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Application of TRIZ Innovation Method to In-Pipe Robot Design

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Abstract: The peristaltic in-pipe robot incorporates multiple actuators, and achieving precise co-operative control among these actuators poses significant complexity. To address these issues, the Theory of Inventive Problem Solving (TRIZ) is applied to identify and resolve physical and technical conflicts in the creative design process of peristaltic in-pipe robots. By highlighting the insights on and technical guidance offered by TRIZ's inventive principles, this paper examines the method for realizing a single-motor-driven peristaltic in-pipe robot from a transmission perspective. By employing a combination of connecting rods, cam mechanisms, and gear systems, a one-DOF peristaltic in-pipe robot was devised. Subsequently, a prototype was constructed, and successful bidirectional motion tests were conducted within pipes. The findings highlight the efficacy of the TRIZ-based design approach in innovatively designing one-DOF in-pipe robots and the unnecessary employment of complex multi-drive cooperative control in peristaltic in-pipe robots.

Keywords: TRIZ; one-DOF; bidirectional; peristaltic; in-pipe robot

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1. Introduction

TRIZ (Theory of Inventive Problem Solving) is a set of theoretical methods, developed from a multidisciplinary approach, that greatly accelerate the process of invention. TRIZ emphasizes the identification and resolution of conflicts as central to solving problems related to invention. By analyzing patents, the 40 most important and universally applicable inventive principles in TRIZ have been extracted [1]. A number of previous studies have solved practical problems by applying TRIZ.

With the current fast-paced product development, the need to adapt to changing customer demands and market dynamics requires the design of new products that are more efficient and innovative [2]. For example, the TRIZ innovation system approach was applied in the design of handlebars, and satisfaction surveys were used to assess whether the handlebars met users' needs, in order to reduce the cost and time of product development [3]. The TRIZ-based product–service design approach can assist designers/engineers in developing innovative products for customer use. During the COVID-19 pandemic, a novel face-mask design was conceptualized to verify the applicability and validity of the proposed design approach [4]. An intelligent lawnmower for uneven lawns was designed using the TRIZ method. TRIZ tools, including cause–effect chain analysis, technical contradictions, physical contradictions, etc., were used. During the development of a design concept, conflicts were resolved using inventive principles, separation strategies, and standard invention solutions [5]. The Theory of Inventive Problem Solving (TRIZ) has been demonstrated in several design studies. The above literature indicates that TRIZ can effectively improve product design efficiency.

To meet this challenge, this study employed TRIZ's principles of innovation and invention to analyze critical requirements and formulate standardized TRIZ problem statements.

For example, in order to better serve the safety and protection of urban residents during cycling, the problems encountered by users wearing helmets during cycling were analyzed, and the corresponding inventive measures were adopted to improve the problems with helmets [6]. The TRIZ method is also very effective in the manufacturing industry; for example, the mechanical arm lacks rigidity and strength when machining parts. Based on the TRIZ method, a new design combining wire EDM and six-axis robot machining was proposed to overcome the limitations of traditional robot machining and expand the application of EDM [7]. In order to conduct patent analysis, a complete framework for patent analysis, based on a combination of sentences and word-level deep neural networks, was proposed. The idea is to mine a patent's motivating problem (also known as contradiction), which is fundamental to understanding the invention and identifying of the purpose for which it could be used [8]. Various problems in the product innovation process are often caused by changes in the external environment of the product. A framework has been proposed to classify these problems into disorder, chaos, complexity, complicated, and simple areas according to the external environmental changes. Each problem domain is then solved by appropriate design tools in TRIZ. The proposed method has been applied in the design of an enterprising mobile bridge-erecting machine [9]. Bai et al. [10] improved an existing modular product design method based on TRIZ and axiomatic design theory. Li et al. [11] proposed an integrated process centered on process and product innovation and solved key problems with the TRIZ method based on process trimming. Chen et al. [12] abstracted the invention problem by using TRIZ in the development of new products. Sauli et al. [13] designed the CAD model of a scissor-lifting mechanism and optimized it with TRIZ's innovative tools. Cempel et al. [14] applied TRIZ to analyze the operating state of mechanical vibration systems. Sen et al. [15] used TRIZ to obtain an analytical solution to solve the sheet metal forming problem in the automobile industry. Li et al. [16] proposed a TRIZ-based cutting method to avoid patent infringement. TRIZ's highly abstract inventive principle and general technical parameters are summarized so that the same principle can be reused in the impracticable field; TRIZ inspires designers to think and solve problems from different angles and to find and solve problems in the designer's innovative design process.

The in-pipe robot is a special robot that performs inspection or maintenance tasks related to pipelines. Its types mainly include wheeled [17–20], spiral [21,22], magnetic [23,24] peristaltic [25–27], and so on. The driving wheels of the wheeled in-pipe robot always press the pipe wall to obtain enough friction. The driving wheels play the role of walking and supporting the pipe wall at the same time. However, due to the limited contact area between the driving wheel and the pipe wall, the driving wheel can slip easily. The effective motion of the spiral in-pipe robot requires the front-drive unit to maintain continuous contact with the pipe wall. Compared with the wheel in-pipe robot, the rotating motion leads to low walking efficiency. The magnetic in-pipe robot is driven by an external magnetic field, and its moving speed is changed by adjusting the current frequency of the magnetic field, which is mainly used in the field of micro-pipelines. The peristaltic in-pipe robot adopts a local motion mode; the contact area with the pipe wall is relatively large, and it cannot easily slip. According to the movement direction of the peristaltic robot, it is divided into the multi-direction type [28], two-direction type [29], and one-direction type [30,31]. The multi-direction peristaltic robot (Figure 1a) can move straight and turn actively (in any direction). It needs a large number of actuators and very complex control. The applicable environment is not limited to pipelines, but can also be applied to complex terrain, such as stairs and mountains. The two-direction peristaltic robot (Figure 1b) can only move forward and backward, and is only suitable for straight pipes or a curved pipe with a very large radius of curvature. The one-direction peristaltic robot (Figure 1c) can only move forward and cannot exit the pipeline backward when encountering obstacles. Neither the two-direction peristaltic robot nor the one-direction peristaltic robot can turn actively. Most long-distance pipelines comprise horizontally arranged straight pipes that require the robot to move forward and backward during the inspection process (Figure 2), and so, the two-direction peristaltic in-pipe robot has a wide range of applications. The existing two-direction peristaltic in-pipe robot usually uses 3-motor coordinated control, and so, the main problems are as follows: (1) Precise sensors and complex control strategies are needed; (2) the installation dimensions of motors and sensors in enclosed pipes are limited; and (3) the stability of the control system and the measurement accuracy of the sensor will be affected by the wet pipe environment.

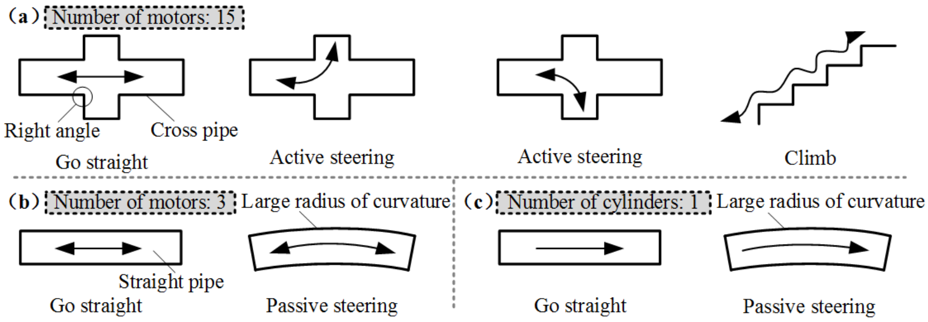


Figure 1. Move direction classification of peristaltic robots: (**a**) multi-direction, (**b**) two-direction, (**c**) one-direction.

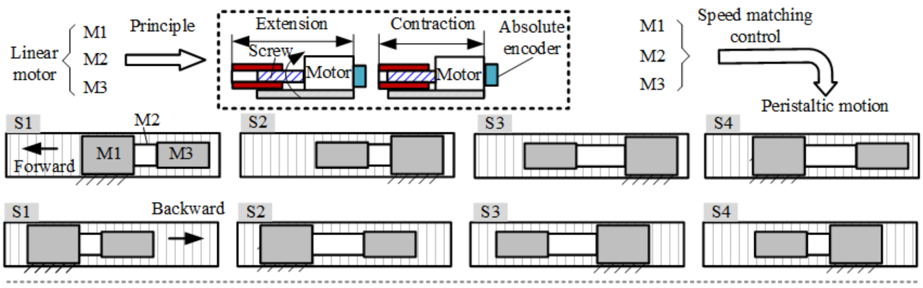


Figure 2. Traditional two-direction peristaltic robot driven by 3-motor structure (move forward and move backward).

To avoid the complexities associated with coordinating multiple actuators, this research paper introduces a novel one-DOF peristaltic in-pipe robot using the TRIZ design methodology. This paper is organized as follows: Section 2 introduces the overall and detailed structure of the novel robot. Section 3 introduces and categorizes the conflicts in the design process. Section 4 applies TRIZ inventive principles to address and resolve these conflicts. Section 5 designs and analyses the key parameters. Finally, in Section 6, the prototype's motion capabilities are tested and validated.

2. Explanation of the Novel Robot

2.1. Overall Introduction

As shown in Figure 3, the proposed robot is mainly made up of three parts: the front body (supporting mechanism), middle body (propulsion mechanism), and rear body (supporting mechanism). This shows that the robot consists of three functional modules: two supporting mechanisms at two ends and one propulsion mechanism in the middle, acting as the driver. The novel in-pipe robot prototype we have developed is illustrated in Figure 4. The in-pipe robot is mainly composed of a motor, guide wheels, support legs, connecting rods, and reset springs.

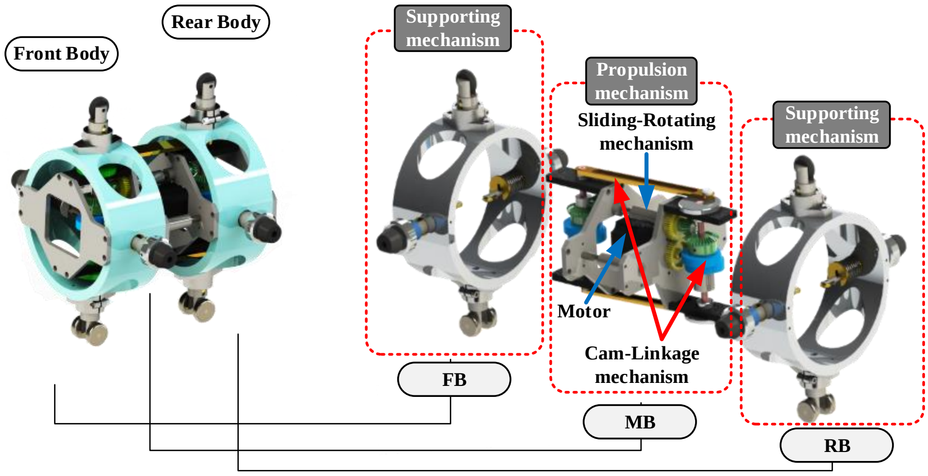


Figure 3. 3D rendering of the novel peristaltic in-pipe robot.

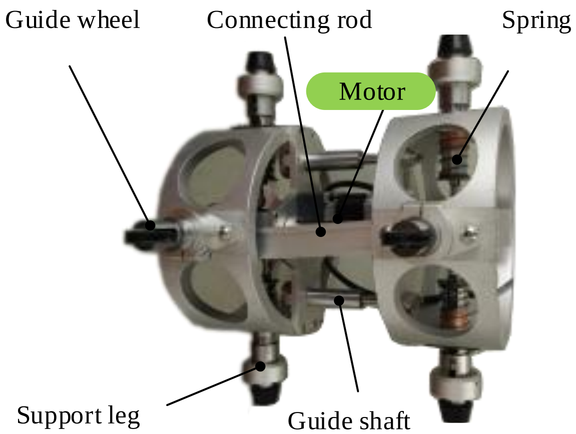


Figure 4. Novel in-pip robot prototype.

2.2. Detailed Introduction

The supporting mechanism mainly consists of cams and push rods, and it drives the push rods to retract and move. As shown in Figure 5, the telescopic transmission shaft can transfer the power of RB to FB. Under the cam drive, FB and RB can produce radial expansion. Under the action of the crank–slider mechanism, MB can produce axial expansion. The propulsion mechanism is mainly made up of the motor, sliding-rotating mechanism, and cam-linkage mechanism, which is used to connect the front and rear supporting mechanisms. The gait process is shown in Figure 6, and the direction of peristalsis can be changed by controlling the direction of the motor.

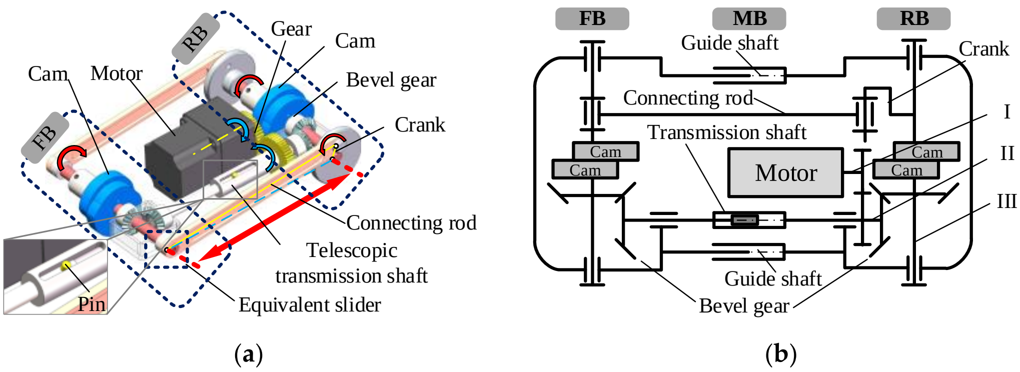


Figure 5. Propulsion mechanism of the novel in-pipe robot. (**a**) 3D; (**b**) 2D.

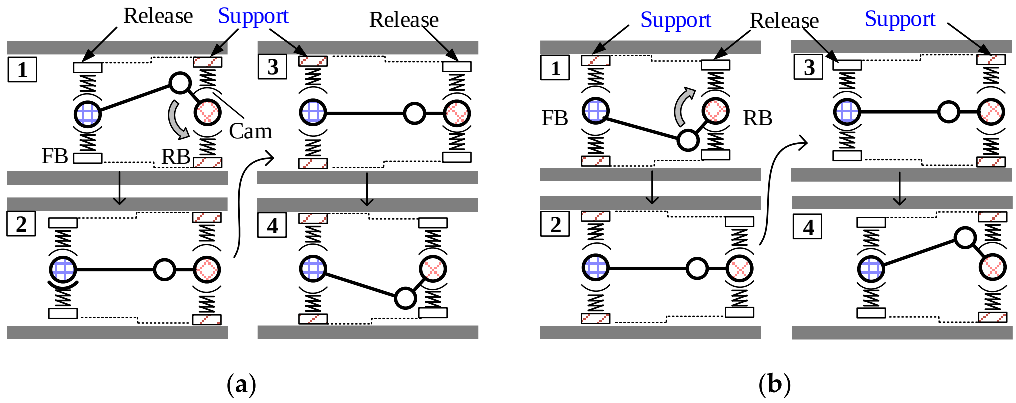


Figure 6. Principle of forward and reverse walking: (**a**) forward walking; (**b**) reverse walking.

The function of the motor is to provide the sole power for the entire robot's step motion. The guide wheel is unpowered and features an integrated spring mechanism, allowing it to accommodate minor variations in the pipe diameter. The function of the support leg is to generate telescopic motion along the radial direction of the pipeline, which is used to contact or detach from the pipe wall. The connecting rod is a part of the crank–slider mechanism that can change the distance between the front and the rear body of the robot, allowing the robot to perform telescopic motion along the axial direction of the pipeline. Additionally, reset springs ensure that the leg (follower) maintains contact with the cam.

3. Finding Design Conflicts

TRIZ can help us discover defects in traditional robots, summarize conflicts, solve conflicts creatively, and, finally, to invent new robots. Bidirectional peristaltic robots typically consist of three parts: the front body (FB), middle body (MB), and rear body (RB). Relative to the pipe, FB and RB can expand and contract radially, while MB can expand and contract axially. The three bodies work together in chronological order to enable the robot to achieve telescopic creep in the pipe. The traditional peristaltic in-pipe robot usually uses three motors to drive FB, MB, and RB. In order to achieve peristalsis, the three motors must be precisely coordinated to reduce the effect of errors; otherwise, the robot cannot walk normally. The traditional approach employs three motors, which presents two significant issues:

(1) Maintaining accurate relative angular positions for the three motor axes over extended periods is challenging. With time and usage, the decline in sensor sensitivity can lead to degradation in the precision of the motors' relative positioning. This, in turn, results in the robot's walking motion malfunctioning. This problem is particularly exacerbated in humid pipeline environments, where sensor failures and malfunctions tend to occur more frequently.

(2) Three motors are too many, and the installation space of the robot is limited. In addition, a reducer is required for each motor to improve the driving force. The motors (M1, M2, M3) of the peristaltic robot work at different times. When one motor operates, the other two motors may remain stationary. Therefore, in the design, if three motors can be reduced to one motor and peristaltic walking can be achieved through transmission, it will greatly reduce the number of motors, reducers, and sensors and the control complexity. Therefore, reducing the number of motors and replacing the motors with clever mechanical designs is an important innovation for us.

The problem addressed in this article is that of reducing control complexity and reducing the number of motors (the weight of the motors and reducers). However, this will result in reduced adaptability to changes in pipe diameter.

The single-motor drive can avoid complex and precise cooperative control, and so, we expect to design an in-pipe robot without control factors. To achieve this goal, TRIZ conflict resolution theory is adopted because TRIZ can help us find and resolve conflicts in the design process. As shown in Figure 7, a specific problem can be seen in terms of conflicts, and these conflicts can be further divided into physical conflicts and technical conflicts. The physical conflicts can be solved according to the separation principle in Table 1. After analyzing and summarizing a large number of patents, modern TRIZ puts forward the corresponding relationship between separation principles and inventive principles, as shown in Table 2. One separation principle can correspond to multiple inventive principles, and related inventive principles can inspire us to solve problems. Some inventive principles are listed in Table 3. In Section 4, the meaning of the adopted inventive principle will be explained in detail.

Table 1. TRIZ separation principle.

Type	Separation Mode	Inventive Principles (IP)
1	Space	Separating the two parties in conflict in different spaces.
2	Time	Separating the two parties in conflict at different time periods.
3	Conditional	Separating the two parties in conflict under different conditions
4	Whole and part	Separating the two parties in conflict at different levels

Table 2. Correspondence between separation principles and inventive principles.

Type	Separation Mode	Inventive Principles (IP)
1	Space	1, 2, 3, 4, 7, 13, 17, 24, 26, 30
2	Time	9, 10, 11, 15, 16, 18, 19, 20, 21, 34
3	Conditional	12, 28, 31, 32, 35, 36, 38, 39, 40
4	whole and part	1, 5, 6, 7, 8, 13, 14, 22, 23, 25, 27

Table 3. Some of the 40 inventive principles of TRIZ.

No.	Name
1	Segmentation
2	Separation/Taking out/Extraction
3	Local quality
4	Symmetry change/Asymmetry
5	Merging/Consolidation
6	Multifunctionality/Universality
7	Nested doll
8	Weight compensation
9	Preliminary counteraction
10	Preliminary action
11	Beforehand compensation
12	Equipotentiality
13	Do it in Reverse
14	Spheroidality/Curature increasel
15	Dynamic parts/Dynamisation
16	Partial or excessive actions
17	Dimensionality change
18	Mechanical vibration
19	Periodicaction
24	Intermediary/Mediator
39	Inert atmosphere/Inert environment
40	Composite materials

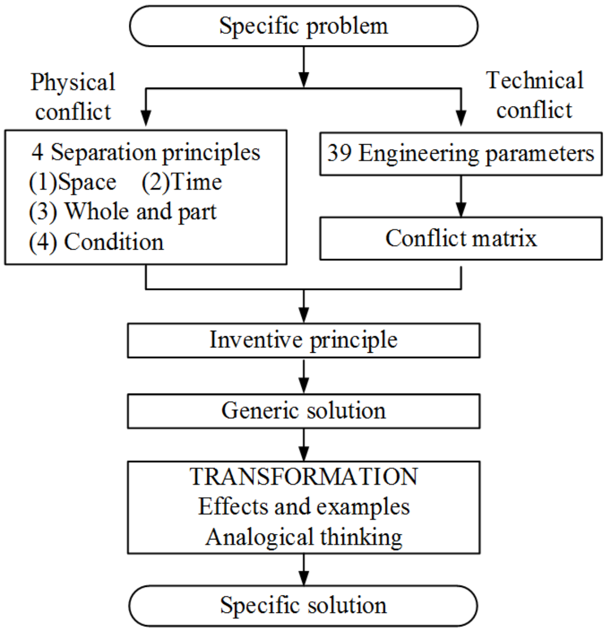


Figure 7. Conflict classification and resolution process.

3.1. Physical Conflict

Physical conflict refers to existence of opposite and contradictory needs within the same object.

(1) Physical conflict 1: length and shortness of FB/RB radial dimension.

As shown in Figures 8 and 9, the radial dimensions of FB/RB have different sizes at different times, and the sizes change periodically. "Size is long" and "size is short" are opposite needs. This is a physical conflict. It belongs to the time separation category in the separation principle. According to Table 2, we choose the most relevant inventive principle: inventive principle 19 (Periodicity).

(2) Physical conflict 2: length and shortness of MB axial dimension.

When the leg of FB moves down, the leg of RB moves up, and the positive and negative rotations of the motor correspond to the contraction or extension of FB/RB. Therefore, when FB contraction and RB extension are simultaneously carried out, the motor needs both forward rotation and reverse rotation in different places. To realize the transformation of two position motion forms, spatial separation can be used. On the basis of Table 2, we choose the most relevant principle: inventive principle 24 (Intermediary/Mediator). Section 4 will solve these problems through specific mechanism design.

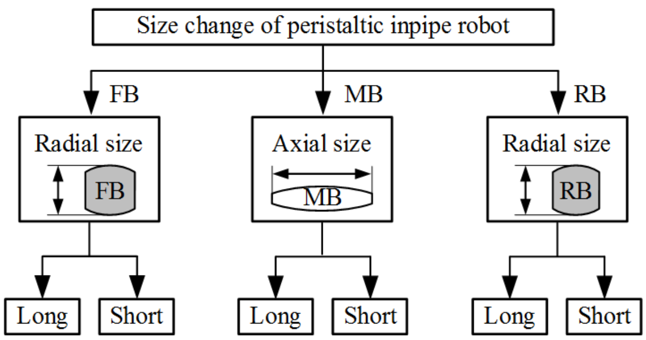


Figure 8. Size change in the peristaltic in-pipe robot.

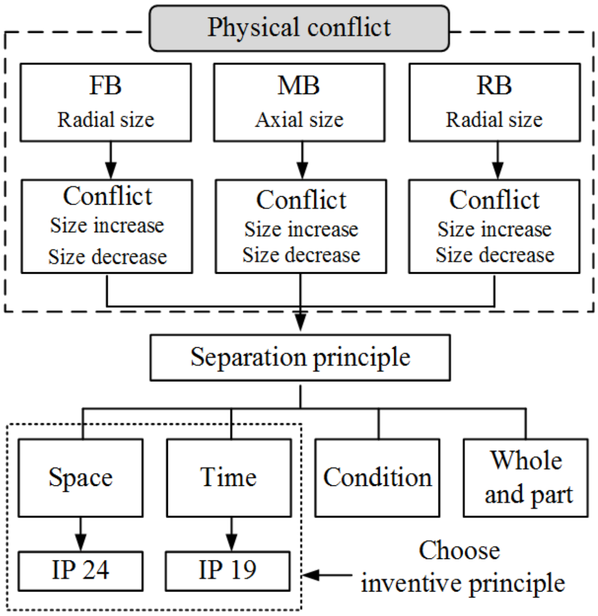


Figure 9. Physical conflict in the peristaltic in-pipe robot.

3.2. Technical Conflict

Technical conflict refers to the function of generating beneficial and harmful results, and refers to the conflict between two subsystems in a system. In the process of practical problem analysis, in order to facilitate the definition of technical conflicts in a system, TRIZ transforms a specific problem into a standard problem with 39 general technical parameters (Table 4) and then finds the corresponding inventive principles (Table 3) using a matrix table (Table 5) to solve the technical conflicts. Our goal is to reduce the number of robots to be driven, but it may lead to poor adaptability in the robots to pipe diameter and manufacturing difficulties. Therefore, the technical conflicts in this paper can be summarized as follows.

Table 4. 39 Engineering parameters of TRIZ.

No.	Name	No.	Name
1	Weight of moving object	21	Power
2	Weight of stationary object	22	Loss of energy
3	Length of moving object	23	Loss of substance
4	Length of stationary object	24	Loss of information
5	Area of moving object	25	Loss of time
6	Area of stationary object	26	Amount of substance
7	Volume of moving object	27	Reliability
8	Volume of stationary object	28	Accuracy of measurement
9	Speed	29	Accuracy of manufacturing
10	Force	30	Harmful factors acting on object
11	Stress/Pressure	31	Harmful side effects
12	Shape	32	Ease of manufacture
13	Stability of object	33	Operability(Ease of operation)
14	Strength	34	Maintainability(Easy of repair)
15	Durability of moving object	35	Adaptability
16	Durability of stationary object	36	Complexity of device
17	Temperature	37	Complexity of control
18	Brightness	38	Automation degree
19	Use of energy by moving object	39	Productivity
20	Use of energy by stationary object		

Table 5. Conflict matrix.

Improved Parameters	Deteriorating Parameter	Inventive Principle
37	35	1, 15
	32	5, 28, 11, 29

(1) Technical conflict 1: Control complexity 37 and pipe diameter adaptability 35.

When the control complexity decreases, the adaptability of the robot to the pipe diameter may be weakened. In order to adapt to a small change in pipe diameter, according to inventive principle 1 (segmentation), we can divide the driven parts into rigid parts and flexible parts to adapt to the small change in pipe diameter.

(2) Technical conflict 2: Control complexity 37 and manufacturing difficulty 32.

When the control complexity of the robot is reduced, its manufacturing difficulty may increase. Because the diameter of the pipe is fixed, the length of the leg (follower) is required to be accurate in order to ensure stable contact between the support leg and the pipe wall. If the leg length error is too large, the pipe wall may not be contacted, resulting in insufficient driving force. According to inventive principle 11 (Beforehand compensation), a pre-compression spring can be applied to the leg to ensure stable support with the pipe wall.

4. Resolving Design Conflicts

Section 3 defined the most relevant inventive principles (19, 24, 1, 11) by analyzing the physical and technical conflicts. Next, we apply these inventive principles to solve the key problems in the design process of a single-drive peristaltic robot.

4.1. Inventive Principle 19 (Periodic Action)

Replacing continuous motion with periodic motion.

The radial dimension of FB/RB increases or decreases in different time periods. According to inventive principle 19 (Periodic action) and consulting the mechanical principles, it can be seen that the motion of the cam follower has periodicity and can design the motion law of the follower according to the corresponding need. Therefore, the cam drive is selected as shown in Figure 10. The cam contour is designed as a piecewise curve that corresponds to the large arc curve in the support state, the small arc curve in the shrinkage state, and the transition curve. From Figure 11, the transition curve CBA can adopt the Archimedes curve, which can ensure that the follower has uniform motion speed. Therefore, when the cam drives the follower, it can produce a periodic supporting effect, which can increase or decrease the radial size of FB/RB in different time periods, thus solving this conflict.

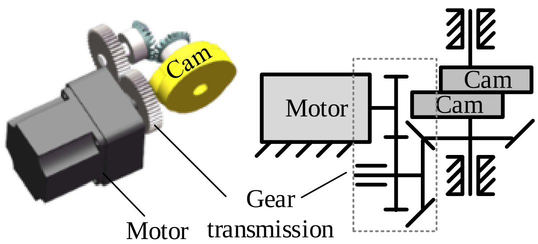


Figure 10. Motor-driven cam.

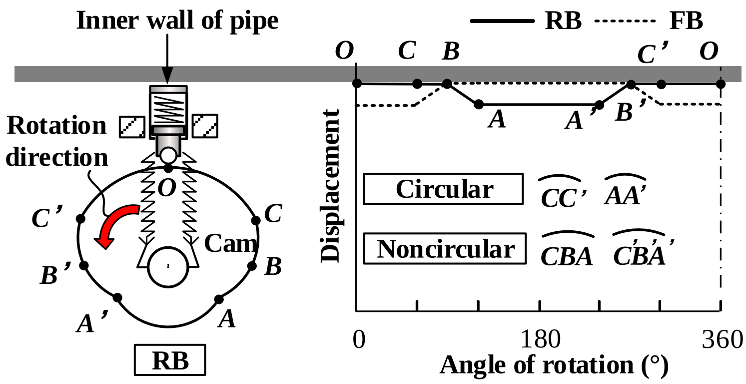


Figure 11. Periodic action of the cam.

4.2. Inventive Principle 24 (Intermediary/Mediator)

Use intermediaries to transfer or perform an action.

From Figure 12, the length changes in the MB axial dimension are physical conflicts. Change in MB length can be regarded as a linear motion. However, the motor provides rotational motion. According to inventive principle 24 and mechanical principles, the crank–slider mechanism is the simplest and most effective way to transform rotational motion into linear motion. A connecting rod is easy to manufacture and assemble. The conflict of the axial dimension can be easily solved by adding a connecting rod.

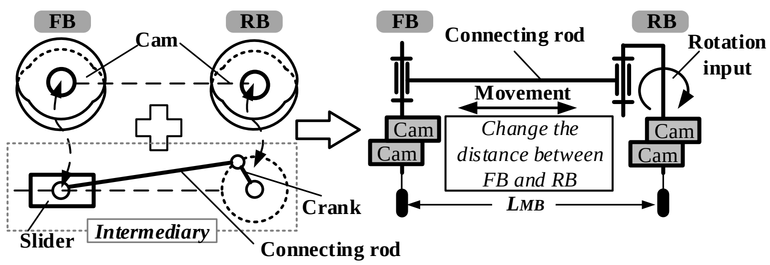


Figure 12. Intermediary—connecting rod.

As shown in Figure 13, the rotation directions of FB and RB are opposite, and MB will expand in the axial direction, and so, we use the telescopic transmission shaft as the intermediary to realize the transmission of power from RB to FB and, at the same time, to meet the requirements of axial telescoping.

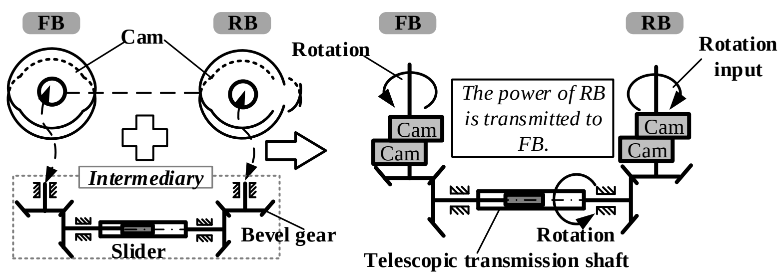


Figure 13. Intermediary—telescopic transmission shaft.

4.3. Inventive Principle 1 (Segmentation)

Divide an object into separate parts.

Divide an object into several combinable parts.

From Figure 14, due to manufacturing and assembly errors, when the legs of the robot extend outward, they may just touch the pipe wall, or they may not touch the pipe wall. According to inventive principle 1 (segmentation), the original rigid leg (follower) can be replaced by the combination of rigid parts and a flexible rubber mat, which can reduce the manufacturing accuracy requirements and save the manufacturing cost.

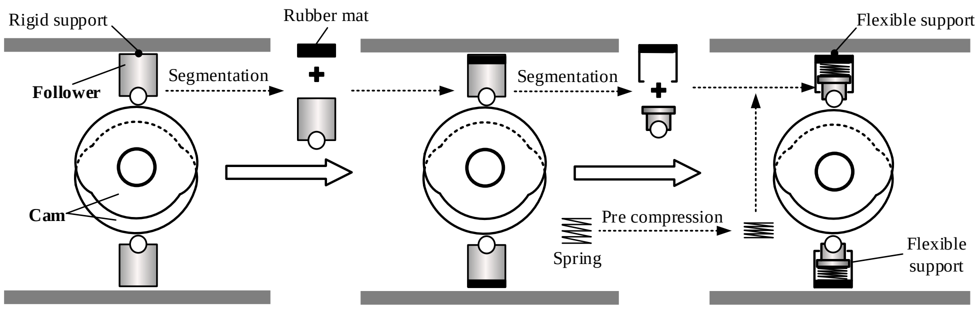


Figure 14. Segmentation and pre-compression images.

4.4. Inventive Principle 11 (Beforehand Compensation)

Prepare in advance to improve reliability

The greater the supporting force of the follower on the pipe wall is, the stronger the traction capacity is. In the actual environment, the pipeline interior may be uneven, and the adaptability of the rubber mat of the follower is limited. When the actual manufacturing dimensions and design dimensions of the support leg are very different, or when the actual inner diameter of the pipeline is larger than the ideal inner diameter, it will lead to the problem of insufficient support force. According to principle 11 of invention, we adopt a pre-compensation method to maintain sufficient initial support force by adding pre-compressed springs. Therefore, the designed follower has changed from using two parts to using three parts: a rigid body, pre-compression spring, and footpad. The use of pre-compression to pre-compensate the support force can not only adapt to the slight change in pipe diameter but also ensure sufficient support force.

5. Parameterized Design of Prototype

5.1. Geometric Parameters of the Robot

Regular variation in geometric parameters (the axial and radial dimensions) is an important parameter for the peristaltic in-pipe robot to achieve effective motion. In the course of the robot traveling in a pipe, both the axial and radial dimensions are related to the rotation angle of the cam. The Archimedes curve is an isokinetic curve, which can make the legs extend stably at a constant speed. According to the geometric relationship in Figure 15, the relationship between the RB cam rotate angle and the axial and radial dimensions is as follows:

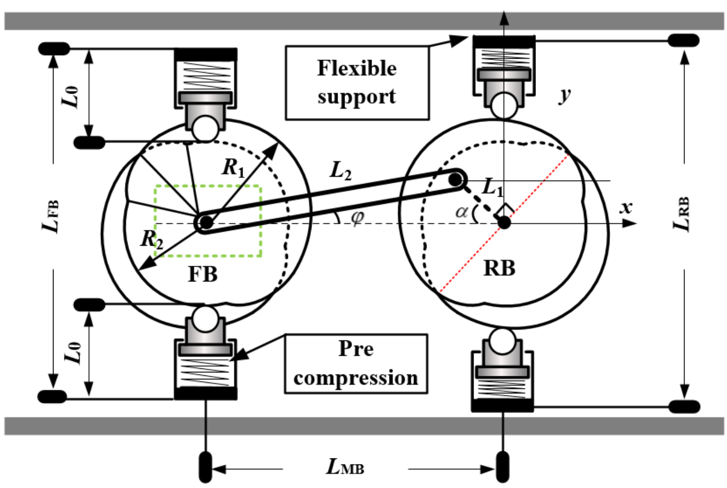


Figure 15. Radial and axial dimensions.

$$\frac{\sin\varphi}{L_1} = \frac{\sin\alpha}{L_2} \tag{1}$$

$$L_{MB} = L_1\cos\alpha + L_2\cos\varphi = L_1\cos\alpha + \sqrt{L_2^2 - L_1^2\sin^2\alpha} \tag{2}$$

$$L_{FB} = \begin{cases} 2L_0+2R_1 - \frac{(R_1-R_2)(\theta+\theta_0)}{\theta_0}, & [0,\ \theta_0] \\ 2L_0+2R_2, & [\theta_0,\ \pi-\theta_0] \\ 2L_0+2R_2 + \frac{(R_1-R_2)(\theta+\theta_0-\pi)}{\theta_0}, & [\pi-\theta_0,\ \pi+\theta_0] \\ 2L_0+2R_1, & [\pi+\theta_0,\ 2\pi-\theta_0] \\ 2L_0+2R_1 - \frac{(R_1-R_2)(\theta+2\theta_0-2\pi)}{\theta_0}, & [2\pi-\theta_0,\ 2\pi] \end{cases} \tag{3}$$

$$L_{RB} = \begin{cases} 2L_0+2R_2 + \frac{(R_1-R_2)(\theta+\theta_0)}{\theta_0}, & [0,\ \theta_0] \\ 2L_0+2R_1, & [\theta_0,\ \pi-\theta_0] \\ 2L_0+2R_1 - \frac{(R_1-R_2)(\theta+\theta_0-\pi)}{\theta_0}, & [\pi-\theta_0,\ \pi+\theta_0] \\ 2L_0+2R_2, & [\pi+\theta_0,\ 2\pi-\theta_0] \\ 2L_0+2R_2 + \frac{(R_1-R_2)(\theta+\theta_0-2\pi)}{\theta_0}, & [2\pi-\theta_0,\ 2\pi] \end{cases} \tag{4}$$

where L_{FB} is the distance between the rubber mats at the ends of the two supporting legs of the front body, L_{RB} is the distance between the rubber mats at the ends of the two support legs of the rear body, L_{MB} is the distance between the cam shaft of the front and rear body, L_1 is the length of the crank, and L_2 is the length of the connecting rod. R_1 and R_2 are the large arc and small arc radius of the cam, respectively. $2\theta_0$ represents the angle of the cam transition curve. L_0 represents the length of the follower (leg). The axial and radial dimension-change curves of the robot are shown in Figure 16. The dimension-change trend of L_{FB} is opposite to that of L_{MB}. The triangle area in Figure 16a shows that if there is no spring, the support leg and the pipe wall cannot be squeezed reliably during the transition curve stage of the cam, which will lead to slipping during the walking process. If there is a spring, the support leg and the pipe wall can be squeezed reliably.

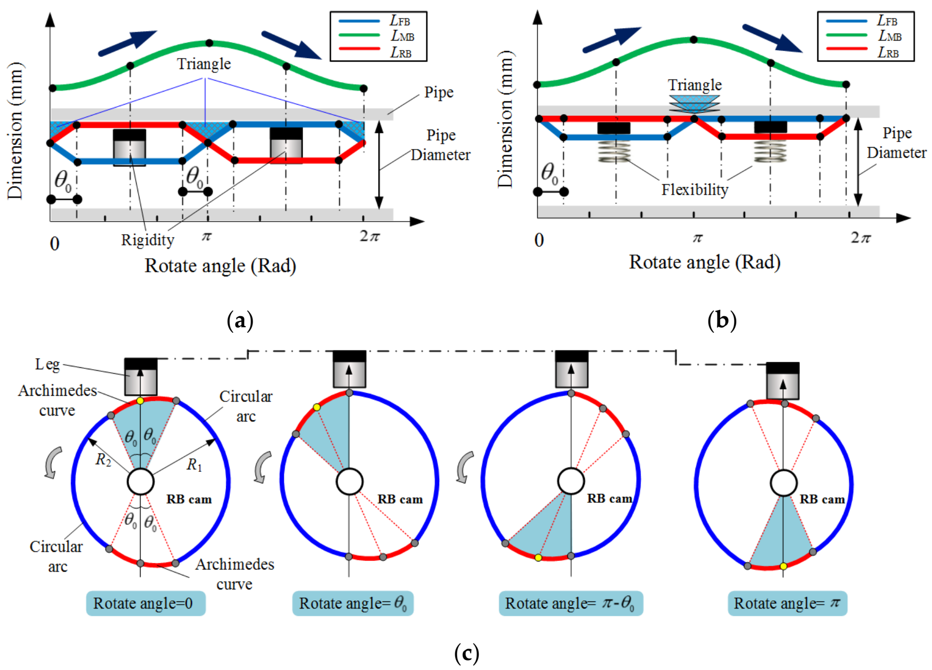


Figure 16. Dimension changes when RB cam rotates: (**a**) rigid leg without spring; (**b**) elastic leg with spring inside; (**c**) RB cam rotation status.

5.2. Dynamic Parameters of the Gear Box

Power is transmitted from the motor through multiple sets of gears and into the cam. The formulas for shaft speed, input power, and input torque are as follows.

(1) Rotary speed

$$\begin{cases} n_{\mathrm{I}} = n_{\mathrm{M}} \\ n_{\mathrm{II}} = \frac{n_{\mathrm{I}}}{i_1} = \frac{n_{\mathrm{M}}}{i_1} \\ n_{\mathrm{III}} = \frac{n_{\mathrm{II}}}{i_2} = \frac{n_{\mathrm{M}}}{i_1 \cdot i_2} \end{cases} \tag{5}$$

Here, n_{I}, n_{II}, and n_{III} are the rotational speeds of the motor shaft, transmission shaft, and cam shaft, respectively; n_{M} is the rotational motor speed; i_1, i_2, and i_3 are the transmission ratios between adjacent shafts.

(2) Input power

$$\begin{cases} P_{\mathrm{I}} = P_{\mathrm{M}} \\ P_{\mathrm{II}} = P_{\mathrm{I}}\eta_1 \\ P_{\mathrm{III}} = P_{\mathrm{II}}\eta_2 = P_{\mathrm{I}}\eta_1\eta_2 \end{cases} \tag{6}$$

Here, P_{I}, P_{II}, and P_{III} are the power values of the motor shaft, transmission shaft, and cam shaft, respectively; P_{M} is the motor power; η_1, η_2, and η_3 are the transmission efficiencies between adjacent shafts.

(3) Input torque

$$\begin{cases} T_{\mathrm{I}} = 9550\frac{P_{\mathrm{I}}}{n_{\mathrm{I}}} = 9550\frac{P_{\mathrm{M}}}{n_{\mathrm{M}}} \\ T_{\mathrm{II}} = 9550\frac{P_{\mathrm{II}}}{n_{\mathrm{II}}} = 9550\frac{P_{\mathrm{I}}\eta_1 i_1}{n_{\mathrm{M}}} \\ T_{\mathrm{III}} = 9550\frac{P_{\mathrm{III}}}{n_{\mathrm{III}}} = 9550\frac{P_{\mathrm{I}}\eta_1\eta_2 i_1 i_2}{n_{\mathrm{M}}} \end{cases} \tag{7}$$

Here, T_{I}, T_{II}, and T_{III} represent the torques of the motor shaft, transmission shaft, and cam shaft, respectively.

5.3. Average Walking Speed

The peristaltic robot moves intermittently, and so, we calculate its average speed. Assuming that the transmission ratio is 1, the motor rotates in a circle, and the in-pipe robot moves forward a certain distance equal to two times the length of the crank, the average speed of the robot is obtained as follows:

$$\overline{v} = 2\omega L_1 \tag{8}$$

where ω is the rotational speed of the motor and L_1 is the crank length. This shows that the walking speed of the robot is determined by crank length and motor speed.

6. Motion Test of Prototype

Figure 17 shows that the robot can successfully walk forward and backward in PVC and acrylic pipelines. In Figures 18 and 19, the walking displacement of the robot is tested, and the corresponding relationship between the number of cam rotations and the walking distance is measured. The actual walking distance is compared with the desired walking distance. The testing performance of robots in PVC is better than that in acrylic pipes because the walls of PVC pipes are rougher and robots are less prone to slipping in them. If there is no pre-compressed spring, the robot will have almost rigid contact with the pipe wall, making it poorly adaptable and more likely to slip. The robot can ensure stable contact with the pipe wall after the pre-compression spring is added, and the slip phenomenon of the robot can be greatly reduced.

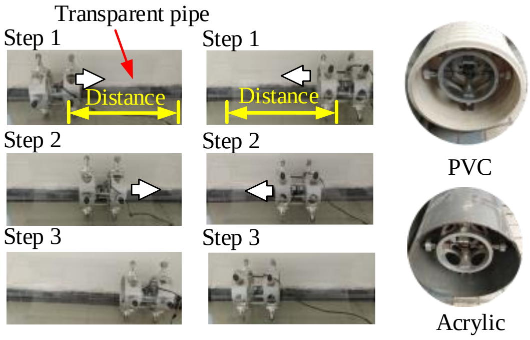
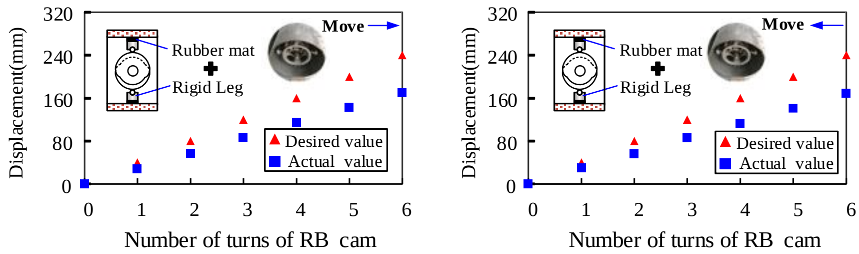
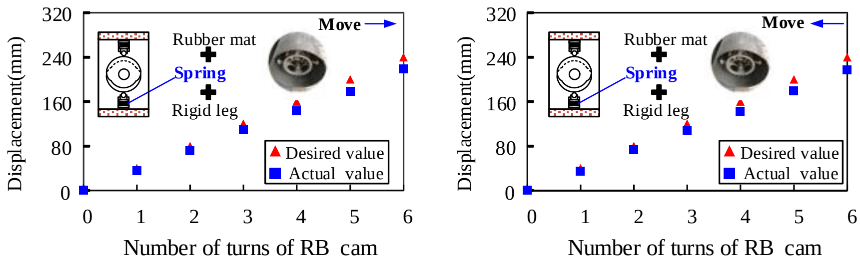


Figure 17. In-pipe robot prototype test of forward and reverse motion.

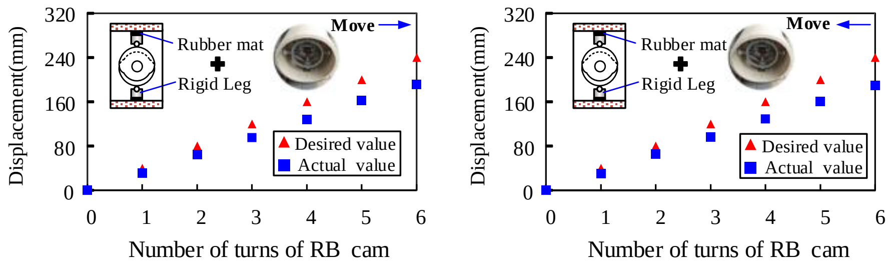


(**a**)

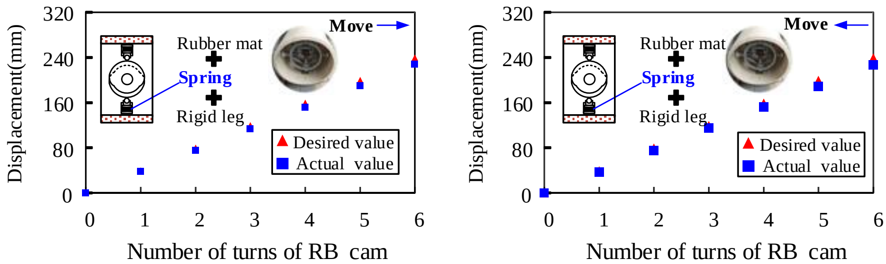


(**b**)

Figure 18. Walking test in acrylic pipe. (**a**) test without spring; (**b**) test with spring.



(**a**)



(**b**)

Figure 19. Walking test in PVC pipe: (**a**) test without spring; (**b**) test with spring.

7. Conclusions

The application of TRIZ's inventive principles and the synthesis of technical parameters accelerate the innovative design process for peristaltic in-pipe robots, furnishing designers with the conceptual knowledge and methodological tools essential for identifying and resolving problems.

(1) The innovative design of the peristaltic in-pipe robot is executed by raising TRIZ's conflict resolution theory, effectively resolving physical and technical conflicts encountered in the design process through the corresponding inventive principles.
(2) Taking inspiration from TRIZ's inventive principles, the periodic expansion of the RB/FB is achieved using a cam mechanism, and power transmission and direction transformation are accomplished through a crank–slider mechanism and telescopic transmission shaft. Control over the single motor's positive and negative rotation enables the bidirectional movement of the robot. This approach eliminates the need for the cooperative control over multiple motors and complicated control algorithms.
(3) Applying TRIZ's inventive principle of "segmentation and beforehand compensation", the support leg (cam follower) is designed as a structure comprising rigid components, pre-compression springs, and rubber padding. The design imparts elasticity to the support leg while maintaining adequate support force, enabling it to adapt to slight variations in pipe diameter and effectively reducing slippage.
(4) The prototype has undergone testing, demonstrating the robot's ability to move in both directions within a pipe. The results present the effectiveness of the innovative single-drive peristaltic in-pipe robot design based on TRIZ principles. This design methodology can serve as a guideline in product upgrading.

8. Patents

The research results were awarded a patent for invention by the United States Patent Office, USA (USA Patent No.: US 10981203B2).

Author Contributions: Conceptualization, Q.X. and Q.L.; methodology, Q.X.; software, Q.X.; validation, Q.X.; formal analysis, Q.X.; investigation, Q.X. and Q.L.; resources, Q.X.; data curation, Q.X. and Q.L.; writing—original draft preparation, Q.X.; writing—review and editing, Q.X. and Q.L.; visualization, Q.X.; supervision, Q.X.; project administration, Q.X.; funding acquisition, Q.X. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data used to support the findings of this study are included in the article.

Conflicts of Interest: The authors declare no conflict of interest.

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