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Design of A Novel Biopsy Capsule Robot with Anchoring Function for Intestinal Tract

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***Abstract*—This paper presents a biopsy capsule robot with anchoring function inside the intestinal tract. The proposed biopsy capsule consists of three modules: biopsy module, anchoring module and decouple-drive module. The design of the biopsy module and anchoring module is based on the eccentric cam mechanism and ratchet mechanism. The structure design and motion analysis of the biopsy mechanism and anchoring mechanism is presented. The designed decouple-drive module consists of two parts: a magnetic-drive shaft and two elastic-pawls. Benefiting from the combination of the elastic-pawls on the decouple-drive module and the ratchets on the two function modules (i.e. biopsy and anchoring module), the two function modules can be driven by a single actuator, which can further help reduce the size of biopsy capsule robots and achieve miniaturization. The design concept and working principles of the proposed biopsy capsule are introduced in this paper and are verified by a prototype with the diameter of 16mm and length of 24mm that successfully integrates the three modules.**

***Index Terms*—biopsy capsule robot, anchoring function, wireless capsule endoscope, intestinal tract.**

I. Introduction

Currently, medical technology is dedicated to the diagnosis and treatment of minor injuries. In the examination of gastrointestinal (GI) diseases, the introduction of wireless capsule endoscope (WCE) subverts the traditional examination method and greatly reduces the discomfort of patients. Commercial WCE [1], such as PillCam SB2, EndoCapsule, MiroCam and OMOM PillCam, have been widely applied in the image acquisition of suspicious tissues inside the GI tract.

However, current WCE require additional functions to complete the comprehensive inspection and treatment of GI tract. A disadvantage of WCE is that it cannot carry out biopsy sampling while suspicious tissues are found, which means additional operation is needed after the examine [2]. Therefore, a variety of capsule endoscope with biopsy function have been designed to enrich the application of WCE. Several biopsy mechanisms with shape memory alloy (SMA) have been reported [3] [4] [5]. However, the SMA actuation has some drawbacks, including high power consumption, low reaction speed (due to the required heating and cooling cycles), poor controllability and short functional lifetime. Furthermore, M.Simi et al. developed a biopsy capsule based on a magnetic torsion spring and the blade [6], which successfully cut a tissue when the external magnetic field is removed in the vitro trials. However, the magnetic torsion spring that composed of four circular magnets occupies a large space and is hard to be integrated into the current commercial WCE. Recently, Manh Cuong Hoang et al. presented a novel active locomotive biopsy capsule endoscope [7], which can perform both locomotion and biopsy operations under the control of external magnetic field from the electromagnetic actuation (EMA) system. When the capsule endoscope is cutting a suspicious targeted lesion, both the external rotating uniform and gradient magnetic fields are required at the same time and the strength ratio of the two kinds of magnetic fields needs to be controlled precisely. Otherwise, it will cause unstable motion of the capsule endoscope and even damage to the intestines.

Meanwhile, the commercial WCE face another problem of active control. WCE used for image collection rely on the natural peristalsis to move inside the GI tract, and it cannot anchor at the specific location at a specific time to monitor suspicious tissues, which limits the further improvement of diagnostic accuracy based on images. Cases of missed diagnosis due to the lack of anchoring ability of WCE have been reported in literature [8]. What's more, the capsule endoscope without anchoring ability is hard to complete the therapeutic applications well such as targeted biopsy and drug delivery [2] [9]. Thus, studies have been carried out for the anchoring modules for WCE [10] [11]. Hao Zhou et al. designed a magnetically actuated anchoring mechanism by using the principle of a switchable magnetic spring [12], which can be actuated by applying an external magnetic field and easily integrated into commercially available capsules. However, the end of the anchoring mechanisms are legged shape and not smooth enough. Thus, it's hard to ensure that when working in the intestine, the anchoring mechanisms do not damage the intestinal wall.

Based on the above analysis, it can be concluded that a capsule should have the aid of anchoring mechanisms to complete the image acquisition, biopsy or targeted drug delivery function well. However, most of the designed capsule prototypes can only perform one of these functions (anchoring,

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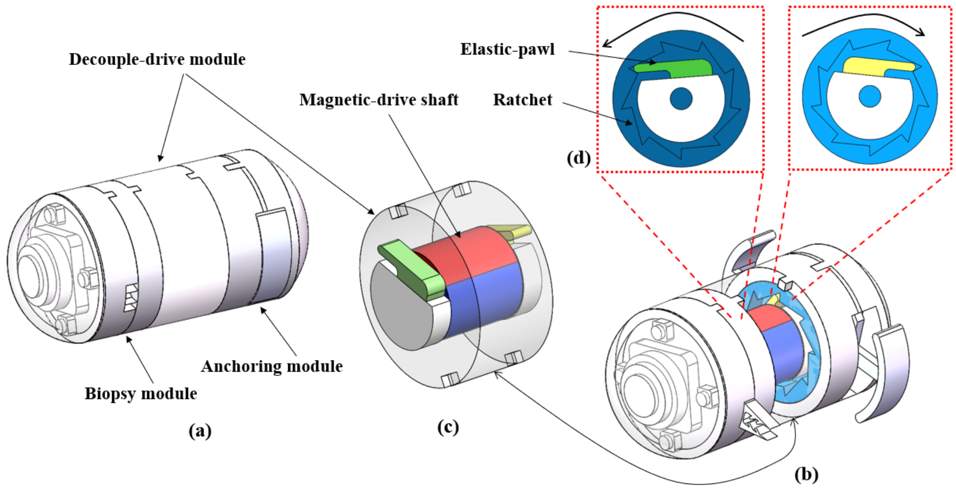

Fig. 1. Concept design of the proposed biopsy capsule robot, which is capable of anchoring at the targeted position and performing biopsy operation under the external magnetic field. (a) initial state of the designed biopsy capsule. (b) the biopsy capsule is in working state with the biopsy spike and circular-arc legs fully extended. (c) structural schematic diagram of the decouple-drive module. (d) schematic diagram of the matching relationship between elastic-pawls and ratchets.

biopsy, drug delivery .etc.), or do multiple functions by using multiple actuators without considering the space consumption or energy consumption. For example, in [13] , Stephen P. Woods et al. proposed a drug delivery capsule with holding mechanism. Driving by two on-board micromotors, the capsule can resist peristalsis and delivery 1ml drug at the targeted location. Nevertheless, the power consumption of the motors and the complex mechanical structure limit its further application. In literature [4], a biopsy device for capsule endoscopy was introduced, which can firmly fix the capsule endoscope in the lumen of the intestine and cut tissues with two cylindrical razors, a spiral spring and a trigger. However, since at least four SMAs require to be heated, it takes at least 300 J energy for one trial of biopsy, which is a huge energy consumption compared with the capacity of a Li-Po battery (30mAh at 5V, the total energy is 540 J).

In this paper, in order to maintain low power consumption and low space occupation when capsule endoscopes have multi-function, we propose an intestinal biopsy capsule robot with the anchoring function, which only integrates one circular-ring magnet as the actuator and can be controlled by EMA system. Based on the ingenious application and combination of the eccentric cam mechanism and ratchet mechanism, the proposed biopsy capsule can realize decoupling between biopsy and anchoring module, so that the two functional modules can be driven by one actuator. Further, the proposed method for decoupling between modules will contribute to the current efforts to widen the capabilities of WCE and other in-body robotic systems.

Structure of this paper is organized as follow: design concept and analysis of the proposed biopsy capsule will be shown in Section II. Fabrication and function testing of the proposed biopsy capsule will be introduced in Section III. Finally, conclusions will be drawn in Section IV.

II. Design

A. Overall Configuration

As shown in Fig.1(a), the proposed biopsy capsule robot consists of three parts: biopsy module, anchoring module, and decouple-drive module, which is capable of anchoring at the targeted position and performing biopsy operation under the external magnetic field. In Fig.1(b), the capsule robot is in working state with the biopsy spike and circular-arc legs fully extended. When the proposed capsule finds the suspicious tissues in the intestine, it can first anchor at the specific location and then reach out with the biopsy spike to sample tissues. Fig.1(c) is the structural schematic diagram of the decouple-drive module. The middle part of the decouple-drive module is the magnetic-driven shaft, which is a shaft fixed with a circular radial magnetizing magnet. And the two ends of the module are elastic-pawls in opposite directions. As shown in Fig.1(d), the input port of the biopsy module and anchoring module are ratchets in opposite direction. Benefiting from the combination of the elastic-pawls on the decouple-drive module and the ratchets on the function modules (i.e. biopsy and anchoring module), the two function modules can be driven by the clockwise and counterclockwise rotating motions of the decouple-drive module respectively. The biopsy and anchoring module are decoupled when the two modules can be driven by a single actuator respectively, which can further help reduce the size of the biopsy capsule robot and achieve miniaturization.

B. Biopsy Module Design

The biopsy module is designed based on the eccentric cam mechanism. Fig.2(a) is the outline of the biopsy module. The biopsy module receives rotating motion through ratchet. As shown in Fig.2(b), the biopsy module can receive one direction rotational motion from the decouple-drive module and then drives internal mechanism to realize biopsy operation. Fig.2(c) is the explosion view of the biopsy module. The biopsy module mainly consists of four components: base plate, biopsy actuator, support plate and ratchet-cam component. The four components are matched by the linear pairs and plane pairs. The support plate is connected to the base plate by the position connection lugs. The biopsy actuator is nested in the base plate through plane pairs and the cam of the ratchet-ram component is nested in the biopsy actuator. Therefore, the biopsy actuator can accept rotational motion from the ratchet-cam and does linear motion. Fig.2(d) is the the internal structure of the biopsy module. The biopsy spike is located at the head of the biopsy actuator and its internal barbed structure can effectively help to sample tissues [3]. When the cam rotates around the eccentric shift, the biopsy actuator does linear contraction movement.

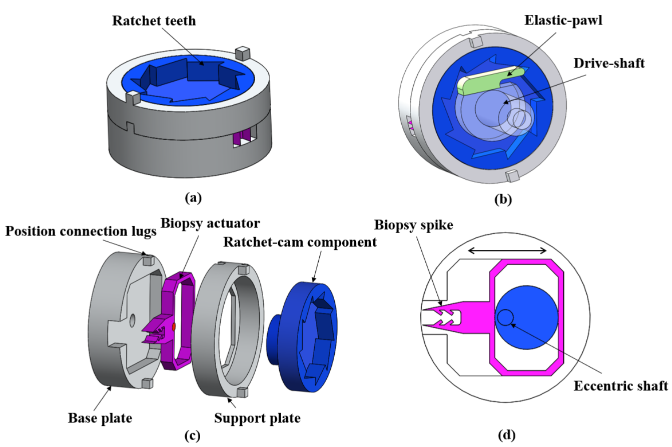

Fig. 2. Introduction of the biopsy module. (a) outline of the biopsy module. (b) the biopsy module receives one- direction rotational motion from the decouple-drive module and then drives the biopsy spike to extend out of the capsule shell. (c) explosion view of the biopsy module. (d) internal structure of the biopsy module.

Fig. 3 is the internal structure and motion diagram of biopsy mechanism. The motion analysis of biopsy mechanism will be done based on Fig.3. The ratchet of ratchet-cam component is hidden from view for clarity. The meaning of symbols in Fig.3 are as followed. The center of the circumference of the eccentric cam is located at point O'. The center of the eccentric shaft is located at the point O. Assume that the vector going from point O to the horizontal right is X-axis. The vector from point O to point O' is Y-axis. R is the radius of the eccentric cam. r is the radius of the eccentric shaft. w is the circumferential offset between the eccentric shaft and the eccentric cam. L is the linear displacement of the biopsy actuator. θ is the angle between X-axis and Y-axis. Fig.3(a) is the initial state of the biopsy mechanism and θ is zero. In this state, biopsy actuator has no linear displacement (L=0) and the biopsy spike is inside the capsule. Moreover, l_0 is:

$$l_0 = w + r \tag{1}$$

In Fig.3(b), θ is between 0 and 90° in this state. As θ increases, the linear displacement of biopsy actuator increases,

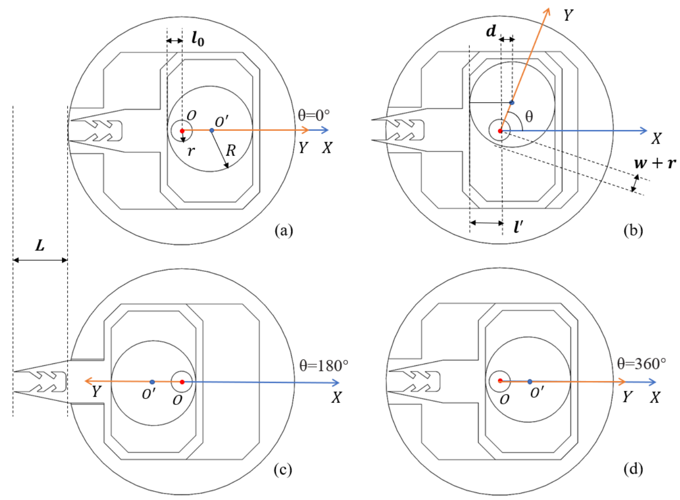

Fig. 3. Internal structure and motion diagram of the biopsy mechanism. (a) initial state of biopsy mechanism. (b)the biopsy spike is gradually extending out of the capsule shell. (c) the biopsy spike reaches its maximum biopsy depth, (d) the biopsy spike completely retracts the inside of the capsule.

and the biopsy spike gradually extends out of the capsule shell. d is the horizontal distance between point O and O', and l' can be calculated as follow:

$$d = (R - w - r)cos\theta \tag{2}$$

$$l' = R - \mathrm{d} = R - (\mathrm{R} - \mathrm{w} - \mathrm{r})\cos\theta \tag{3}$$

When the cam rotates around the eccentric shaft, the eccentric cam pushes the biopsy actuator out of the capsule shell. So, the displacement difference between l_0 and l' is the moving displacement of the biopsy actuator L:

$$L = l' - l_0 = (R - w - r)(1 - cos\theta) \tag{4}$$

In Fig.3(c), θ is 180° and the biopsy actuator reaches its maximum linear displacement L_{max}. Also, the linear displacement L_{max} of the biopsy mechanism is the maximum depth that the biopsy spike can insert into the suspicious lesion. What's more, by properly configuring the sizes of R, r and w, the desired maximum linear displacement can be easily obtained:

$$L_{\max} = 2(R - w - r) \tag{5}$$

As θ continues to increase between 180 and 360°, the biopsy spike gradually retracts into the capsule until it reaches the state shown in Fig.3(d). The four stages described above illustrate the motion of the biopsy mechanism during a complete biopsy sampling process. After the above motion analysis of the biopsy mechanism, we highlight the advantages of the biopsy mechanism based on eccentric cam:

- (1) The proposed biopsy module based on the eccentric cam mechanism is compact in structure and stable in movement. The contractile movement of biopsy spike is realized by simple and reliable contact motion pairs.

- (2) Comparing with the biopsy mechanism based on cylindrical blade, the biopsy spike can extend deeper and sample the lesion located deep in the intestinal tract through the barbs structure.
- (3) Comparing with the spring-based biopsy module that can only biopsy once, the proposed structural can realize repeated sampling at the suspicious lesion by just rotating in one direction thanks to the reciprocating linear motion characteristics of the eccentric cam mechanism. The successive jabbing movements in and out of the tissue with the spike can help collect sufficient volume of tissue(1$\sim$5mm^3) [14] [15], thus improving the success rate of biopsy [16].

C. Anchoring Module Design

Anchoring mechanisms are critical for biopsy and drug delivery capsules, which allows the capsule to be better undertake the sample collection, diagnostic and therapeutical tasks by providing the capsule with sufficient stopping force to resist the peristaltic force in the intestinal tract. The anchoring mechanism is designed by applying the principle of eccentric cam mechanism again, which can be driven by one direction rotational motion and extend two circular-arc shape legs at the same time.

Fig.4(a) is the outline of the anchoring module. Same as the biopsy module, the designed anchoring module receives rotational motion through ratchet. The difference is that the rotational motion that can be received by the anchoring mechanism is opposite to the biopsy module (i.e. clockwise and counterclockwise). The principle and application of ratchet mechanism to realize decoupling will be explained in detail in the decouple-drive module design. In Fig.4(b), the anchoring module receives the rotational motion from the shaft of decouple-drive module and then drives internal mechanism to open the circular-arc legs. Fig.4(c) is the explosion view of the anchoring module. The anchoring module mainly consists of five components: base plate, support plate, double cams-ratchet component, thin spacer, and two circular-arc leg components. Fig.4(d) is the internal structure of the anchoring module. The two cams of the double cams-ratchet component are nested in two rectangular frames of the circular-arc leg components. The two circular-arc leg components are nested in the sliding path of the base plate and support plate respectively through the plane pairs. The thin spacer separates the circular-arc leg components to make them move more steadily. Therefore, the two circular-arc leg components can accept rotational motion from the double cams-ratchet and do linear motion simultaneously. The motion analysis of the anchoring mechanism is similar to the biopsy mechanism, and the extension length of each circular-arc leg can be calculated by formula (4).

D. Decouple-Drive Module Design

According to the design requirements about energy consumption described above, the proposed decouple-drive module used for a wireless capsule endoscope is better to be

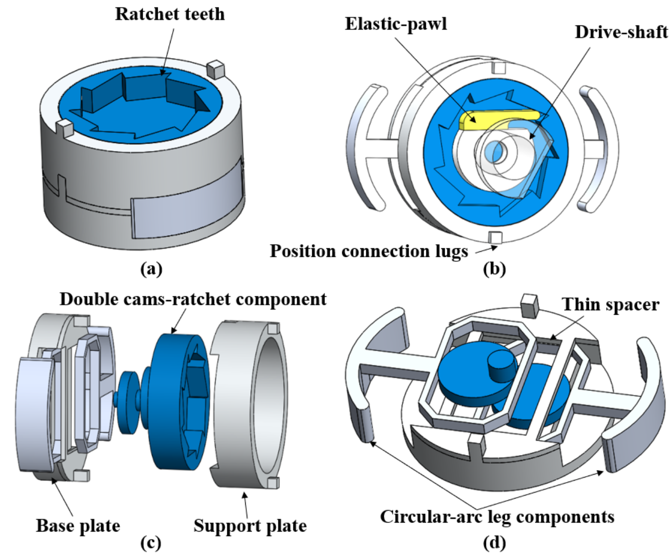

Fig. 4. Introduction of the anchoring module. (a) outline of the anchoring module. (b) the anchoring module receives one-direction rotational motion from the decouple-drive module and then drives the two circular-arc shape legs to extend out of the capsule shell. (c) explosion view of the anchoring module. (d) internal structure of the anchoring module.

battery-less or externally powered, so that function modules (i.e. biopsy and anchoring module) can work well in intestinal examination without affecting the battery life of image acquisition and transmission modules. Therefore, the magnetic actuation is a good choice. As shown in Fig.5, the magnetic-driven shaft will drive the two elastic-pawls to rotate simultaneously under the external rotating uniform magnetic field. In this section, we will focus on the working principle of the decouple-drive module to realize decoupling between two function modules.

Ratchet mechanism is a one-way intermittent motion mechanism composed of ratchet and pawl, which looks like gears. Its function is to convert continuous rotation or reciprocating motion into one-way stepping motion. In the designed decouple-drive module, we skillfully used the unidirectional motion property of the ratchet mechanism to achieve the decoupling between the biopsy and anchoring module. As shown in Fig.6, the elastic-pawl is fixed on the drive-shaft by the binder and rotates with the drive-shaft. The orange line is set to give a clearer view of the ratchets rotation. In Fig.6(a), the drive-shaft rotates counterclockwise and the upper surface of the elastic-pawl contacts the surface of the ratchet teeth. Due to the pressure on the upper surface of the elastic-pawl, the front end of the elastic-pawl will bend downward and then the elastic-pawl slid through the ratchet teeth without driving the ratchet. In Fig.6(b), the drive-shaft rotates clockwise and the front end of the elastic-pawl is set in a groove of the ratchet teeth. In this state, the ratchet can be driven by the rotating drive-shaft. Therefore, when the ratchets of the biopsy and anchoring module are in the opposite direction, the biopsy module and anchoring module can be driven by the clockwise and counterclockwise motions of a single drive-shaft respectively.

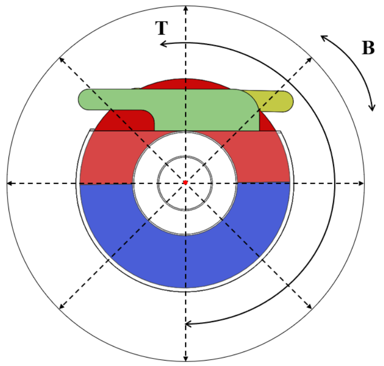

Fig. 5. Schematic diagram of torque action on the magnetic drive shaft under external rotating uniform magnetic field.

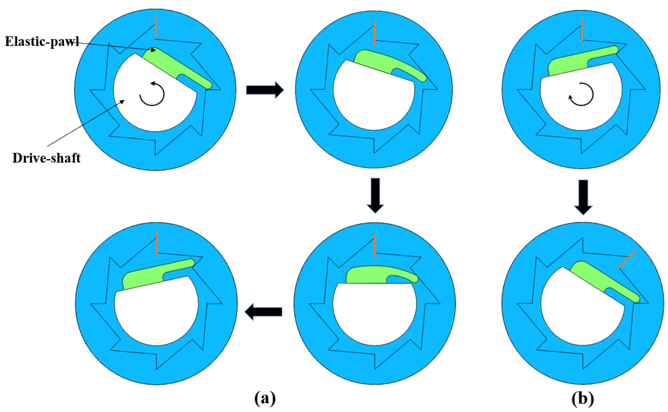

Fig. 6. Schematic diagram of decoupling principle of the ratchet mechanism. (a) the drive-shaft rotates counterclockwise. (b) the drive-shaft rotates clockwise.

It is assumed that the clockwise motion of the drive-shaft can effectively drive the biopsy module and the anticlockwise motion can effectively drive the anchoring module. When the proposed biopsy capsule is about to do biopsy operation in the intestinal tract, the magnetic-drive shaft first rotates 180° counterclockwise to open the circular-arc shape legs and help the capsule to anchor at the specific position. Then, the biopsy module completes the biopsy operation driven by a 360° clockwise rotation of the magnetic-drive shaft. Finally, the magnetic-drive shaft rotates another 180° counterclockwise to retract the circular-arc shape legs, allowing the capsule to move on propelled by the natural peristalsis of the intestine. However, this method based on the ratchet mechanism to achieve decoupling between two function modules has certain requirement on the driving torque force of the two functional modules. When the elastic-pawl is bent and slides through the ratchet teeth, a small torque force is applied to the rotating shaft of the function module. Therefore, when using this ratchet mechanism to achieve decoupling between function modules, it is necessary to ensure that the functional modules have some resistance to disturbance torque. In the future, we will measure the disturbance torque on the rotating shaft of function modules when the elastic-pawl slides through the ratchet teeth, so as to quantitatively select a magnet of suitable size to use on the magnetic-drive shaft.

III. Capsule Prototype Fabrication and Function Testing

In order to verify the feasibility of the biopsy capsule designed in this paper, we processed a prototype whose diameter is 16mm and length is 24mm. The three modules of the biopsy capsule, shown in Fig.7(a), was fabricated in aluminum by using CNC machining technology, wire cutting technology and 3D printing technology. The elastic-pawl was manufactured by using lase cutting method with the material of polytetrafluoroethylene, which has the characteristic of high toughness and no poison to human body. Fig.7(b) is the prototype that successfully assemble the three modules. In Fig.7(c), the prototype of the designed biopsy capsule is in the working state with the circular-arc legs fully opened. In this state, the maximum outer diameter of the capsule can reach 24mm. In Fig.7(d), the prototype of the designed biopsy capsule extended the biopsy spike completely and the maximum extension length of the biopsy spike is 4mm.

Further, we tested the motion of the capsule prototype, especially the decoupling performance between two function modules. In our tests, an external permanent magnet is used to control the rotating motion of the magnetic-drive shaft in the decouple-drive module. After the experimental tests, we found that the mechanical friction of the function modules can not completely resist the disturbance torque produced by ratchet decoupling mechanism. When the magnetic-drive shaft rotates to drive the biopsy module to extend the biopsy spike, the two circular-arc legs will vibrate and fall back slightly. By applying a slight axial force to the two circular-arc legs to increase the mechanical friction of the anchoring module, we found that the two legs can be well maintained in the original state by repeating the tests. Therefore, when the mechanical friction of the function module is insufficient to resist the disturbance torque, it is necessary to introduce some additional friction to achieve complete decoupling between function modules.

IV. Conclusions

In this paper, a novel biopsy capsule robot for intestinal tract was proposed. The proposed biopsy capsule consists of three modules: a biopsy module to sample tissue with biopsy spike, an anchoring module to help the capsule locate at the specific position in intestinal wall and a decouple-drive module to provide power for function modules by using only one actuator. A prototype with the diameter of 16mm and length of 24mm was fabricated to verify the feasibility of the concept design of the biopsy capsule. The research so far has been focused on the mechanism design of the three modules for capsule. In the future work, the designed biopsy capsule will undergo two *in vitro* experiments to test its performance. The first experiment is the biopsy experiment to test whether the biopsy module has sufficient force to penetrate the intestinal

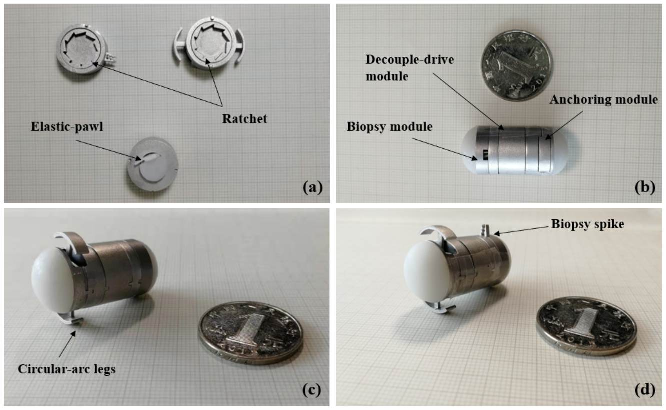

Fig. 7. Prototype of the designed biopsy capsule. (a) prototype of the biopsy, anchoring and decouple-drive module. (b) prototype that successfully assemble three modules. (c) prototype of the designed biopsy capsule with the circular-arc legs fully extended. (d) prototype of the designed biopsy capsule with the circular-arc legs and biopsy spike fully extended.

tract wall and sample the tissues by using the biopsy spike. The second experiment is the anchoring experiment to test whether the anchoring module can effectively support the circular-arc shape legs and help the capsule resist the natural peristalsis of the intestine. Meanwhile, the disturbance torque on the rotating shaft of function modules when the elastic-pawl slides through the ratchet teeth will be measured and used to guide that how much extra friction is needed in the function modules and that the selection of the magnet for magnetic-drive shaft.

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