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Study on driving mechanical model of microcapsules based on fluid-structure interaction in intestinal tract

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The research of the active capsule endoscopy in the digestive tract is current hotspot. However, the difficult control of capsule endoscope restricts its further application. In this paper, stress of Capsule in a viscous liquid environment was analysed theoretically and the mechanical model of Capsule with different sizes of round and oval head shapes was established. Based on the drive model, the dynamic characteristics of the magnetic drive capsule with different shapes in the gut traveling was studied under the action of Fluid-structure Interaction. With COMSOL Multiphysics bidirectional Fluid-structure interaction module, the relationship of the capsule exercise stress with the gut dynamic viscosity, the capsule size and capsule shape was analysed. Based on the standard k - epsilon turbulence model, the intestinal fluid model and the intestinal wall model were created. With the different created model of capsule, intestinal fluid and intestinal wall, the multiple factors and levels of numerical simulations were carried out. The results were listed as follows: 1) At the same level of dynamic viscosity and intestinal wall dimension parameters, oval head capsule driving resistance decreased about 9.3-16.3% compared to that of circular capsule. 2) The stress model of the capsule could be used as an active control model in the intestinal diagnosis and treatment of magnetic displacement active capsule endoscope, which is of great significance to the application of the capsule endoscope.

Keywords: Fluid-structure interaction, microcapsule endoscopy, intestinal tract, driving mechanical model

INTRODUCTION

The microcapsule robot has a broad development prospect in the medical field as the new digestive tract medical device. The drive mode of capsule endoscope driven by external magnetic field mainly includes the rotary magnetic field control and the permeability control of quasi-static magnetic field control. At present, the problems of inaccurate localization and low attitude control accuracy of capsule robots are the shackles of the development of microcapsules. Tan Renjia et al. [1] established a Ciarletta hyperelastic resistance model for the critical sliding resistance of quasi-static interaction between magnetic-driven capsule endoscopy and intestinal tract. The results showed that the ratio of endoscopy diameter to intestinal tube diameter (R/r) had a significant effect on sliding resistance. The friction force of the head of the capsule was less than 1%. Li Chuanguo et al. [1] proposed an inchworm-like capsule robot which can achieve axial and radial expansion. It uses DC motor to control and clamp the oil bag to achieve peristalsis. Its maximum radial output force is 150 g, and its complete peristaltic step distance is 9.5 mm. Zhang Yu et al. [1] in viscous Newtonian fluid environment, the liquid resistance moment of petal-shaped and cylindrical side-wall rotary capsule robot was analyzed in the pipeline. The cylindrical side-wall tiles in the four capsule structures showed large eccentricity e_s, which reflected good driving effect. The intestinal wall was defaulted to be rigid body in the model. Chi Minglu et al. established the space magnetic moment model of the universal rotating magnetic vector, improved the slip angle and horizontal angle of the magnetic precession petal capsule endoscope, improved the non-contact driving performance, and had a significant effect on reducing the distortion of the intestinal tract when the capsule turned.

In this study, a force model of capsule motion in viscous resistance fluid environment of elastic intestinal tract was established for a permeable capsule robot with elliptical and circular head shell shapes. Two kinds of capsules with different shapes were numerically simulated under different viscous fluid environments with different dynamic

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viscosities and intestinal diameters. The stress distribution of the permeable capsule under the interaction of the elastic intestinal wall and viscous fluid and the influence of the capsule on the fluid and intestinal tract were analyzed. The theoretical basis was provided for the shape optimization and accurate positioning of the magnetic-driven capsule robot in viscous and elastic intestinal environments.

STRESS ANALYSIS OF CAPSULE

The mechanical model of the capsule in the liquid intestinal fluid environment can be approximated as the force model of moving objects in the liquid pipeline [1]. The resistance to motion of the capsule F_d is mainly divided into two parts: fluid dynamic pressure F_p and viscous resistance of fluid F_f, namely:

$$F_d = F_p + F_f \tag{1}$$

Head impact resistance

When the capsule is moving in the intestinal flow field, v_r is the axial relative motion velocity of the capsule robot and the fluid in the intestinal tract and dS is the head surface unit of the capsule shown as Fig.1 below. The axial force that fluid impact on the head of the capsule is F_p:

$$F_p = \int_{\Omega} dF_{p1} \tag{2}$$

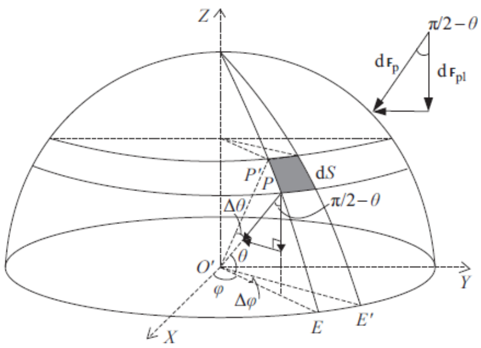


Fig.1. Schematic diagram of force element on the head of capsule

And:

$$df_{p1} = \sigma_c(\theta) \cdot \vec{n} \cdot dS \tag{3}$$

$\vec{n}$ - unit normal vector to the center.

$\sigma_c(\theta)$ - impact stress of unit body is subjected to fluid, which can be known from the fluid dynamics:

$$\sigma_c(\theta) = \rho {v_r}^2 \sin^2 \theta \tag{4}$$

To the unit surface dS :

$$dS = R^2 \sin\theta d\theta d\varphi \tag{5}$$

The formula Eq,(3), (4) and (5) are introduced into Eq,(2) :

$$F_p = \int_0^{2\pi} \int_0^{\alpha} R^2 \rho {v_r}^2 \sin^4 \theta d\theta d\varphi \tag{6}$$

where:

θ - Angle between the unit method (pointing to the center O) and the XOY Plane, -;

R - radius of capsule head, m;

ρ - fluid density, kg/m^3;

φ - the Angle between the unit surface normal vector and the XOZ Plane, -;

v_r - the axial average velocity of the fluid relative capsule, m/s.

Viscous resistance

The viscosity of the intestinal fluid is not negligible [5], Viscous resistance of capsule head is F_{f_1}, resistance of the middle cylinder is F_{f_2}, F_f is viscous resistance of the fluid in the capsule movement:

$$F_f = F_{f_1} + F_{f_2} \tag{7}$$

(1) Viscous resistance of capsule head

For the intestinal wall head unit dS, there is a corresponding resistance unit dF_{f_1}:

$$dF_{f_1} = \frac{\mu v_t \cos\theta}{h(\theta)} dS \qquad (8)$$

$h(\theta)$ is the distance from the inner wall of the intestinal tract, as a function of θ.

For the sphere:

$$h(\theta) = H - R\cos\theta \qquad (9)$$

References Eq,(2) include:

$$F_{f_1} = \int_{\Omega} dF_{f1} \qquad (10)$$

Bring Eq,(9) back to the above formula and integrate:

$$F_{f_1} = \int_0^{2\pi}\int_0^{\alpha} \frac{\mu v_t R^2 \sin^2\theta \cos\theta}{H - R\cos\theta} d\theta d\varphi \qquad (11)$$

(2) Viscous resistance of column

The viscous resistance between the capsule and the intestine can be considered as the model of viscous resistance between two parallel plates. According to the calculation formula of viscous resistance:

$$F_{f_2} = \mu A \frac{v_r}{h} \qquad (12)$$

A is the contact area of capsule side and liquid:

$$A = \pi R(l - 2R) \qquad (13)$$

So:

$$F_{f_2} = \mu\pi R(l - 2R)\frac{v_r}{H} \qquad (14)$$

v_r - the axial average velocity of the fluid relative to the capsule, m/s;

R - the spherical radius of the capsule, m;

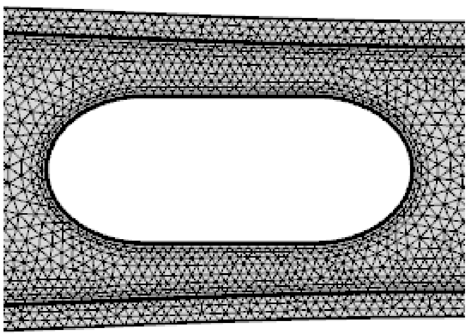
l - length of the capsule, m;

H - average distance between capsule wall and intestinal wall, m;

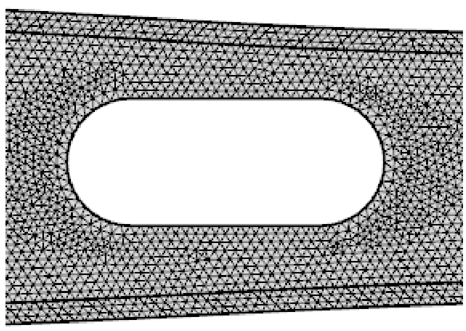
μ - dynamic viscosity of the intestinal fluid, $Pa \cdot s$.

NUMERICAL SIMULATION MODEL

Considering the coupling effect of human intestinal wall elastomers on intestinal fluid motion, the COMSOL Multiphysics bidirectional Fluid-structure interaction module was used to simulate the drive of the capsule [5]. Flow field was set as *k* - *epsilon* turbulence transient model. The intestinal model parameters were set as: Length: *l* = 200mm, Width: *B* = 25mm, Intestinal wall thickness: *b* = 2mm. The intestinal material model USES hyperelastic material. In order to reduce the stress concentration distortion caused by fixed constraints at both ends, the distance between the ends of the capsule and the outlet of the fluid was set as L_0 = 35mm, The physical field control grid is used to improve the grid quality to eliminate the boundary effect.



(a)



(b)

Fig.2. Model grid division $\mu = 5.3, D = 22.1$ (a) Elliptical (b) Circle

The left and right sides of the intestinal wall model are set as fixed end constraints, and the speed of the capsule moving wall was set as v = 20mm/s. The average of the flow velocity $\overline{v_n}$ = 20mm/s. Stress monitoring points were inserted into the middle head and middle of the capsule shell in order to fully detect the force of the outer wall of the capsule. The von-mises stress value σ_m which obtained by the probe were main evaluation parameters of the force of the capsule [5].

NUMERICAL SIMULATION

The kinetic viscosity of the intestinal fluid μ and the intestinal tract size *D*, each of the two parameters takes two levels which are used for coupling field simulation:

Table 1. Parameter values of each factor

Intestinal fluid dynamic viscosity	Intestinal size	Shape of capsule
μ / mPa·s	D / mm	S / -
5.3	22.1	Circle (C)
20.7	24.5	Ellipse (E)

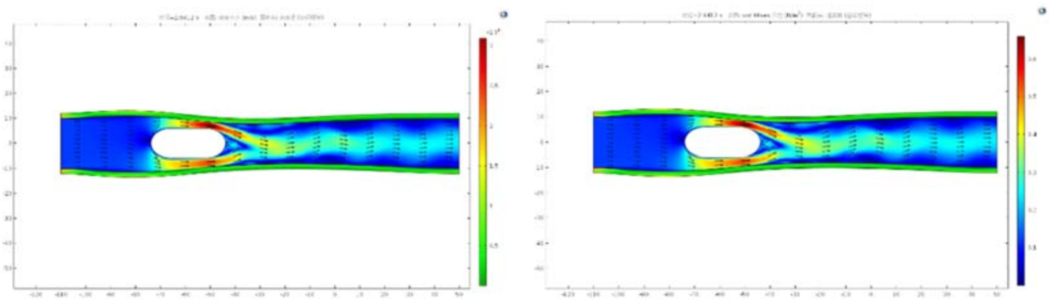
There are few parameters in this numerical simulation [8].
Dynamic viscosity parameters and intestinal size parameters only set two parameter levels, so there is no orthogonal numerical simulation. According to the experimental group combination matching model listed below, 8 groups of prepared capsule intestinal models were imported into COMSOL. The stress probe is inserted at the designated monitoring point and is solved. The transient solver adopts full coupling automatic (Newton) nonlinear method. The value of Relative tolerance is to be determined to 0.001. The damping factor was restored to 0.75 to ensure the efficiency of the solution.

Table 2. Parameter configuration of the experimental group

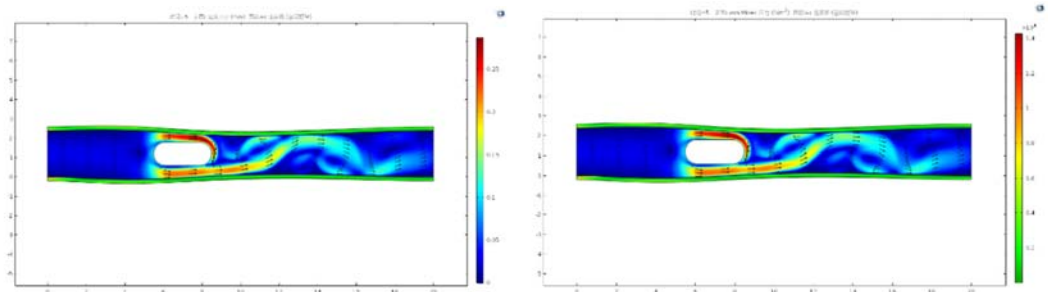
FACTOR	μ $\times 10^{-3}$ Pa·s	D mm	S -
NO.1	5.3	22.1	C
NO.2	5.3	22.1	E
NO.3	5.3	24.5	C
NO.4	5.3	24.5	E
NO.5	20.7	22.1	C
NO.6	20.7	22.1	E
NO.7	20.7	24.5	C
NO.8	20.7	24.5	E

INTERPRETATION OF RESULT

The numerical simulation results of 4 sets of endoscope parameters at D = 22.1mm were selected [8]. The distribution of stress distribution and the distribution of the flow velocity field of intestinal fluid are shown as Fig.3.



(a) $\mu / D / s$, $5.3/22.1/E$ (b) $\mu / D / s$, $20.7/22.1/E$



(c) $\mu / D / s$, $5.3/22.1/C$ (d) $\mu / D / s$, $20.7/22.1/C$

Fig.3. Velocity distribution and intestinal stress cloud diagram of the same intestinal size (D=22.1mm) under t=3.0s

The results showed that the maximum velocity was found near the capsule at low viscosity: μ=5.3 and μ=20.7. The velocity of the third second is respectively $v = 0.315$m/s(E) and $v = 0.310$m/s(C), Maximum stress in the model wall are 7.75kPa(E) and 9.07kPa(C) which mainly happens near the fixed end of the entrance. This indicates that there is still gravitational concentration at the fixed end. Another thing to note is that, group 2 and 6 of elliptic shapes formed a stable wake. In contrast, group 1 and 5 of the round capsule showed a more obvious disturbance.

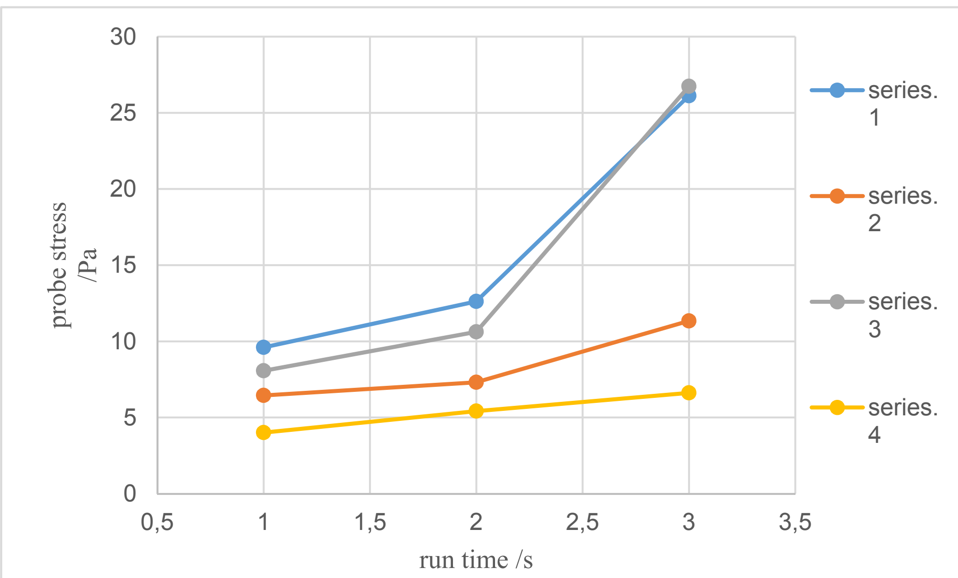


Fig.4. Stress of capsule head $\mu = 5.3\times10^{-3}\,\mathrm{Pa\cdot s}$

Table 3. The stress value of the head probe $\mu = 5.3 \times 10^{-3}\,\mathrm{Pa \cdot s}$, σ_t / Pa

GROUP	1	2	3	4
T=1S	9.605	6.450	8.070	4.010
T=2S	12.617	7.310	10.620	5.420
T=3S	26.12	11.340	26.740	6.620

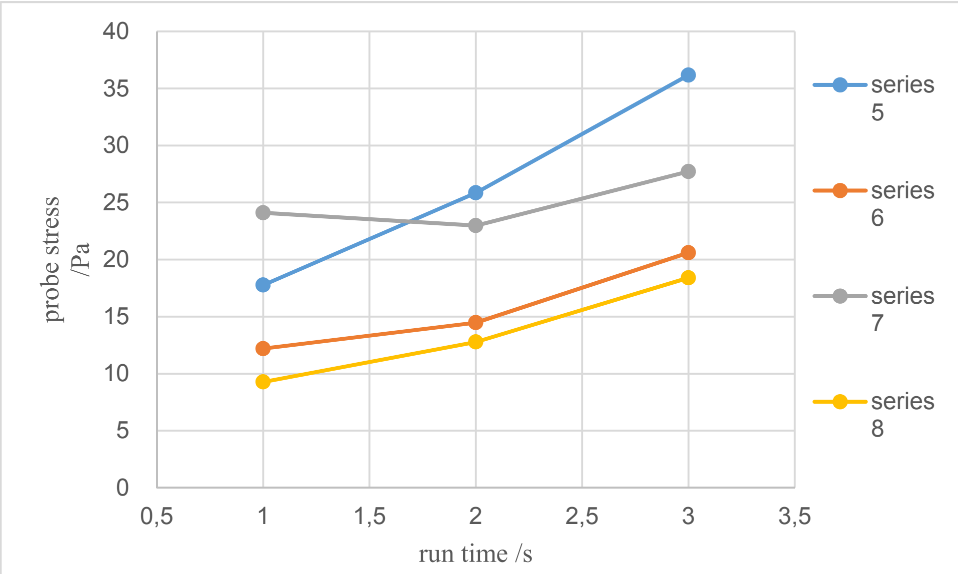


Fig.5. Stress of capsule head $\mu = 20.7 \times 10^{-3}\,\mathrm{Pa \cdot s}$

The stress distribution of the index points of each group in 3s was measured and the results were grouped according to the shape of the capsule (Fig.4, 5). The results showed that the movement stress of the capsule was higher when the viscosity was higher. In the level of the dynamic viscosity parameter $\mu = 20.7 \times 10^{-3}\,\mathrm{Pa \cdot s}$. Series 3, 4 represents the elliptical head stress within the different sizes of the intestinal tract, the stress mean 19.21Pa is lower than the circular head 21.17 Pa, which represents a 9.3% lower than that of the series 1, 2 in 3s, and the head stress is 16.3% lower than the stress under the level of $\mu = 5.3 \times 10^{-3}\,\mathrm{Pa \cdot s}$.

Table 4. The stress value of the head probe $\mu = 20.7 \times 10^{-3}\,\mathrm{Pa \cdot s}$, σ_t / Pa

GROUP	1	2	3	4
T=1S	17.760	12.190	24.097	9.270
T=2S	25.850	14.470	22.972	12.770
T=3S	36.170	20.600	27.717	18.400

CONCLUSIONS

In this numerical simulation, the dynamic force model of active capsule robot in viscous fluid of human intestinal environment was analyzed theoretically. The Comsol Multiphysics module was used to simulate the fluid solid coupling in different environments for capsule movement. The results showed that:

(1) Under different dynamic viscosities and

intestinal diameters, the average stress on the monitoring point of the head of the elliptical head capsule is low, and the maximum stress on the intestinal wall is low, which indicates that the head shape of the elliptical head capsule has better stress distribution and intestinal comfort under the fluid-solid coupling environment.

(2) The stress changes of capsules in 3 seconds are more gentle when they move in liquid environment with high motion viscosity. Under the same capsule size, the larger the intestinal diameter, the lower the stress on the capsule head. The force calculation value of capsule is slightly lower than that of simulation. It is necessary to further study the influence of intestinal expansion factors on capsule movement under coupling state.

(3) The shape of the capsule head disturbs the flow field distribution of the low dynamic viscous fluid. The maximum flow velocity of the two capsules is almost the same (1.5%), but the flow field distribution shows that the elliptical capsule head exhibits motion stability at low speed and straight line motion.

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