

\[ T = m \times B \]  

where \( m \) is the magnetic moment of the magnet and \( B \) is the magnetic flux density of the ERMF. The magnetic torque generates a rotating motion of the body magnet along the ERMF. The ERMF can be expressed as follows:

\[ B_R(t) = B_0 (\cos 2\pi f_U + \sin 2\pi f_N \times U) \]  

where, \( f_U \), \( f_N \), and \( U \) are the rotation frequency of the ERMF, the unit vector of the rotation axis, and the unit vector perpendicular to \( N \), respectively. Because the rotating motion of the body magnet generates a propulsive force on the FLUMR, the FLUMR can be manipulated using the ERMF.

The delivery catheter is composed of a flexible tube, AM, and a spacer. The spacer has a cup-shape with wider top than bottom, which makes the coupling with FLUMR easier while retaining the minimum distance from FLUMR, securing the axis when the FLUMR rotates and enabling stable separation and retrieval. When AMs in the FLUMR and delivery catheter encounter opposite polarities, they can be assembled based on attractive forces. When the rotating motion of the FLUMR occurs due to the ERMF and the same poles of the AMs in the FLUMR face the AMs with the delivery catheter, a repulsive force is generated and the FLUMR is separated from the delivery catheter. Therefore, based on the ERMF, the SSA mechanism can be operated by selectively generating attractive and repulsive forces as shown in Figure 1(b). After separation, the FLUMR can perform a propulsive, drilling motion, or maintain a position using the flexible legs attached to the front and rear parts.

The magnetic assembling torque between the two AMs and the resistance torque are generated when the FLUMR rotates in the vessel. The resistance torque includes the environmental conditions, such as the shear stress of the fluid and friction generated in the
vessel wall and combining part. Therefore, the condition of the FLUMR separating from the delivery catheter is as follows:

\[ T_{\text{ERMF}} > T_{A} + T_{R}, \quad \text{(Separating)} \]

where \( T_{\text{ERMF}} \) is rotational torque caused by ERMF, \( T_{A} \) is assembling torque between AMs, and \( T_{R} \) is the resistance torque generated by environmental conditions.

### III. RESULTS AND DISCUSSION

To verify the SSA mechanism, the IMR has been prototyped as shown in Figure 2. The FLUMR is 2 mm in diameter and 17 mm in total length and includes a diametrically magnetized cylinder magnet (N52 grade NdFeB) 10 mm in length as the body magnet and two axially magnetized half-ring type magnets (N52 grade NdFeB) 1 mm in length as AMs. The delivery catheter consists of an AM and a spacer in a 6 Fr silicon tube. The front part, rear part, and spacer are made of ultraviolet curable acrylic plastic using 3-dimensional printing technology. The thickness of the spacer is 0.3 mm.

The MNS used in this study consists of a Helmholtz coil that produces uniform magnetic fields along the x-axis and two pairs of saddle coils that produce uniform magnetic fields along the y- and z-axes.\(^5\) It can generate a magnetic flux density of up to 14 mT and rotating magnetic field in all direction. Rotational torque produced at the body magnet by ERMF and assembling torque produced between the two AMs were calculated using the finite element analysis with ANSYS Maxwell, as shown in Figure 3(a).

To obtain the resistance torque, the prototyped IMR was placed in a glass tube (10 mm inner diameter) filled with water, as shown in Figure 3(b), and the ERMF with frequency of 5 Hz was applied in MNS at 1 mT intervals to determine the magnetic flux density of the ERMF to separate the FLUMR. The FLUMR was

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**FIG. 3.** (a) Assembling and rotational torques calculated using finite element analysis (b) Separation experiment.
separated by the magnetic torque generated at 9 mT for the 0.3-mm-thick spacer. The resistance torque can be estimated using equation (3). In the analysis, the assembling torques were 99.01 μN m for the 0.3-mm-thick spacer, and the rotational torques generated by ERMF were 171.2 μN m at 6 mT, 199.9 μN m at 7 mT, 228.6 μN m at 8 mT, and 257.3 μN m at 9 mT. Thus, the resistance torque can be estimated as between 129.59 μN m (=228.6-99.01) and 158.29 μN m (=257.3-99.01), which corresponds to the rotational torques generated by the application of the ERMF between 3 mT and 6 mT.

Finally, in vitro experiments were conducted in a pseudo vessel environment to verify the proposed SSA mechanism of the proposed IMR, as shown in Figure 4. In a water-filled Y-shaped glass tube with an inner diameter from 7 mm to 11 mm, a pseudo blood clot was made with 5% agar on one branch of the glass tube. In step 1, the IMR was inserted into a glass tube with an inner diameter of 11 mm, and in step 2, to perform the SSA mechanism, an ERMF of 10 mT greater than the minimum condition (9 mT) was applied at a rotational frequency of 5 Hz around the x-axis, which rotates the FLUMR to perform a separating motion. Once the FLUMR was separated, the same ERMF was applied to rotate FLUMR and generate propulsive motion with a velocity of 4 cm/s. In step 3, the ERMF of 10 Hz was applied along 30° with respect to the x-axis to enter the branch, and the FLUMR moved within a narrow tube with a 7 mm inner diameter with a velocity between 1 and 2 cm/s to reach the front of the pseudo blood clot. After reaching the clogged region, ERMF with a frequency of 20 Hz was applied to drill a pseudo blood clot, as shown in step 4. By applying the ERMF with the opposite direction, the FLUMR moved back to the region near the delivery catheter. Finally, the FLUMR was retrieved by reassembling with the delivery catheter by applying an ERMF of 3 mT in step 6, which was smaller than the separating magnetic field. In this experiment, the proposed IMR successfully performed SSA mechanism and demonstrated its mobility and tunneling performance, as shown in Figure 4(b).

IV. CONCLUSION

In the present study, an SSA mechanism was proposed and utilized to develop an IMR composed of a delivery catheter and a FLUMR. The proposed SSA mechanism can be operated by applying the appropriate ERMF to generate attractive and repulsive forces between AMs to selectively and stably separate and assemble the FLUMR from the delivery catheter. To verify the effectiveness of the proposed mechanism, the IMR was prototyped and several experiments conducted. The experiments showed the proposed IMR could overcome the assembling torque between AMs and the resistance from the environmental conditions and perform SSA mechanism within the pseudo vessel based on the ERMF. The results from this study can contribute to expanding the application area of magnetic robots by proposing a safe and effective delivery and retrieval method of magnetic robots in the human body.

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