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Anchoring of Radially Expandable Microcapsule Robots in Blood Vessels Based on the Anchoring Method in Fan-Shaped Peristaltic Tubes

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Abstract: Radially expandable capsule robots are essential in alleviating thrombosis due to their unique anchoring and expansion capabilities within blood vessels. Despite their potential, research in this area remains limited, highlighting the need for further exploration. This study draws inspiration from the stable anchoring mechanisms observed in fan-shaped peristaltic tubes to establish a robust anchoring resistance model specifically for capsule robots in vascular environments. The research investigates the biomechanical characteristics of blood vessels under expansion conditions, deriving the longitudinal profile equation to better understand these interactions. Based on the established model, various optimization methods are proposed to enhance the anchoring performance of the capsule robots. To validate the model's accuracy, anchoring resistance is tested using a phantom vessel on an experimental platform. By integrating kinematic and mechanical analyses, an inchworm-type expansion force model is developed to evaluate anchoring performance quantitatively, allowing for an in-depth analysis of how design parameters influence anchoring resistance. This provides vital theoretical support for the design and optimization of capsule robots aimed at improving clinical outcomes in thrombotic conditions.

Keywords: Microcapsule robot, Hemorrhagic location, Hemostatic technique, Thrombus

1. Introduction

In recent years, China's aging population has led to a notable increase in the incidence of thrombosis, presenting a significant health threat that requires urgent attention. Traditional drug treatments often exhibit slow action, while surgical interventions carry substantial risks, making them less favorable for many patients. In this context, capsule robots have emerged as a promising alternative for non-invasive thrombus diagnosis and treatment. Among the various designs, radially expandable capsule robots that utilize specialized expansion mechanisms to dilate blood vessels show significant potential for achieving stable anchoring within the vascular environment.

To ensure the effective operation of these capsule robots within the gastrointestinal tract, it is essential to study their anchoring performance in detail. The constitutive models of blood vessels, which primarily include viscoelastic and hyperelastic models, provide insights into how blood vessels respond to different strains and stresses. Drawing inspiration from the anchoring mechanisms employed by fan-shaped peristaltic worms, researchers have designed a capsule robot shell that

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mimics this structure. Through a series of friction experiments and theoretical modeling, we have investigated the effects of various factors on the anchoring resistance of the capsule robot within blood vessels. Anchoring resistance is defined as the maximum force the robot can withstand without sliding within the vessel. This paper establishes a comprehensive anchoring resistance model for capsule robots and validates its accuracy through experimental results. By integrating both kinematic and mechanical models, this study not only analyzes anchoring performance within blood vessels but also proposes optimization recommendations to enhance the efficacy and safety of capsule robots in medical applications.

2. Materials and Methods

2.1. Radial Pressure Analysis of Blood Vessels

Blood vessels are considered as cylindrical pressure tubes. The circumferential principal stress SC is influenced by the radial pressure P. The relationship between SC and P is given by:

$$S_C = \frac{P \cdot r}{h} \tag{1}$$

Where S_C is the circumferential principal stress. R is the internal radius of the tube during expansion, and H is the thickness of the tube wall during expansion.

The radial pressure F_{NP} per unit length of the tube can be obtained as follows:

$$F_{np} = P \cdot 2\pi r = S_C \cdot 2\pi h \tag{2}$$

2.2. Anchoring Resistance Model

To examine how external hooks can achieve stable anchoring within the smooth and moist environment of blood vessels, we conducted detailed physical simulations of capsule robot hooks. This investigation focuses on understanding how different hook angles impact the micro-robots' ability to securely engage with the vessel wall, particularly under high flow conditions.

In our experiments, we utilized seven steel hooks, each with a different angle ranging from 0° to 90°, at intervals of 15°. These hooks were designed and modeled using SolidWorks 2016, a powerful 3D CAD software. Once the models were created, they were imported into ANSYS Workbench 15.0 for comprehensive finite element analysis (FEA).The primary goal was to analyze how variations in hook angle influence the anchoring effectiveness of the micro-robots. By simulating the interactions between the hooks and the vessel wall, we aimed to determine the optimal hook angle for stable anchoring. The study considered the impact of high flow conditions, which are characteristic of blood vessels, on the hook's performance. This approach provided insights into the mechanical behavior of the hooks and their ability to withstand dynamic forces within the blood vessel environment.

2.3. Experimental Results

The experiment demonstrated variations in the number of hook rings with six different fiber cluster types. In the experiment, the interior wall of a fiber-wrapped barrel simulated the small protrusions of a blood vessel wall. The hook arm length was 1.0 cm, and the target penetration depth was set to 4.5 cm. The variation in the number of hook rings can be categorized into three regions:

Small Hook Angle Region: When the hook angle is less than 20°, the number of hook rings remains nearly constant because the small angle allows the hooks to only engage with the tip fibers, not effectively grasping more fibers.

Increasing Hook Angle Region: As the hook angle increases, the number of hook rings gradually increases because a larger angle allows more fibers to be hooked, increasing the number of rings.

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Critical Angle and Beyond: When the hook angle exceeds the critical angle, the number of hook rings starts to decrease with further increase in hook angle. This occurs because, with a fixed hook arm length, the projection length of the hook arm decreases, making it less effective in increasing the number of rings. When the hook angle is less than the friction angle, rings cannot slide to the hook tip and only engage tip fibers. Beyond the critical angle, while all rings below the hook can be engaged, the reduced projection length leads to fewer rings.

Additionally, systems with larger displacement tend to have smaller critical angles. In these samples, the maximum displacement was 1.2 cm, with the smallest critical angle being 45°. When the hook angle reached 90°, the number of rings was similar to that observed between 0° and 15° due to the projection length approaching zero.

3. Anchoring Performance Analysis Example

A similar involute unfolding device has been developed, incorporating micro steel hooks attached to the mechanical arms of the capsule robot. These hooks extend from both ends of the device, creating a versatile mechanism for interaction with vascular structures. As the mechanical arms gradually extend, they apply controlled pressure against the vessel wall, prompting the robot to shift toward the opposite wall. This movement effectively pushes the vessel wall outward, facilitating the expansion of the vessel lumen. As a result, any previously obstructed areas are cleared, significantly improving blood flow and alleviating thrombotic conditions that can compromise circulation. The design prioritizes precise control over the expansion process, ensuring that the mechanical actions are both deliberate and measured. Furthermore, it emphasizes stability throughout the operation, minimizing the risk of damaging the vessel walls during the unfolding process. This innovative approach represents a promising advancement in medical devices aimed at treating vascular blockages safely and effectively.

4. Result

In analyzing the performance of nylon 2 hooks, the relationship between the number of hook rings and penetration depth was examined under different hook angles:

Type A (0° to 15° Hook Angles): With angles less than the friction angle, the rings cannot slide along the hook arm and only engage tip fibers, resulting in fewer rings and rapid saturation.

Type B (30° to 45° Hook Angles): Rings slide along the hook arm, increasing lateral displacement. As penetration occurs, fiber clusters compress, limiting ring displacement. Initially, the number of rings increases but eventually reaches a saturation value.

Type C (60° to 75° Hook Angles): The hook can engage all rings below, with the number of rings linearly related to penetration depth. In withdrawal tests, arc-shaped hooks made of fine steel wire were used to simulate real separation behavior. The tests showed that the pull-out force rapidly increased with displacement until saturation. Pull-out force was related to the hook's radius and arc angle, with hooks of smaller radius exhibiting higher pull-out force due to greater stiffness. Thus, hooks with angles between 60° and 76° had the best anchoring effect.

5. Discussions

To ensure stable anchoring of the Robotically Enhanced Controlled Release (RECR) system in the intestines, it is essential to optimize the robot's anchoring mechanism. The study explored the influence of various factors on anchoring performance, particularly focusing on the friction coefficient and the length of the contact device. A significant increase in the friction coefficient has been shown to enhance anchoring resistance. This enhancement can be achieved through advanced techniques such as surface micro-patterning or the application of high-friction coatings. However,

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while increasing the friction coefficient theoretically boosts resistance, it may inadvertently lead to heightened radial pressure, which can compromise the overall effectiveness of the anchoring. As a result, although the approach may seem promising, it could result in reduced actual resistance, rendering it less ideal for practical applications. Therefore, careful consideration of these trade-offs is crucial in developing an effective anchoring solution for the RECR system in gastrointestinal settings.

6. Conclusion

This study established an anchoring resistance model for radially expanding micro-capsule robots in blood vessels, considering friction coefficient and contact device length. Experimental results showed that: 1) When hook angles are less than the friction angle, only rings around the hook tip connect, with experimental values matching theoretical values, validating the model's accuracy. 2) Rings below the hook can slide to the tip, affected by ring lateral constraints and friction. 3) When hook angles exceed the critical angle, all rings can be hooked. An involute-shaped capsule robot was designed, and its expansion force model was established. The structural design was optimized to increase friction coefficient. This study provides a theoretical basis for the anchoring performance of capsule robots in blood vessels and proposes relevant optimization methods. Future work will focus on optimizing the capsule robot and exploring its applications in vascular environments.

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