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Performance Evaluation of the Wireless Micro Robot in the Fluid

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***Abstract* - The capsule robot is one of important development direction in the field of wireless micro robot in-pipe and it is becoming a powerful tool for gastrointestinal tract inspection. In this paper, we proposed the symmetrical spiral micro robot with gravity compensation mechanism and then analysed the buoyancy and resistance of the robot in the fluid. Finally, we carried on the performance evaluation experiments of the robot in the fluid. The experimental results indicated that the micro robot has a good dynamic performance when the flow is about 26ml/min, compared to other flow value. In the horizontal direction the maximum velocity of the robot is about 30.44mm/s and 6.49mm/s in the case of downstream and counter current respectively. In the vertical direction the maximum velocity of the robot is about 10.1mm/s and 1.34mm/s in the case of downstream and counter current respectively while it is doing upward movement. In the vertical direction the maximum velocity of the micro robot is about 10.11mm/s and 1.337mm/s in the case of downstream and counter current respectively while it is doing downward movement. In addition, the flow has influence on transition frequency of the micro robot. The faster flow is, the lower transition frequency of the micro robot has. The experimental platform we set up can reflect the conditions of human gastrointestinal tract, so the performance evaluation of the micro robot in this paper will provide a strong support for the future clinical application.**

Index Terms* - *symmetrical spiral micro robot, fluid environment, clinical application

I. INTRODUCTION

With the development of MEMS technology, people pay more and more attentions on the micro robotics. On the other hand, confronted with the higher incidence and fatality rate of the digestive tract diseases, human are urgently seeking for a diagnostic method which can inspect lesions timely, effectively and accurately. But the traditional stomach examinations have all sorts of deficiencies. Not only can it cause the damages to the body tissues and serious discomfort to a patient during the inspection, but it has a high miss rate and an expensive examination fee [1]. In short, the innovation of technology and the needs of medical science promote the emergence of the capsule robot, and then it has become a research hotspot for the relevant scholars from the domestic and international.

The M2A capsule endoscopy had been launched by Given Image Inc since the late 1990s, opening up the medical study of the micro robot in-pipe and playing a major role in the clinical diagnosis [2]. But the battery power makes its work time short and security low. After this the RF System Lab developed the Norika3 that had a broader field of vision than M2A and joined the rotation function. The performances of Norika3 series are more comprehensive and it can even have inspection on young children's gastrointestinal tract up to this day, but its actuator is still the gastrointestinal peristalsis [3]. Korea Aerospace University developed a kind of inchworm-like micro robot under the guidance of Lim, adopting a cable actuator [4]. The existence of the cable can produce friction with the gastrointestinal tract and bring the pain to the patients. Guo developed a robot like a fish based on the bionics, with the external magnetic field as the driving force [5-8]. It can only realize the basic movement, such as forward motion, relying on the motion of a tail. And then they improved the structure of the robot and designed the spiral structure [9-11]. Y Zhao et al developed a pipeline robot, utilizing SMA as the actuator [12]. Considering that the intestinal temperature is higher and the heat resistance of gastrointestinal tract is poor, the available temperature difference is relatively small. So the dynamic performance of the micro robot is poor. Y Zhang et al developed the micro capsule robot with variable diameter and then proposed the spatial universal rotating magnetic field system in order to achieve the three-dimensional motion of the micro robot [13]. Shanghai University of Science and Technology developed the first global localizable capsule endoscopy at the end of 2012 and had been put into the clinical application after the M2A [14].

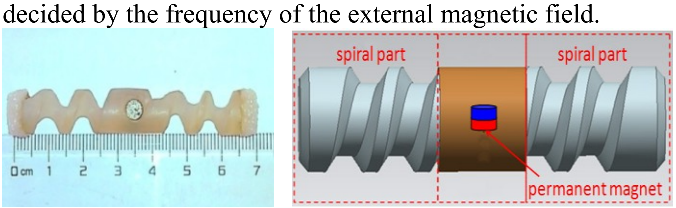
People have made some achievements in the field of medical robot through the untiring efforts of the researchers, but under the influence of complexity and particularity of the gastrointestinal tract, the researchers still encounter many technical bottlenecks. For instance, design the shape and structure of the robot in order to reduce the damages of tissue walls at the maximum degree, look for more effective way to drive instead of the gastrointestinal driving and the cable type driving, achieve multiple degrees of freedom of the robot movement and accurate positioning. The researchers are committed to research and development a micro robot that can provide human with a new method of detecting the gastrointestinal disease, reducing or even eliminating the pain caused by the traditional detection.

Considering that the current performance evaluation of the medical robot is carried out in the stationary liquid or vitro biological gut and this way ignores the influence of the gastrointestinal peristalsis, causing a control deviation in the clinical practice, we add a peristaltic pump to the existing experimental platform in order to better simulate the gastrointestinal environment and get more realistic movement characteristics of the robot. The intestinal peristalsis is a kind of continuing contraction motion between the circular muscle and longitudinal muscle. The velocity of the intestinal peristalsis is 0.5mm/s to 20mm/s [15]. The velocity in the proximal segment is faster than that in the distal segment for the small intestine. In addition, although there is lots of mucus in the stomach, causing a large viscosity, the patients often drink water 500ml in order to maintain a liquid diet before the examination [16]. In the meantime, we design a circuit that could adjust on-line the number of pulses per minute to control stop and start of the pump, imitating the pulse of the human body.

This paper is structured as the following. In section II, we propose the structure and prototype of the symmetrical spiral micro robot. In section III, we analyze the force of the robot in the fluid from the buoyancy and resistance. In section IV, we carry out the experiments based on the experimental platform of set and evaluate the performances of the robot in the fluid. The last is our conclusions.

II. THE PROPOSED WIRELESS SYMMETRICAL SPIRAL MICRO ROBOT

We adopted the symmetrical spiral robot in this paper as shown in Fig. 1. The design parameters are shown in Table I. Through the previous researches we come to a conclusion that the robot can obtain higher velocity and dynamic performance in the spiral motion. Under the effect of rotating magnetic field the robot will spin in the tube and then obtain the displacement with the help of spiral structure [17]. In addition, this robot has gravity compensation mechanism in order to solve the difficulties existing in the upward motion [18]. The reciprocating is realized by changing the direction of the external magnetic field and the adjustment of the velocity is decided by the frequency of the external magnetic field.



(a)The prototype of the robot (b) The structure of the robot

Fig. 1 Design of the symmetrical spiral micro robot

TABLE I
THE DESIGN PARAMETERS OF SYMMETRICAL SPIRAL MICRO ROBOT

Design indicators	Design parameters
Size(mm)	ϕ 12×70
Number of thread interval	5
Depth of the thread(mm)	5
Thread angle(radian)	$\pi/4$

III. THE FORCES ANALYSIS OF MICRO ROBOT IN THE FLUID

Assuming that the liquid used in the experiment is Newtonian Fluid, we made force analysis of the micro robot in the fluid.

A. *Buoyancy Analysis of the Robot*

Whether the horizontal or the vertical motion, the robot will be the effect of the buoyancy, but the buoyancy discussed in this paper is different from the buoyancy calculated by Archimedes. The buoyancy in the fluid is essentially a pressure difference forced on the object [19].

The Bernoulli's equation is shown in Equation (1).

$$\frac{v^2}{2g} + z + \frac{p}{\rho g} = const \tag{1}$$

where $\frac{v^2}{2g}$ is the kinetic energy of per unit weight of the fluid, v is the velocity of fluid, $\frac{p}{\rho g}$ is the pressure of per unit weight of the fluid relative to the atmospheric pressure, ρ is the density of the fluid, g is the acceleration of gravity, z is the potential energy of per unit weight of the fluid relative to a datum.

The velocity is fast where the pressure is small and the velocity is slow where the pressure is big for the fluid from (1). According to Bernoulli's equation, the pressure of the same sites in the fluid is smaller than that in the stationary liquid, so the buoyancy in the fluid is less than the weight of the displaced liquid.

The buoyancy of the robot in the fluid is shown in Equation (2).

$$F_b = \rho g V_d - \frac{1}{2}\rho v^2 S \tag{2}$$

where F_b is the buoyancy of the robot, V_d is the volume of the displaced liquid, S is the contact area with the fluid.

The buoyancy has connection with the structure of the robot and the velocity of the fluid and the buoyancy will reduce when the liquid is flowing from (2). The decline in buoyancy further increases the difficulties of upward motion, weakening the role of gravity compensation mechanism to a certain extent.

B. *Resistance Analysis of the Robot*

The robot has a force whose direction is consistent with the flow's but opposite to the robot motion when the fluid flows through it. This force is called the resistance. The resistance is caused by the tangential stress and pressure difference so it can be divided into the frictional resistance and pressure resistance [20].For the purpose of application and analysis, people are accustomed to use a coefficient of the resistance whose value is 1 to take place of the resistance in engineering. The coefficient of friction and pressure are shown in Equation (3) and Equation (4).

$$C_D = \frac{F_D}{\frac{1}{2}\rho v^2 A_D} \quad (3)$$

$$C_P = \frac{F_P}{\frac{1}{2}\rho v^2 A_P} \quad (4)$$

where C_D is the coefficient of friction, F_D is the frictional resistance, A_D is the feature area of frictional resistance, C_P is the coefficient of pressure, F_P is the pressure resistance, A_P is the feature area of pressure resistance.

But it is an extremely difficult work for people to determine those coefficients of the object of arbitrary shapes; we can only qualitatively say they are a function of shape of the object and Reynolds number [21]. Their values are usually identified by the experiment. Reynolds number is a combinatorial number relating to the velocity of fluid v, the pipe diameter d, the dynamic viscosity of fluid μ and the density of the fluid ρ. The expression of Reynolds number is shown in Equation (5).

$$R_e = \frac{\rho v d}{\mu} \quad (5)$$

IV. Experiments and Results

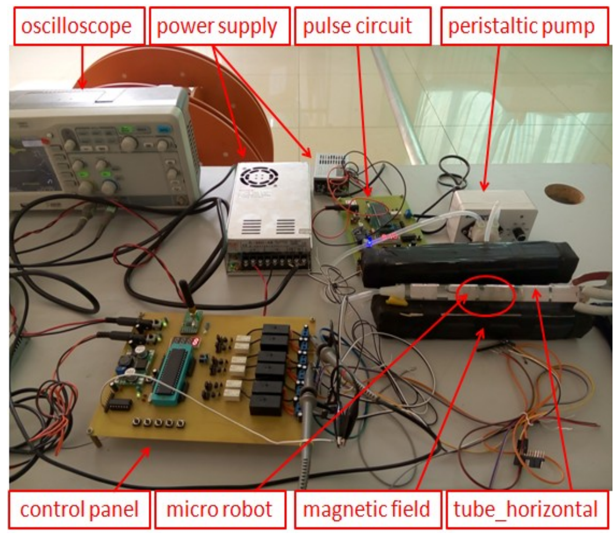
As we all know there is a certain amount of the liquid in the body cavity and the velocity of the liquid each is not identical, we simulated the velocity of the fluid by changing the flow of the peristaltic pump in the experiments. There is a centigrade scale on the peristaltic pump panel and the different scale corresponds to the different flow. Based on the type of pump pipe we selected, the range of the flow is 0 to 65 ml/min. So we put the centigrade scale into the flow through mathematical conversion as shown in Table II. Through the qualitative observation we found that the flow is too low to affect the motion of the robot when the flow is less than 13 ml/min while the motion of the robot is not controlled by the magnetic field when the flow is more than 39 ml/min. So the following experiments were carried out when the flow is 13 to 39 ml/min. In addition, considering that the pulse of a normal adult was 60 to 100 times/min and the average value are 72 times/min [22], the output of pulse circuit was 70 pulses per minute. The experimental platform was shown in Fig.2.

We defined the downstream situation where the direction of the robot motion was consistent with the direction of the flow in this paper. Conversely, we defined the counter current, as shown in Fig.3.

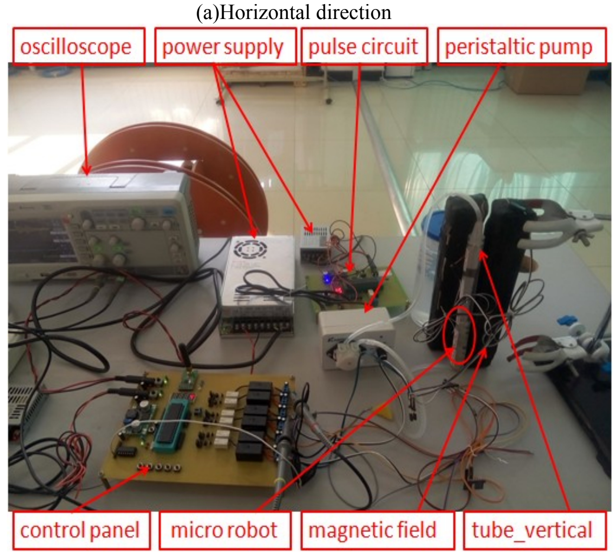
TABLE II
CONVERSION RELATION BETWEEN CENTIGRADE SCALE AND FLOW

Centigrade scale (%)	0	20	40	60	80	100
Flow (ml/min)	0	13	26	39	52	65

Through the experimental data, we found the performances of the robot were similar to the performances in the stationary liquid when the flow was 13ml/min and the push of the flow seriously affected the performances of the robot, counter current, in particular, when the flow was 39ml/min, so we drew the contrast curves when the flow was 26ml/min.



(a)Horizontal direction



(b)Vertical direction

Fig. 2 The experimental platform

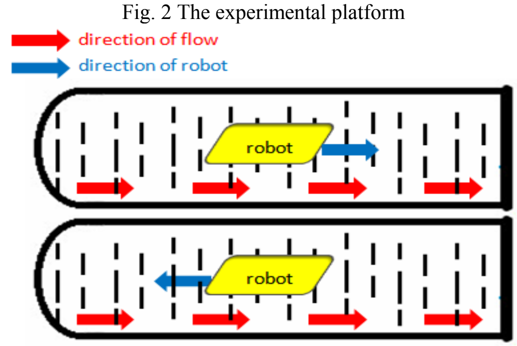


Fig. 3 The downstream and the counter current

A. In the Case of Downstream

Firstly, we evaluated the performance of the horizontal direction. We changed the frequency through the buttons and then obtained the velocity of the robot in the case of downstream. After this we changed the flow by virtue of the knob on the pump and began to do the next set of experiments. At the same time, we measured the velocity of the robot through the relationship between the displacement and the time. The experimental results were shown in Fig.4.

After this, we evaluated the performance in the vertical direction. The process of vertical direction was consistent with the horizontal direction. The experimental results were shown in Fig. 5.

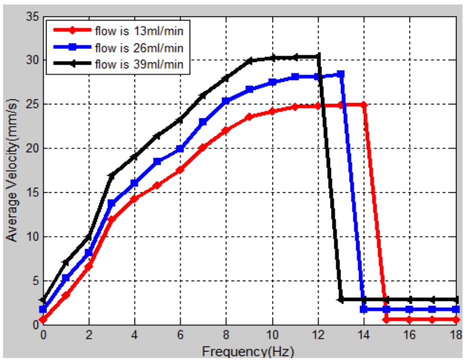
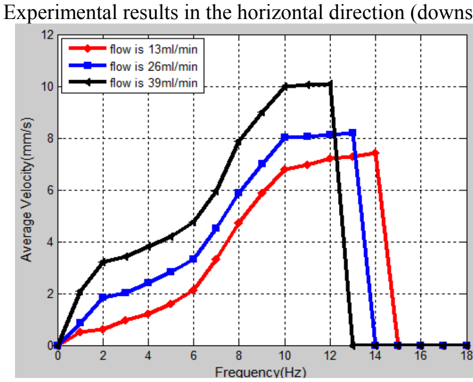
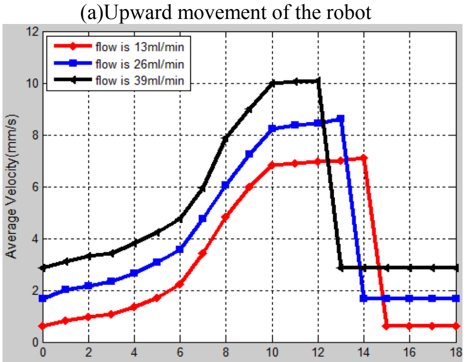


Fig. 4 Experimental results in the horizontal direction (downstream)



(a)Upward movement of the robot



(b)Downward movement of the robot

Fig. 5 Experimental results in the vertical direction (downstream)

From the Fig.4 and Fig.5, the average velocity of the robot presented a trend of fast but the transition frequency was reducing with the increase of flow. That was to say the ability to spiral with magnetic field was falling. This micro robot had the maximum average velocity about 30.44mm/s and 10.11mm/s in the horizontal and vertical direction respectively when the flow was 39 ml/min and the frequency was about 12Hz. In addition, the micro robot still had a certain velocity even without the external magnetic field or the frequency of the magnetic field was more than the transition frequency. This velocity was caused by the push of fluid as M2A can motion by means of gastrointestinal peristalsis, but this velocity was relatively small and this driving force will be invalid in the process of vertical upward due to the effect of the gravity.

Under the condition of downstream movement, as for the vertical direction we drew back and forth curve to verify the gravity compensation mechanism when the flow was 26 ml/min. The experimental results were shown in Fig. 6. From Fig. 6 the contact ratio between upward and downward curve was not high, especially when the frequency of the magnetic field was too high or too low. This was mainly because the buoyancy of the robot in the fluid was in reducing according to (2) and the gravity was the same, in addition to the push from the fluid.

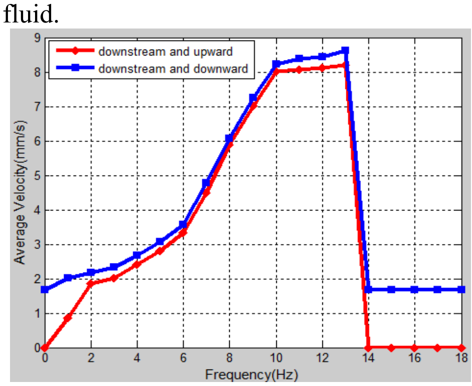


Fig. 6 Experimental results in the vertical direction (downstream)

B. In the Case of Counter Current

Considering that the doctor would let the robot back again to check carefully when they found suspicious lesions in clinical practice, we made the experiments of the horizontal and vertical direction in the case of counter current [23]. This group of experiments can better reflect the motion of the robot that overcomes gastrointestinal peristalsis. The experimental results were shown in Fig. 7 and Fig. 8.

The maximum average velocity of the robot in the horizontal direction was about 6.49mm/s when the flow was 13 ml/min and the frequency was about 14Hz as shown in Fig.7.The transition frequency was still smaller when the flow was quicker.

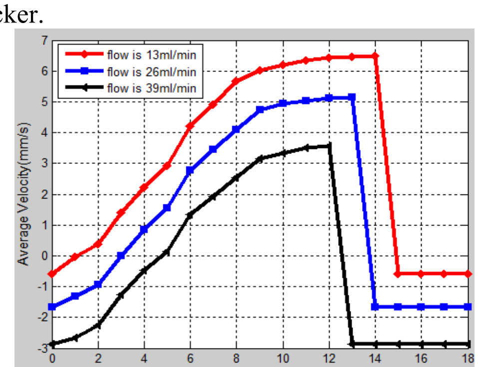
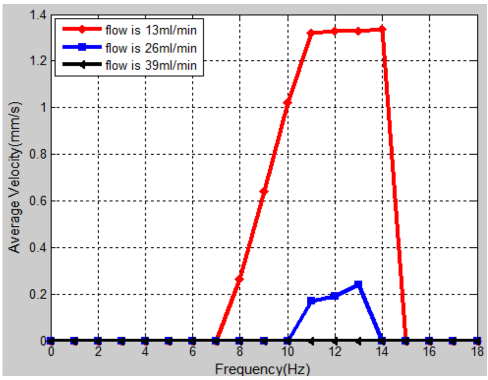
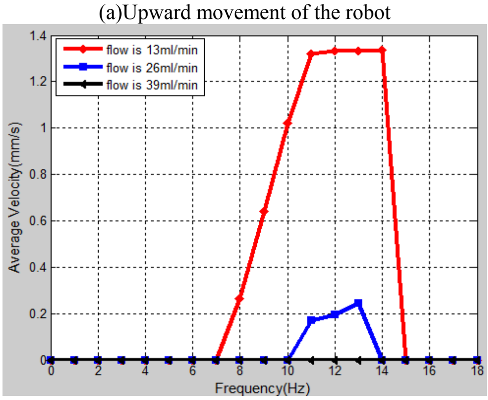


Fig. 7 Experimental results in the horizontal direction (counter current)

The average velocity of the robot appeared negative values when the magnetic force was too large or too small. From this experimental result, how to ensure relatively dormant of the robot will become the focus of our researches. For Fig.8, the maximum average velocity in the vertical direction was only about 1.337mm/s when the flow was 13 ml/min and the frequency was about 14Hz.



(a)Upward movement of the robot



(b)Downward movement of the robot

Fig.8 Experimental results in the vertical direction (counter current)

Under the condition of counter current movement, as for the vertical direction we also drawn back and forth curve when the flow was 26ml/min. The experimental results were shown in Fig. 9. From Fig.9 the contact ratio between upward and downward curve was higher than that in the case of downstream.

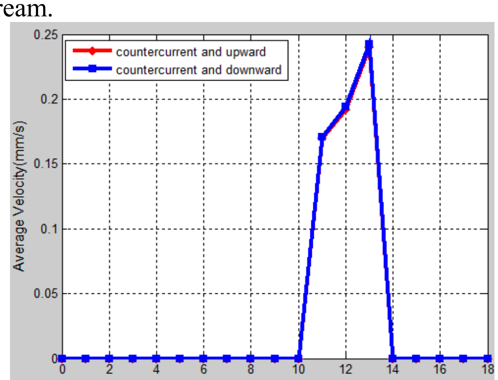


Fig. 9 Experimental results in the vertical direction (counter current)

C. *In the Case of Downstream and Counter Current*

We also drew a set of curves of downstream and counter current movement in the horizontal and vertical direction when the flow was 26 ml/min in order to clear the influence of the flow on the robot. The experimental results were shown in Fig. 10 and Fig.11.

The Fig.10 and Fig.11 showed that the gaps between the average velocity of the robot in the case of downstream and counter current. The maximum average velocity in the case of downstream was quicker than the velocity in the case of counter current by six times in the horizontal direction. The gap in the vertical direction increased thirty-six times. So we should not ignore the influence of fluid on the performance of the robot because the micro robot will work in the fluid environment.

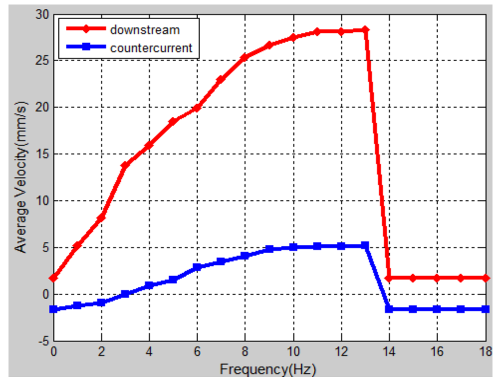
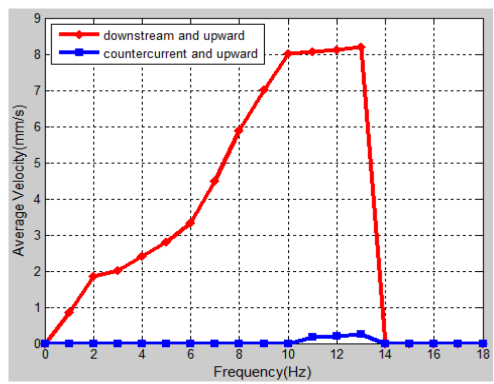
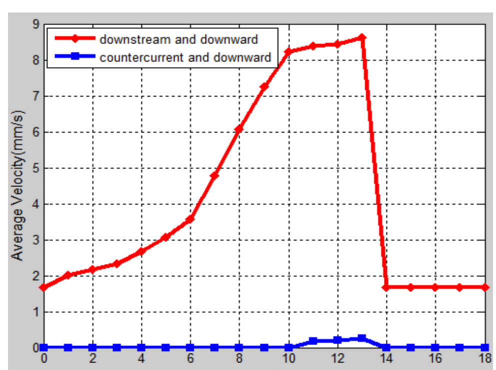


Fig. 10 Experimental results in the horizontal direction



(a)Upward movement of the robot



(b)Downward movement of the robot

Fig. 11 Experimental results in the vertical direction

V. Conclusions

In this paper, we proposed the structure and the control principle of the symmetrical spiral micro robot. And then we analyzed the buoyancy and resistance of the robot in the fluid. In the end, we more fully evaluated the performance of the robot in the new experimental platform and analyzed the experimental results.

The experimental results indicated that in the horizontal direction the maximum velocity of the micro robot is about 30.44mm/s and 6.49mm/s in the case of downstream and counter current respectively. In the vertical direction the maximum velocity of the robot is about 10.1mm/s and 1.34mm/s in the case of downstream and counter current respectively while it is doing upward movement. In the vertical direction the maximum velocity of the micro robot is about 10.11mm/s and 1.337mm/s in the case of downstream and counter current respectively while it is doing downward movement. Through these data we found the dynamic performances of the micro robot are superior. Also, we found although the velocity of the micro robot is the largest, its transition frequency is the smallest in the case of downstream and the phenomena in the case of counter current are similar. In addition, we further realized the influence of fluid on the performance of the robot through the comparison of downstream and counter current. At the same time, through the experimental curves we obtained the velocity of the robot in the horizontal direction is 0.6mm/s, 1.67mm/s and 2.86mm/s corresponding to the different experimental flow in the case of downstream when the flow acts on the robot only. The velocity of the intestinal peristalsis is 0.5mm/s to 20mm/s and the velocity in the proximal segment is faster than that in the distal segment for the small intestine. So the fluid environment coheres with the intestinal actual situation, especially for the distal segment. The experimental platform we set up can reflect the conditions of human gastrointestinal tract, so the performance evaluation of the micro robot in this paper will provide a strong support for the future clinical application.

In the future, we will focus on performance evaluation of the micro robot with Helmholtz coil.

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