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Intestinal Tattooing Mechanism Integrated with Active Wireless Capsule Endoscope

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***Abstract* — Recently, a wireless capsule endoscope with active locomotion has become an effective endoscopic method for diagnosis and treatment of diseases of gastrointestinal (GI) tract. Various modules such as biopsy and drug delivery were developed for the wireless capsule endoscope (WCE) to extend its application. In this paper, we present a marking module so-called tattooing module for WCE to localize the lesions and tumors in digestive organs before the laparoscopic surgery. The WCE with tattooing module is manipulated by an Electromagnetic Actuation (EMA) system, where a moderate magnetic field intensity is generated to drive the WCE reaching to a target of the digestive organs. The tattooing module is capable of stowing the needle inside the WCE's body to avoid pathway organs damage during locomotion and extruding to puncture the target for tattooing. The magnetic field is controlled to activate the micro-reed switch and triggers a chemical reaction that generates gas pressure. The produced gas increases the pressure in the propellant room and pushes the piston to eject the ink into the target. The prototype of the tattooing capsule endoscope is fabricated with dimension of 13 mm in diameter and 33 mm in length. The working principle and the mechanism of the tattooing module are suggested and the feasibility test with the prototype is demonstrated through in-vitro experiments.**

***Index Terms* — active locomotive capsule endoscope, wireless capsule endoscope, tattooing capsule endoscope, electromagnetic actuation, gastrointestinal tract**

I. Introduction

Wireless Capsule Endoscope has revolutionized the endoscopic method for gastrointestinal (GI) tract since introduced in 2000 [1]. There have been several companies launched commercial Capsule Endoscope (CE) such as Miro (Intromedic, Korea) [2], PillCam (Given Imaging, Israel) [3], OMOM (Jinshan, China) [4], and Endocapsule (Olympus, Japan) [5]. The pill-size capsule is equipped with a camera to visualize the inner wall digestive organs. The CE then is moved by peristaltic motions and send the captured images to the external storage device for historical analysis. However, because of the passive locomotion, the CE has many limitations of working environment, it can scan only tubular organs such as esophagus and small intestine. Moreover, they are not able to interact with tissue to take biopsy samples or deliver drug due to lack of active movement [6]. To address these limitations, the next generation of WCE with a magnetic object inside was proposed which can be externally driven and controlled by an Electromagnetic Actuation (EMA) system in digestive organs [7]-[13]. Afterward, many research groups focused on developing the functional wireless capsule endoscope for sensing, drug delivery and biopsy which can be done by traditional flexible endoscopy [14]-[18].

In this paper, for the purpose of expanding the WCE applications at clinical sites, we present a novel mechanism of tattooing module for active locomotion intestinal capsule endoscope (ALICE). The proposed system can localize the lesions, tumors or polypectomy sites in digestive organs which remains a challenge to endoscopic clinicians. Traditionally, this procedure can be done by endoscopic tattooing in which the doctors use a flexible endoscopic instrument for the marking of small colorectal lesions before the laparoscopic [19], [20]. However, this tool can cause pain, fear or sedation side effects for the patient. Moreover, the stiffness of the device limits the abilities to mark the depth positions. Hence, we develop a tattooing module which can be integrated to the ALICE for identification of GI lesions by utilizing the advantages of active capsule endoscope [21]. Despite the introduction of several function for WCE such as biopsy and drug delivery, developing tattooing module is not widely studied due to many difficulties. The size of capsule is too small so designing a controllable injection mechanism is a big challenge. Moreover, for safety issue the tattooing needle must be controllable. It should be kept inside CE's body during locomotion and extruded out to puncture target.

The remainder of this paper is organized as follow. Section II presents the conceptual design of the ALICE with tattooing module. The details about the module's components, working principle and how the needle is extruded are described in this part. Section III shows the fabricated prototype of the tattooing module integrated ALICE and the in-vitro tests of the tattooing capsule endoscope in a segment of pig's small intestine is demonstrated. Finally, we draw a conclusion in Section IV.

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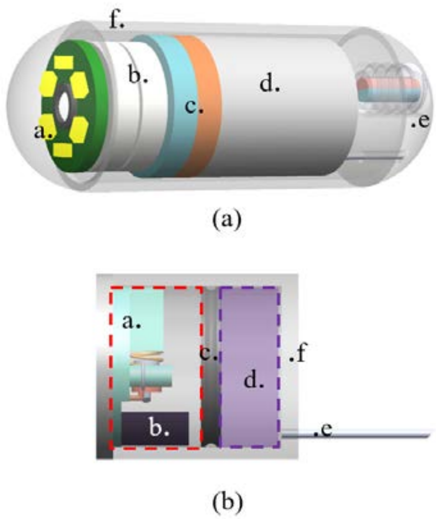

Figure 1. Schematics of the ALICE with tattooing; (a) Conceptual design of the ALICE with tattooing tool; a. camera and telemetry module, b. battery, c. cylindrical permanent magnet, d. tattooing module, e. needle extrusion module, and f. capsule endoscope outer body; (b) Side view of the tattooing module; a. spring-gun part using SMA, b. water container, c. piston, d. ink, e. needle, and f. tool body.

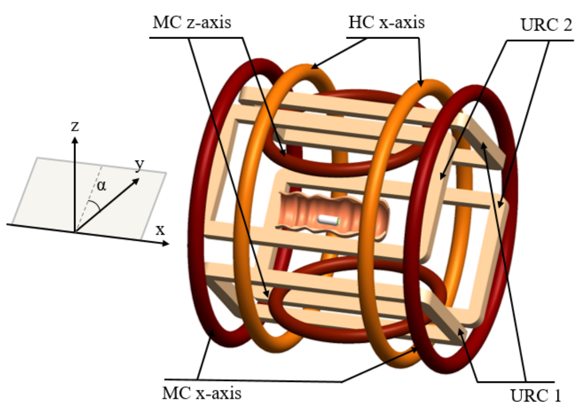

Figure 2. EMA system configuration in which MC is Maxwell coil, HC is Helmholtz coil and URC is Uniform rectangular coil.

II. Material and Method

A. System overview

The suggested tattooing module is based on the active locomotion wireless capsule endoscope that can scan the entire whole digestive organs utilizing magnetic actuation [21]. A conceptual design of the active locomotion capsule endoscope equipped with tattooing tool is shown in Fig. 1(a). The capsule has shape of a large pill and composed of four main functionalities: visualization, active locomotion, tattooing, and needle extrusion. Normally, the CE has a tiny camera with lighting system powered by batteries and the captured images are transmitted to external monitor or storage device for analysis. In order to control the capsule motion actively in GI tract, the locomotion part including a permanent magnet (LPM) is added inside the CE. In the region of interest (ROI), the LPM interacts with the dynamic magnetic field

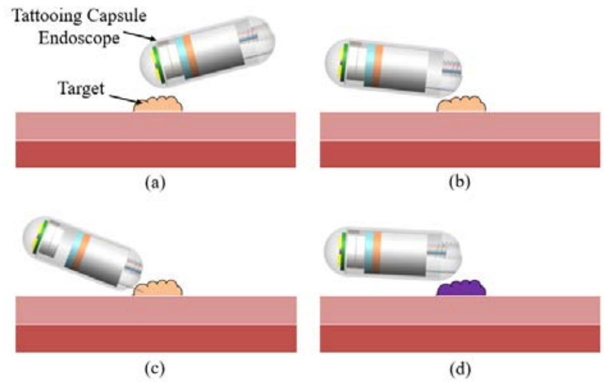

Figure 3. Tattooing procedure in sequence (a) Locomotion for scanning the GI tract, (b) Going to the target, (c) Extruding the needle and Tattooing, (d) Withdrawing needle and moving out.

generated by an EMA system as depicted in Fig. 2. The schematic of the tattooing tool is introduced in details in Fig. 1(b). The tool's body is closed with two compartments separated by a piston: propellant chamber and ink cartridge. The propellant chamber contains a mixture of two chemical powders (1.3 mg citric acid and 0.5 mg sodium carbonate) and a reservoir with 0.02 ml water. The chemical reaction between these substances occurs with contacting of the water that generates carbon dioxide (CO_2) gas. The produced gas increases the pressure in the propellant chamber. When the pressure reaches to approximately 7kPa the resultant force is sufficient to push the piston. As the result, the ink is ejected from its cartridge to the desired layer of the organ via a tattooing needle. We used a 26-gauge needle for actual implementation of the ink ejection mechanism. The amount of pressure can be regulated in accordance with the ratio of the solutions and water. In this research, we use the India Ink which is common in endoscopic tattooing [22], [23]. The ink is diluted with water in ratio of 1:100 to reduce the viscosity [24].

In order to keep the needle safe inside the CE's body, the needle extrusion mechanism is suggested for the tattooing capsule. When the patient swallows the CE, the needle should be stowed inside the capsule body during scanning procedure to avoid the damage to the internal wall of the pathway organs. And the needle is extruded out 2 mm when the CE reaches to the target lesion. The CE then is controlled to puncture the mucosal layer with depth of about 1 mm angle of 30-degree with respect to tissue surface. Finally, the ink is injected beneath the mucosal layer with a depth which is from 0.6 to 2.2 mm that depends on the organs [22]. After completing the tattooing process, the operator controls to withdraw the needle to the initial position and continue visual diagnosis task. To achieve this procedure, we used a small-size permanent magnet and utilized screw mechanism. The permanent magnet, together with screw mechanism, can move along the longitudinal direction of the CE and the wireless control of the needle motion can be implemented. Finally, the operator can control the needle pushing out or pulling into the capsule body by the gradient magnetic field as well as locomotion. The details will be explained at the next sections. Fig. 3

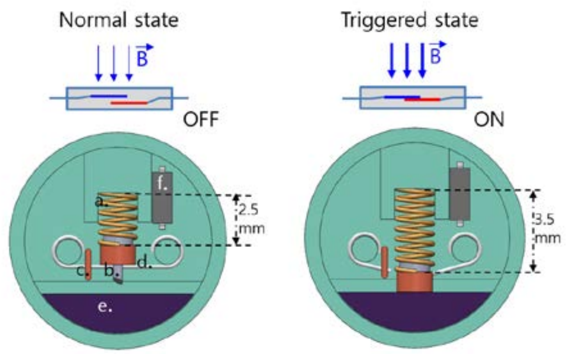

Figure 4. SMA triggering module using reed switch with components (a. spring, b. micro-needle, c. shape memory alloy, d. polymer string, e. water reservoir, f. reed switch).

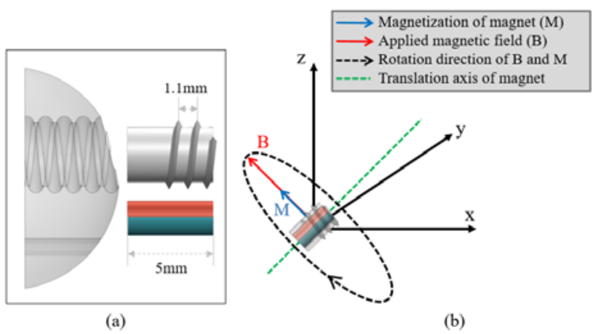

Figure 5. (a) Needle extrusion module components, (b) Actuation mechanism using rotation magnetic field.

describes in sequence the tattooing procedure with proposed capsule endoscope equipped tattooing module.

B. *Tattooing: ink ejection module*

The tattooing procedure should be performed at the exact time when the CE reaching to the target; otherwise, the chemical powder mixture is separated from water to have no chemical reaction. For the tattooing triggering, we incorporated a reed switch that can switch on and off a shape-memory alloy (SMA) wire by controlling external electromagnetic field. The reed switch is a small-size electrical device excited by specified threshold of magnetic field intensity.

Fig. 4 shows the design of the SMA module for triggering the chemical reaction. The water reservoir contains 0.02 ml water and is sealed by a membrane made of polyamide which is inert with acid citric and sodium carbonate. A micro-needle is attached at the end of a helical spring and suspended above the membrane 0.7 mm by a polymer string so that the initial compression distance of the spring is 2.5 mm. When the reed switch is on, the SMA wire is heated up by the electrical current and cuts the polymer string. The micro-needle then is released to break the membrane. At that moment, water in the reservoir contacts with the chemical powder mixture and the chemical reaction takes place producing the carbon dioxide gas. The tattooing module is closed; therefore, the chemical powders and produced solutions including the gas could not leak out. In order to turn on the reed switch, one needs to apply the magnetic field intensity that has a value higher than excited level (pull-in value) of reed switch. In this study, we used a normally-open-contact type RI-80 SMA Series Dry reed switch (Shenzhen Fast Sensors Company), which is single-pole and single-throw type with 5 mm in length and 1.8 mm in height. Because of the magnetic field flux density around the LPM, it is necessary to boost the pull-in value of the switch for wireless control. By using the Mu metal sheet to cover the switch, the excited level can be modified to a desired value which is 50 mT in our design. It means when the magnetic field density is equal or higher than 50 mT, the switch turns on and triggers indirectly the chemical reaction to produce the carbon dioxide gas.

We also considered the power consumption for the tattooing module due to the limitation of the battery. We used a SMA made of Nickel-Titanium with the diameter of 0.3 mm and the length of 7 mm. By experiment, the SMA wire consumed approximately 20 W to cut the string in 2 second, which is about 2.3% of the full capacity of the CE's cell battery (3.0V, 160mAh).

C. *Tattooing: needle extrusion module*

Keeping the tattooing needle inside the capsule to avoid the damage to the digestive organs is important for tattooing capsule endoscope, because it will be swallowed through the mouth and controlled to move in GI tract. Hence, we designed a module to extrude and retract the needle in utilizing screw motion. Fig. 5(a) shows the needle extrusion mechanism using a cylindrical permanent magnetic, named key permanent magnet (KPM), with diameter of 1 mm and length of 5 mm. The KPM is attached to a screw-shape body with the 3 pitches of 1.1 mm and they can rotate along their axial axis. Fig. 5(b) describes the actuation mechanism of extrusion needle module. The rotation magnetic field causes the rotating of the KPM inside the needle module body due to the magnetic toque. The screw mechanism converts the rotation motion of the KPM to the translation motion along the rotation axis. The changing in rotation direction of the applied magnetic field reverses the translation direction of the magnet, which works as a key to lock or unlock the motion of tattooing module. During the locomotion time, the KPM locks the tattooing module, the LPM interacts with the external magnetic field making the motion of the CE as depicted in Fig. 3(a). At the target, the KPM is rotated by the external magnetic field to unlock the tattooing module as illustrated in Fig. 3(b). After the tattooing process finishes, the needle is withdrawn, the rotation magnetic field is generated with reverse direction to lock the motion of the tattooing module.

Table 1. Specification of the EMA system

Coils	HC x-axis	MC x-axis	MC z-axis	URC 1, 2
Radius (mm)	195	195	100	n/a
Width x Length (mm)	n/a	n/a	n/a	156 x 337
Distance (mm)	195	337	173	200
Coil turns	710	1426	660	600

D. *ALICE controlled by the EMA system*

To test the tattooing mechanism, we used a lab-scale EMA system to generate electromagnetic field as shown in Fig. 2. The EMA system has 5 pairs of coil which can control the proposed CE in 5 degree-of-freedom (DOF). The system has two pairs of Uniform rectangular coils and one pair of Helmholtz coils to generate the magnetic torque aligning the microrobot to the desired direction, and two pairs of Maxwell coils are used to produce the propulsion force of the CE. Coils of two pairs of uniform rectangular coil are fixed on four sides of the square which conjugate with *xy* plane an angle α of 45 degrees as shown in Fig. 2. The specification of the EMA system is summary in Table 1.

The magnetic torque and force exerting on permanent magnet in region of interest (ROI) of the magnetic field can be expressed as the following formula:

$$\vec{\tau} = \mu_0 V \vec{M} \times \vec{H} \tag{1}$$

$$\vec{F} = \mu_0 V (\vec{M} \cdot \nabla) \vec{H} \tag{2}$$

where μ_0, V and $\vec{M}$, $\vec{H}$ are magnetic permeability of free space, volume and magnetization value of microrobot and the magnetic field intensity, respectively. The magnetic torque performs aligning the CE to the desired direction while the magnetic force produces the propulsion force to drive the CE following the planned path. We can get these values to control the CE in GI tract by calculating magnetic field intensity generated by each coil. The magnetic field near the center of the Helmholtz coils are calculated as followings [21]:

$$\vec{H}_h = [d_h \quad 0 \quad 0]^T \tag{3}$$

$$d_h = 0.7155 (n_h \times i_h) / r_h \tag{4}$$

where i_h, r_h, n_h are the applied current, radius and number of turns of Helmholtz coil, respectively. Since, the pair of rectangular coil is placed on a plane of 45-degree surface corresponding to *xy* plane, the magnetic field of near the center between two coils in *xyz* coordinate can be described as followings:

$$\vec{H}_{uc} = [0 \quad \frac{\sqrt{2}}{2} d_{uc} \quad -\frac{\sqrt{2}}{2} d_{uc}]^T \tag{5}$$

$$d_{uc} = 0.373 \frac{n_{uc} \times i_{uc}}{w_{uc}} \tag{6}$$

where d_{uc} is the magnetic field intensity in Ampere per meter unit in the ROI of the Uniform rectangular coil. n_{uc}, i_{uc}, and w_{uc} denote the number of turn, current and the width of the coil, respectively. The magnetic field creates the magnetic torque are aligning the microrobot within the effective region. After navigating the microrobot to the desired direction, Maxwell coils are powered to produce uniform gradient field which pushes the CE moving along with the determined path line. The magnetic field intensity $\vec{H}_m$ of the Maxwell coil is given as the following formula [18]:

$$\vec{H}_m = [g_m x \quad -0.5 g_m y \quad -0.5 g_m z]^T \tag{7}$$

$$g_m = 0.6413 (n_m \times i_m) / r_m^2 \tag{8}$$

where i_m, r_m, n_m are the applied current, radius and number of the Maxwell coil turns, respectively.

III. Experimental Results

A. *Fabrication of the ALICE with tattooing module*

The prototype of the capsule endoscope with the tattooing tool was fabricated using commercial components and rapid prototyping method. Fig. 6(a) illustrates the printed components of capsule body and tattooing tool using 3D printer Objet 30 Pro (Stratasys Direct Manufacturing Ltd, USA) with material VeroWhitePlus RGD835. The spring-gun using SMA module in Fig. 6(b) consists of a helical type spring with 5 mm in total height and spring constant of 0.5

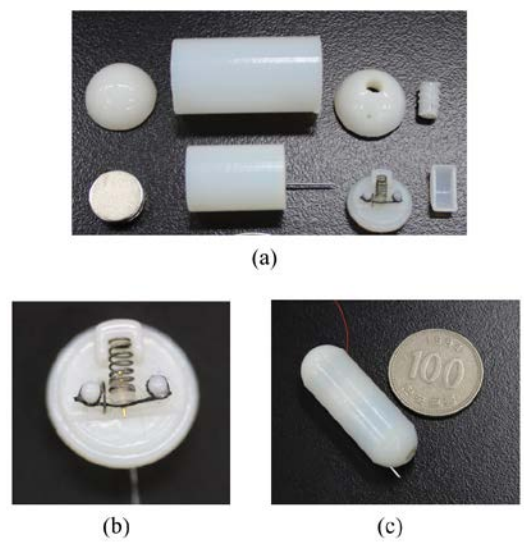

Figure 6. (a) 3D-printed components of the ALICE with tattooing module, (b) Spring-gun using SMA module, (c) Assembled tattooing capsule endoscope.

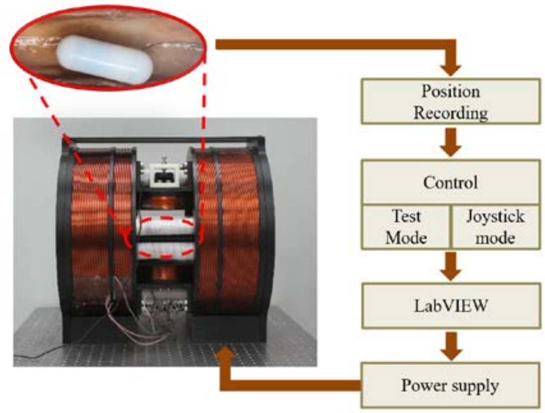

Figure 7. Schematic of experiment setup.

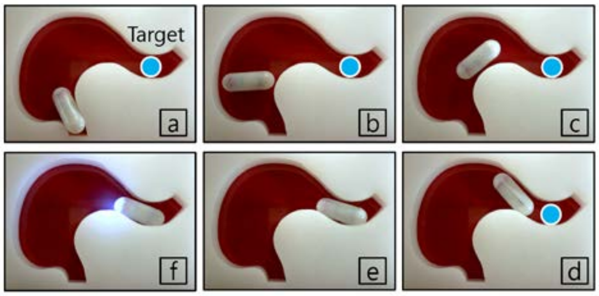

Figure 8. Verification of the performance of reed switch in stomach phantom. (a) Starting position, (b)-(d) Going to the target-the cyan, (e) Reaching to the target, (f) Activating the micro-reed switch.

N/mm purchased from MISUMI Corporation (Korea). The SMA made of Nickel-Titanium has dimension of 0.3 mm in diameter of and the 7 mm in length. The permanent magnet for locomotion has cylindrical shape (JL Magnet, Korea) with the diameter of 10 mm and the height of 3 mm, the magnetization direction is along with the longitudinal axis of the magnet. Fig. 6(c) shows the assembled tattooing capsule endoscope that has the dimension of 13 mm in diameter and 33 mm in length. In this research, to test the performance of proposed tattooing mechanism, the capsule body was fabricated using 3D printer with the thickness of 1 mm and the gap between tattooing module and capsule body is 0.5 mm. So the capsule size can be reduced by minimized these parameters with other material and better fabrication method.

B. *Experimental setup*

The experimental setup is illustrated in Fig. 7 to evaluate the performance of proposed tattooing module. A small size camera from Logitech was attached inside the EMA system for recording position of the CE. For the direction controlling, we used a conventional joystick controller from Logitech while the magnitude of magnetic field and gradient field are inputted from keyboard. The power suppliers were MX12 (2EA) and 3001LX (3EA) from California Instrument controlled by LabVIEW to provide input current into coils.

C. *In-vitro experiments*

The tattooing process of the suggested tattooing mechanism can be divided into two steps: locomotion to the target lesion and turning on the reed switch to break water reservoir that can trigger the gas production chemical reaction.

Firstly, we conducted a verification test of the reed switch performance with modified pull-in value due to the invisible activation process from outside of the CE. We replace the SMA module with a LED circuit connected in series to the reed switch and cell batteries in the ALICE prototype to check if the reed switch works correctly. The state of reed switch must be inactive during the locomotion; the magnitude of external magnetic field intensity is lower than modified pull-in value of the switch. The applied magnetic field is increased to the activation threshold of the reed switch to close the LED circuit once the ALICE reaches to the target. Fig. 8 shows the performance of the reed switch in a stomach phantom. The CE was controlled by the EMA system moving to the target while the LED is off, which is corresponding to the inactive state of the reed switch. When reaching to the target position, the operator adjusted the value of the applied magnetic field intensity to higher than 50 mT. The LED was turned on, which corresponds to the activated state of the switch. Therefore, we could confirm that the performance of the modified reed switch was correctly working.

Secondly, we conducted an *in-vitro* tattooing test using the fabricated ALICE prototype with the tattooing tool. For the feasible experiment of the tattooing capsule endoscope, we used a segment of the small intestine extracted from a pig. The CE was powered by external power supply due to the limitation in fabrication. As shown in Fig. 9(a), the CE moved forward and backward smoothly by generating the external magnetic field to align the CE to the desired direction and then overlaying the gradient field to push it along the planned path.

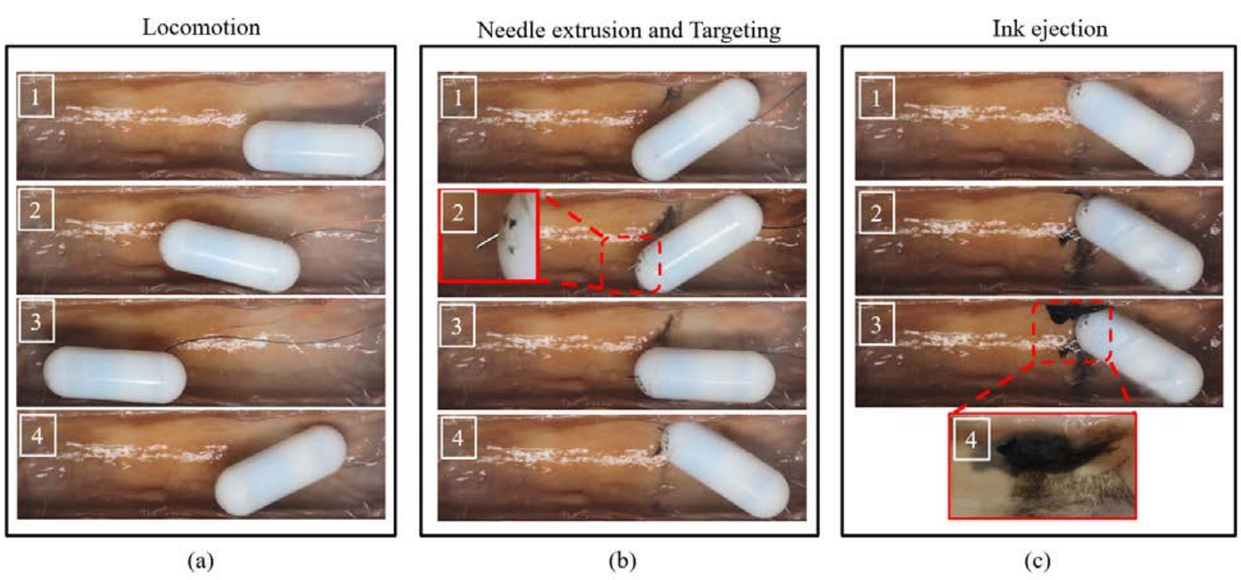

Figure 9. In-vitro experiment. (a) Locomotion forward (1-2-3)/backward (4) of the tattooing capsule endoscope; (b) Needle extrusion and rotation for targeting of lesion position (2-lower, 3-side, 4-upper); (c) Ink injection process (1-2-3), closed-up view of tattooing point (4).

When the CE reached to the target point, the rotation magnetic field was created to translate the key permanent magnet, which unlocks the tattooing module. Then, the operator aligned the CE body an angle of 30 degrees with respect to tissue surface and created gradient magnetic field in the same direction to push the tattooing module out. Afterward, the gradient field was turned off, the needle was orientated to the position of the target as shown in Fig. 9(b). Next, the gradient field was applied again to inject the needle to the intestinal wall until the whole needle penetrate the tissue with estimation depth of 1 mm. Finally, the SMA was heated to trigger chemical reaction, the ink was ejected into the target after 28 second as shown in Fig. 9(c). The intestine then was taken out for inspection at close-up view. From Fig. 9(c), we confirm that the presented tattooing capsule endoscope could puncture and eject the ink into the correct position beneath the mucosa layer.

IV. CONCLUSION

In this paper, we proposed a tattooing module for the active locomotion capsule endoscope to localize the lesions or tumors in GI tract, which is currently performed by a flexible tattooing endoscope with skillful clinician. The suggested tattooing CE was wirelessly operated by an external EMA system utilizing fully the multi-degree-of-freedom locomotion. The fabricated capsule endoscope with tattooing module was successfully driven inside the GI tract, approached to the target lesion, and performed tattooing. The EMA could activate the magnetic reed switch to power the SMA and eventually trigger tattooing ink ejection. The resultant force of the generated gas pressure from chemical reaction could push the piston and eject the ink into the target. Up to our knowledge, this is the first prototype of active locomotive capsule endoscope equipped with tattooing functionality. The suggested tattooing capsule endoscope can be a promising alternative approach for endoscopic tattooing in clinical sites. Future works will include developments of multifunctional capsule endoscope mechanisms by utilizing the suggested triggering method and chemical reaction as well as integration to the capsule endoscope.

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