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Design, Simulation and Fabrication of the Leg of Capsule Endoscopy

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***Abstract*—This paper describes a novel structural design scheme for hybrid capsule endoscopes which has both internal and external drives. The article specifically introduces the structure design and processing of the device. Besides, we place the structure inside the intestinal tract for simulation. The device will be placed in an externally driven capsule endoscope. The device is driven by a micro motor. After that, the three legs inside the device will protrude from the interior of the capsule through the transmission device to open the blocked part of the intestine. Afterwards, we can continue to drive the entire capsule forward by the external driver, and at the same time, it is possible to more easily achieve image capture and post-diagnosis by adjusting the spread angle of the legs. Upon staying in a certain lesion position, if the internal space allows, we can fully extend the leg mechanism to fully contact with the inner wall of the intestine, so as to achieve the purpose of the robot's staying or standing. Furthermore, this improvement will provide a strongly structural support for future breakthrough areas such as sampling and application. The author also simulates the structure and measured the contact force between the leg and the inner wall of the intestine.**

***Index Terms*—capsule endoscopy, hybrid, active locomotion, leg.**

I. Introduction

Over the past decades, people have been increasingly investing minimally invasive and endovascular devices for surgical or diagnostic applications. One of the main research activities of these inputs is the development of small robots which can explore the human body in a controlled manner. The cavity, such as the gastrointestinal tract, these robots are intended to enter the body through the body's natural tract (eg, mouth, vagina, anus, etc.) for a series of tests and diagnostic procedures. Compared to traditional gastroscopy techniques, the use of miniaturized and swallowable robots can actively move within the body, perform diagnostics, drug delivery, and even surgery[1], which contributes to reduce hospital stay and associated health care costs. Whats more, it is very convenient for early diagnosis[2].

There are currently several commercial wireless capsule endoscopy platforms on the market: 1) PillCamSB2 (Given Imaging, Yokneam, Israel); 2) MiroCam (IntroMedic Co, Seoul, South Korea); 3) EndoCapsule (Olympus, Tokyo); 4) OMOM (Jinshan Science and Technology, Chongqing, China); 5) PillCam Colon 2 (Given Imaging, Yokneam, Israel); 6)PillCam ESO2 (Given Imaging, Yokneam, Israel)[3], [4]. These capsule endoscopes are similar in size to traditional pills (26 mm in length and 11 mm in diameter). They consist of a shell, a vision unit (composed of miniature cameras), a control unit, an energy unit, and a transmission unit[5]. Relying on the instruction of the control unit and the energy supplied by the energy unit, the camera photographs the inner wall of the intestine at a certain frequency, and finally the relevant images are transmitted to the external receiver through the transmission unit. However, the disadvantages of the above five types of capsule endoscopes are that they are passively moving through the peristalsis of the intestinal tract in the body[6]. In the contrary, the doctor hopes that they can adjust the view of the camera at random, obtain multiple viewing angles and move toward the suspicious lesions. Moving forward and backward instead of relying on the peristalsis of the intestines to drive the capsule. Apart from the above drawbacks, if the passive driving device is faster at some important pathological places, it will lead to diagnostic omissions. Correspondingly, it will remain in some healthy areas for a long time, wasting a lot of image transmission space.

Recently, some works have been devoted to solving this passive movement problem. We hope to improve the working environment of the capsule endoscope through active driving, so as to improve the diagnostic efficiency. The active drive of the device is divided into internal drive and external drive[7]. The external drive includes adding a magnet that paired with an external magnetic field inside the capsule[8], and controlling the advance, the retreat and the turn of the endoscopic robot in the body through changes of the external magnetic field[9]. The biggest advantage of this method is that it does not require batteries to provide energy, which greatly saves the capsule endoscope space. The internal drive is adding some mechanical devices into the capsule robot to achieve active movement of the capsule endoscope[10]. The

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comparison between the two methods shows that the internal drive has a higher requirement for the power design and the operation time is limited; the external drive is affected by the structure of the internal tract and some pathological changes, and may be hindered during the forward or backward process[11]. Therefore, it is necessary to combine the external drive with the internal drive to realize the complementary advantages of the two drive modes. In this paper, we design a novel mechanical device that is based on the external drive. This device is aimed to solve the problem that the intestinal blockage affect the advancement of endoscopic robots. At the same time, the mechanical device can also help maintain the robot's stay in the chamber, providing important structural support for further functions such as robot sampling[12], [13], application, and video recording[14].

II. Design

This kind of capsule for medical use needs to perform very well in terms of size, sealing and safety. It cannot cause harm to the digestive system when entering the body.

A. Design Principles

1) The size needs to be able to be swallowed. We refer to the five commercial wireless capsule endoscopes mentioned above. This type of endoscope has been widely used in hospitals and has become the gold standard for small intestine testing. A capsule with a length of 26mm and a diameter of 11mm is considered swallowable, and our device will also be designed according to this size.

2) Safety issues are the key points of medical facilities. Considering that there is no nerve on the surface of the small intestine, when the surface is damaged, the humans brain does not receive pain, so the contact between the leg and the intestinal cavity needs to be rationally designed to avoid damaging the surface of the inner wall. In the late period, we will also use the simulation to evaluate the contact force between the leg and the inner wall so as to determine whether the device will cause injury to the intestines.

3) Sealing is also critical for this type of charged device, as there will be various types of body fluids in the body's natural lumen, and once it enters the device through the apertures, internal structural failure may be caused.

B. Detailed design process

The structure will be triggered when it reaches the blocked area and needs to be expanded. Through the internal transmission device, the leg will extend from the inside to achieve the role of open the intestine.

The first thing that needs to be considered is the number of legs. Only after this determination been made can the next structural arrangement been made. Although theoretically the greater the number of legs, the smaller the bowel pressure on each leg, the more conducive to the device to achieve the opening operation of the intestine, but too many legs will challenge the mechanical transmission, and the internal space of the capsule will also be greatly affected. Finally, considering the above factors, we use a three-legged design. In the case of three legs, the legs can also be balanced with the circular inner wall when they are extended, and the three legs are also the most stable state when space is needed for stagnation.

Finally, it is determined that the device is attached inside the capsule endoscope. The control mechanism, the camera and the motor that installed in the capsule endoscope are all waterproof structures as shown in Fig.1. The capsule of the capsule endoscope is provided with an active window for extending and contracting the supporting leg structure. The device is provided with a screw. The top end of the screw is fixedly connected with the output shaft of the motor. The screw of the screw is provided with a fixed plate, a mobile plate, and a screw nut arranged cooperatively with the screw as shown in Fig.2. The fixed disk that set on the bottom end of the screw rod is fixedly connected with the screw rod screw; the outer side of the fixed plate is connected with one end of the connecting link through the movable member of the rotating shaft; the other end of the connecting link is sleeved with the supporting leg through the limiting sleeve, and one end of the supporting leg is connected with the mobile plate through the rotating shaft moving part.

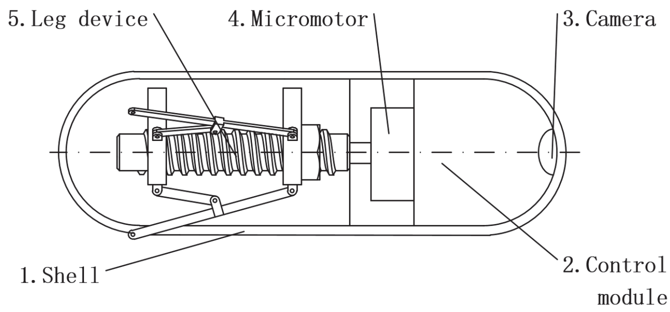

Fig. 1. The entire composition unit of the whole capsule endoscope and their mutual positional relationship.

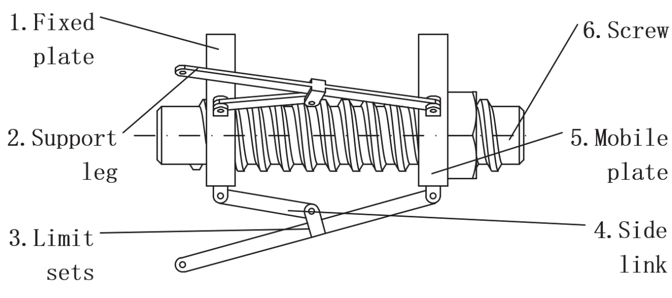

Fig. 2. Schematic view of the leg device.The leg device insists of six different parts.

Each support leg is a structural design based on a deformed crank connecting link mechanism. The ratio of the length of the connecting link to the supporting leg length is 1 to 3, and the number of supporting legs is three. The three support legs are centered on the center axis of the lead screw and are spaced 120 degrees apart as shown in Fig.3. When the angle

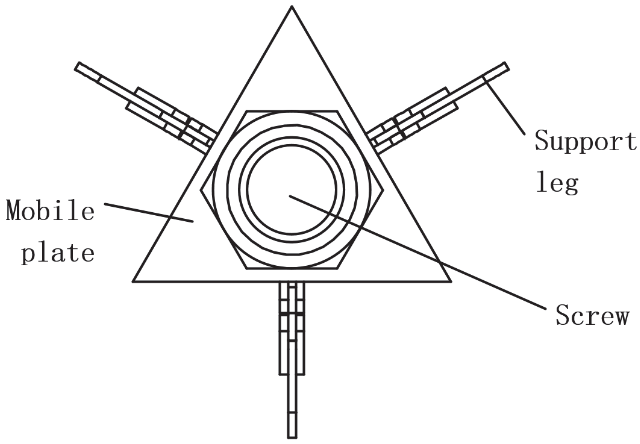

Fig. 3. From the side view of the device, we can see that the angle between the three legs is 120°.

between the frame link and the lead screw is at an acute angle or a right angle, the leg structure achieves the expansion or contraction function. When the included angle is obtuse, the leg structure realizes the support upright function.

The screw-based active leg extension and retraction device of the endoscopic robot, with the help of the improvement of the leg structure, and the cooperation of the camera and the motor, it can well prevent from been blocked by the structure of the lumen tube and some lesions in the process of advancement while ensuring the complexity and operation time. Furthermore, it can reduce the cost while facilitating the use of the user. The robot enters the body cavity of the organism, and at the blocked or bent position of the body cavity, the lumen can be stretched by the extension and contraction of the leg structure, and the movement of the endoscopic robot can be realized by driving the motor in the control mechanism; In some lesions, when the robot needs to stop or stand, the full support of the leg mechanism contacts the inner wall of the intestine, so that the robot can finish the function of stay and stand.

When in use, the motor rotates in the control mechanism to drive the screw to rotate. Through screw fitting, the rotation of the screw transforms into the movement of the nut, which drives the mobile plate together to push the supporting leg to extend or contract. The principle is the crank-slider mechanism that composed of a supporting leg, a limiting sleeve and a connecting link.

III. Kinematic Analysis And Fabrication

There are many limitations in the actual design, and the specific dimensions of related components also need to be determined on the premise of meeting these limitations. At the same time, virtual simulations are required to test the contact force between the top of each leg and the inner wall of the intestine. The following will list some limitations:

1) When the leg device is not activated, the three legs need to be completely retracted inside the capsule to avoid swallowing difficulties or unnecessary injuries.

2) The overall size of the capsule needs to be referenced to a commercial wireless capsule endoscope to ensure that the capsule is swallowable, that is 26mm in length and 11mm in diameter.

3) It is necessary to coordinate the module of the screw and the number of revolutions of the motor properly, and we choose to make the whole process of motion last for about six seconds. The short time will be inconvenient to control, and it will also result in too much impact force, result in damage to the internal cavity. Besides, if the time is too long, it will increase the operating cycle.

4) It is necessary to ensure that the included angle between the legs is greater than 90 degrees to ensure a more stable contact between the legs and the inner wall of the intestinal tract.

5) The entire device can only have one degree of freedom. Only the degree of freedom of the rotation of the screw is retained, which also means that the device requires only one motor.

A. Analysis

First, the length of the lead screw occupies the main part of the entire leg structure. Given the size of the entire capsule is 26mm, the diameter of the lead screw is now determined to be 2mm and the length is determined to be 10mm, where the lead length is 6mm, it can be reflected by the Fig.5. As is shown in the picture, the value represents the distance between the mobile plate and the fixed plate, the Min is 1.4mm, and the Max is 7.4mm. In the following, we need to design the crank slider mechanism as shown in Fig.4, in which the active part is the slider and the rotation of the motor is converted into the translation of the slider by means of a screw drive. The translational distance of the slider is the lead of the screw which is 6 mm. From Fig.7, we can see that when the link AB and the slider DE are perpendicular to each other, the top point of the support leg is at the furthest distance from the straight line AD. Taking into account the size of the intestine, the size of the intestine, we define the circumscribed circle when the three legs are fully stretched in a circle with a diameter of 20 mm. Then we can assume that when the angle between AB and AD is minimum Θ, the whole device shrinks in a circle with a diameter of 10mm and when the angle between AB and AD is 90 degrees, the entire device shrinks in a circle with a diameter of 20 mm. What we need to be aware of is that the distance between the straight line AD and the central axis of the screw is 2.1 mm. First take $\overline{AB}$ is 3.2mm, let the length of limit set is 0.6mm, let the minimum angel Θ is 6 degree. Then according to the initialization size and the cosine theorem of the triangle, we can calculate $\overline{BD}$ based on the formula (1). Furthermore, according to the right angle triangle Pythagorean Theorem, the length of the CD can also be calculated as is show in the formula (2). Finally, according to the triangle $\triangle DAH$ and the triangle $\triangle DGF$, the length of the FG is known as 10 mm, and the length of the support leg can be obtained. The length of each bar will be written in the Table.I.

$$\overline{BD}^2 = \overline{AB}^2 + \overline{AD}^2 - 2\overline{AB}\cdot\overline{AD}\cos\Theta \tag{1}$$

$$\overline{CD}^2 = \overline{BD}^2 - \overline{BC}^2 \tag{2}$$

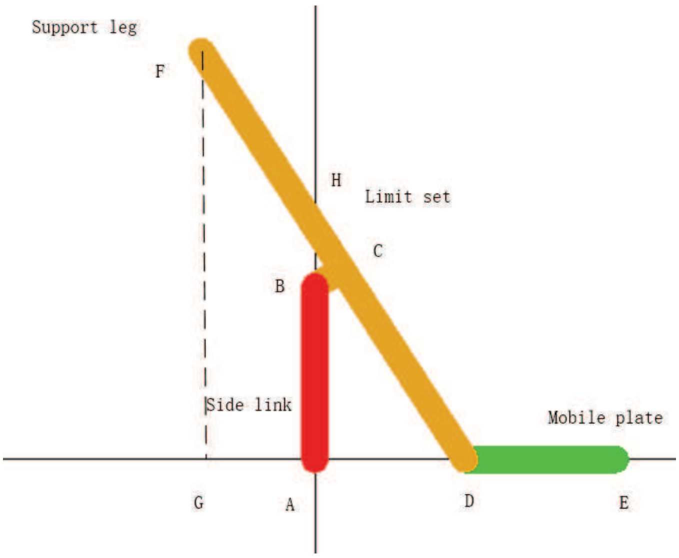

Fig. 4. The leg mechanism is deformed by the illustrated crank-slider mechanism, and the state in the figure is a transient state in which the link bar and the slider guide are vertical.

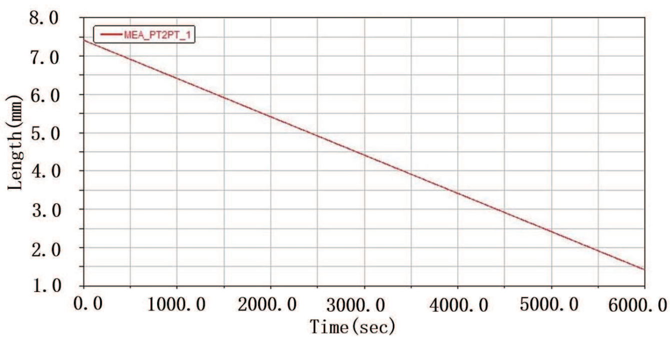

Fig. 5. The curve of the distance between the mobile plate and the fixed plate along the direction of the circumference of the screw.

TABLE I
THE LENGTH OF LINKS

Link	Length(MM)
$\overline{AB}$	3.2
$\overline{FG}$	10
$\overline{CD}$	4.2
$\overline{BC}$	0.6
$\overline{CF}$	4.8

After knowing the structural dimensions of each part, we need to verify the whole structure. As is shown in the Fig.6, from the line named "Distance", we can get the point-to-point vertical transition of the point F to the screw axis, and its value ranges from 4.05mm to 9.67, which is in line with the previously proposed opening and contraction range. The line named "$\angle FDG$" represents the change of $\angle FDG$ over time, the range of change is from 11.03 to 55.66. The line named "$\angle BAD$" represents the curve of $\angle BAD$ with time, and its initial value is 6, the maximum value is 125.16. According to the image, it can be finally concluded that the size is consistent with the previous assumption and also meets the limitation on the size extension range.

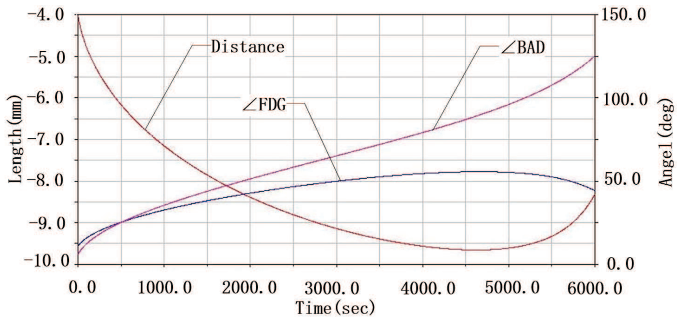

Fig. 6. In order to verify whether the size of the crank slider complies with the relevant restrictions, the maximum circumcircle diameter and the minimum circumcircle diameter are tested when the leg moves, and the relevant angle is tested. The line named "Distance" represents the point-to-point vertical transition of the point F to the screw axis. The line named "$\angle FDG$" represents the change of $\angle FDG$ over time. The line named "$\angle BAD$" represents the curve of $\angle BAD$ with time.

Next, the force between the leg and the inner wall of the intestine will be tested. We will set the material properties of the two contact originals respectively. Considering the fact that a ball rubber will be added to the tip of the leg in order to reduce its effect on the inner wall of the intestine, the leg material is directly set to rubber in this simulation. For the intestine, we referred to many other documents and finally we make the decision that the Poisson's ratio was 0.35[15], the Young's modulus was 5000 Pa. When it comes to the density, we chose to use the same value as the liver and it is $1.005g/cm^3$. As we can see from the figure, from 3343 MS to 5245 MS, the tip of the leg comes into contact with the inner wall of the intestine and generates a contact force, where the force in the Y direction occupies a major part of the contact force, and its maximum value is 0.11 N. So each leg undertakes the force of 0.11N. Assume the radius r of the contact rubber ball is 2.5mm, the pressure on the inner wall of the intestine can be determined as what we can see from the formula (3). It is known that the maximum negative pressure that the human intestine can withstand is about $-3.7 * 10^6 Pa$ [16], [17], and the pressure that we finally calculated is $2.8 * 10^6 Pa$, so in this case, no damage will be caused to the inner wall of the intestinal tract.

$$P = \frac{F}{S} \tag{3}$$

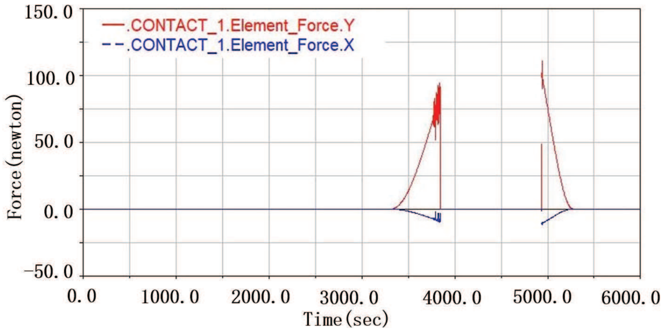

Fig. 7. The size of the contact force between the tip of the leg and the inner wall of the intestine. The red curve is in the direction of the vertical screw axis and the blue curve is in the direction of the axis of the screw.

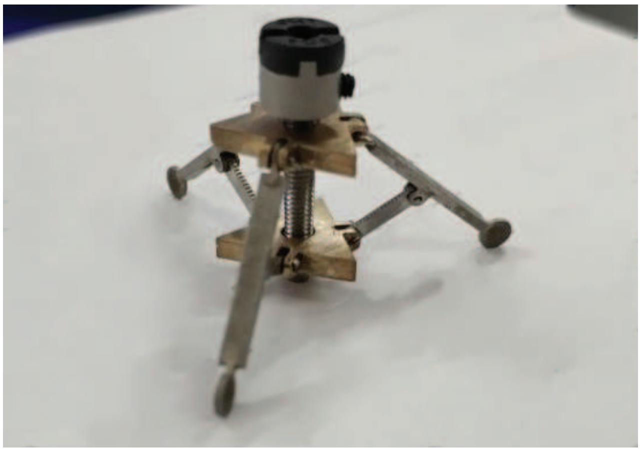

Fig. 8. Physical map of processed leg structure.

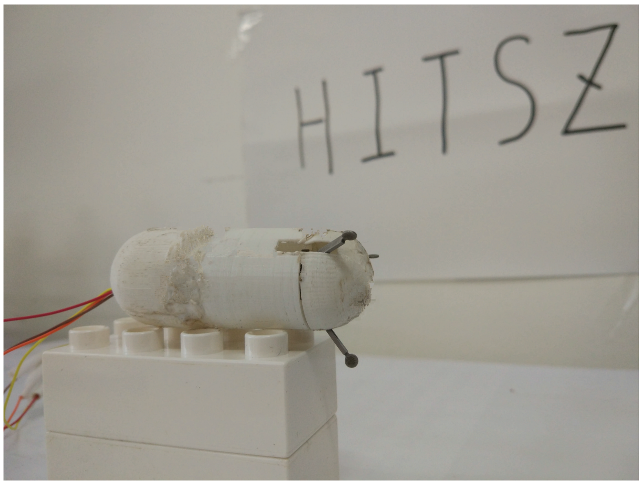

Fig. 9. The state of the capsule robot when it is stretched until it reaches the maximum circumscribed circle.

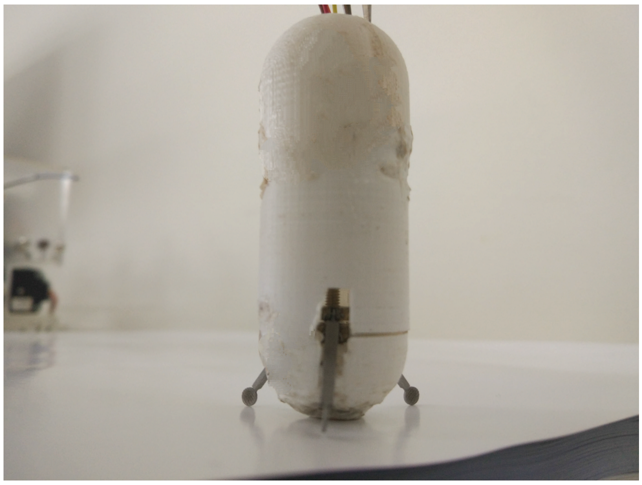

Fig. 10. The state of the capsule robot at the end of the motion cycle.

B. Fabrication

The device will be processed according to the above design parameters. In order to adapt the force to meet the conditions, the material used for the screw and the leg is aluminum, and the material used for the mobile plate and the fixed plate is copper. As we can see from the Fig.8, the leg structure of the processed endoscopic robot is shown. In this state, the fixed plate is not completely constrained. We use 3D printing to produce the outer shell of the capsule in the later stage, and we embed this leg mechanism inside the capsule and the Fig.9 shows the state of the capsule robot when it is stretched until it reaches the maximum circumscribed circle the Fig.10 shows the state of the capsule robot at the end of the motion cycle. The above two correspond to the two main functions of the robot respectively. The first one represents the function of opening the blocked area. The second one represents the function of stagnating at a specified position.

IV. Conclusions

In this paper, a leg device designed for internal driving of a capsule endoscope is designed. The leg device can provide two functions: 1) open the blocked or the fold area; 2) assist the capsule robot to stay in the designated position or upright. Therefore, the device needs to work cooperatively with the external drive, so that the capsule endoscope can smoothly advance in the digestive system. What's more, the function of being able to stagnate at the local position also provides structural support for further sampling and administration functions. In the article, we elaborate on the design process of the leg structure, and analyse and verified the working space and trajectory of the leg to ensure the feasibility of the mechanism. Considering that the tip of the leg may cause damage to the inner wall of the intestinal tract during the working process, we also performed a dynamic analysis of the entire mechanism. Through simulation, we measure the contact force generated when the tip of the leg was in contact with the inner wall of the intestinal tract. It has been verified that under the initial conditions set, the leg will not cause damage to the intestinal wall. Based on the above design and analysis, we processed the device and successfully implemented the two major functions it needed.

One of the more effective methods of the capsule endoscope driving method is to combine the internal drive with the external drive. This method can make full use of the advantages of both to achieve a smooth advance of the capsule endoscope. In the following step, we need to perform a distraction test on the leg device to check whether it can achieve the desired effect in practice. In the end, we hope to cooperate with the micro camera to conduct an experimental test in the intestine of pigs.

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