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Flexible Endoscopic Surgical Robots: A Review of Technologies for Gastrointestinal Diagnosis and Therap

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Abstract. Surgical operation and therapeutic robots are pivotal to minimally invasive surgical systems, designed to overcome the limitations of traditional rigid instruments in complex anatomical lumens, reduce operator dependence, and enhance procedural precision and safety. This review summarizes key technological breakthroughs, including a variable-stiffness flexible manipulator driven by low-melting-point alloy, intraluminal robotic systems that lower the technical threshold for endoscopic submucosal dissection (ESD), and specialized platforms such as the STRAS robot for colorectal ESD and Fiberbots for ultra-precision ablation. Supporting advancements in sensing, feedback, and structural optimization for clinical adaptability are also reviewed. Preclinical and initial clinical validations demonstrate that these systems can improve outcomes, such as increasing lesion detection rates, reducing complications, and shortening operation times. However, challenges remain in miniaturization, sensor integration, and the need for larger-scale clinical data. Collectively, these robotic technologies present promising solutions for treating early gastrointestinal tumors and other conditions, with several advancing toward clinical translation.

Keywords: Surgical Robots, Endoscopic Submucosal Dissection, Minimally Invasive Surgery, Flexible Manipulators

1. Introduction

Surgical operation and therapeutic robots represent the core application carriers of the minimally invasive surgical robot system. Their primary objective is to address the operational bottlenecks of traditional rigid instruments that struggle to adapt to complex human lumens and curved anatomical structures [1-3]. Meanwhile, they aim to reduce reliance on the operator's experience and enhance surgical precision and safety [2, 4, 5]. Centered on the three core demands of flexible adaptation, precise actuation, and clinical safety, these robots have formed a development pattern with multiple technical routes advancing in parallel [1, 6, 7]. Most of them have completed in vitro or animal model validation, and some have entered the clinical translation stage [2-8]. This paper focuses on the technological breakthroughs and clinical validation of surgical operation and therapeutic robots, and also discusses the supporting technologies and related diagnostic statistical research of the robot

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system, in order to provide a comprehensive reference for the subsequent development and clinical application of the technology.

2. Technological breakthroughs and preclinical validation of core robotic systems

2.1. Low-melting-point alloy-driven variable stiffness flexible manipulators

Traditional flexible manipulators often face the contradiction of incompatibility between flexibility and stability: the flexible state is prone to positioning deviations caused by external interference, while the rigid state fails to adapt to complex lumens [1]. To address this issue, a flexible manipulator based on Low-Melting-Point Alloy (LMPA) was proposed, which achieves an integrated design of actuation and stiffness regulation through the thermally induced phase change characteristics of LMPA [1].

With a diameter of only 7 mm (adapting to the anatomical size of the narrowest part of the esophagus, 14–15 mm), the manipulator features a multi-luminal silicone tube as the main body, incorporating 3 LMPA actuation lumens (filled with gallium-indium alloy with a melting point of 29.78 °C) and 3 water circulation temperature control lumens [1]. Bending is achieved by injecting liquid LMPA into the target LMPA lumen (the maximum unidirectional bending angle reaches 238.6°, covering the operational requirements of gastroscopes with a 210° range) [1]. After bending, cold water is introduced to solidify the LMPA, enabling a switch to the rigid state [1]. Experimental data show that in the rigid state, its transverse stiffness reaches 95.54 N·cm² and bending stiffness 372.1 N·cm², while in the flexible state, these values decrease to 7.26 N·cm² and 0.78 N·cm², with stiffness gains of 13.15 and 477.05, respectively [1]. The rigid-flexible conversion efficiency is excellent: the transition from rigid to flexible takes only 9.2–10.3 s (driven by 55–65 °C hot water), and from flexible to rigid 15.4 s (driven by 0 °C cold water) [1]. Moreover, the motion characteristics show no significant attenuation after 12 thermal cycles (standard deviation: 3.88°), meeting the requirements of repeated clinical operations [1].

In addition, a 2.1 mm working channel is designed in the center of the manipulator, compatible with instruments such as confocal microprobes and biopsy forceps. Successful tissue imaging and grasping were achieved in a porcine gastric tissue phantom experiment, verifying its potential for integrated diagnosis and treatment [1].

2.2. In vitro and preclinical feasibility validation of intraluminal surgical robots

Targeting Endoscopic Submucosal Dissection (ESD)—a core minimally invasive technique for the treatment of early gastrointestinal tumors—an intraluminal access surgical robot was developed to address the issues of traditional ESD, which relies heavily on highly experienced operators and suffers from limited degrees of freedom of instruments [2, 4, 5].

Based on traditional flexible endoscopes, the system integrates 2 articulating operational instruments (with a diameter adapted to the 2.8 mm working channel of endoscopes) [2]. Each instrument has 3 degrees of freedom (up-down, left-right, and anterior-posterior) [2]. The bending segment adopts a concave-convex stacked hinge design (made of plastic, without hinge pins, assembled by steel wire constraints), which reduces costs and minimizes friction, enabling a bending angle of over 180° and a short bending radius (adapting to the requirements of short-distance intra-gastric operations)[2]. In in vitro porcine gastric ESD experiments, 5 operators with no endoscopic experience all successfully completed the surgery without complications [2]. The specimen size ranged from 10 to 25 mm (mean: 16.0±5.5 mm), and the total surgical time was 15–44 min [2].

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Although slower than clinical experts (average dissection speed: 2.7 min/cm²), there were significant differences in the learning curve among operators (some achieved a dissection speed of 3.4 min/cm²), proving that the system can lower the technical threshold of ESD [2, 4, 5].

Notably, the system is compatible with existing endoscopic equipment, requiring no additional modification of operating rooms. Furthermore, only one operator is needed to synchronously control the endoscope and operational instruments, which significantly reduces labor costs and provides the possibility for the popularization of ESD in primary hospitals [2].

2.3. Preclinical breakthroughs of the master-slave robot (STRAS) dedicated to colorectal ESD

Colorectal ESD is significantly more difficult than gastric ESD and carries a higher risk of complications (e.g., perforation) due to anatomical characteristics such as numerous intestinal folds, frequent peristalsis, and a thin intestinal wall [3, 8]. The Endoluminal Surgical Triangulation 2.0 robot (STRAS) developed by Légner et al. addresses this issue in a targeted manner through master-slave control and triangulation operation design.

The main body of the robot is an 18 mm diameter flexible endoscopic platform, including 2 4.2 mm working channels (for robotic instruments) and 1 2.8 mm channel (for traditional endoscopic tools) [3, 8]. The endoscope tip is designed with openable support arms that fix the operational space through triangulation positioning, avoiding interference from intestinal peristalsis [3, 8]. The master console adopts an intuitive joystick design, allowing a single operator to realize coordinated control of instrument grasping, cutting, and dissection [3, 8]. In ESD experiments on the colorectum of 8 pigs, 18 surgeries were attempted, with 12 successfully completed. The average specimen area was 18.2±9.8 cm², and the total surgical time was 73 min [3, 8]. A significant learning curve was observed: only 2 of the first 6 surgeries were successful (including 3 perforations and 2 system failures), while all the last 6 surgeries were completed successfully without complications, with the dissection speed increasing from 0.186 cm²/min to 0.344 cm²/min. This system for the first time verified the feasibility of master-slave robots in colorectal ESD, and its triangulation operation design provides a new idea for achieving precise operations in the dynamic intestinal environment [3, 8].

2.4. Application of ultra-precision robotic fibers (Fiberbots) in minimally invasive ablation

To meet the demand for precise operations in narrow surgical spaces (e.g., around the biliary tract and blood vessels), Fiberbots robotic fibers were proposed, which achieve sub-100-micron motion precision through thermal actuation [6].

The fiber is fabricated by a thermal drawing process, with a polycarbonate (PC) tube as the main body (diameter <2 mm, length 10–15 cm), embedded with 8 50 μm stainless steel resistance wires (4 pairs, distributed at 90°) [6]. Bending of the fiber is driven by energizing the target resistance wires (Joule heating), which causes local thermal expansion of the PC. The bending direction is determined by the energized resistance wire pair, and the bending angle is linearly correlated with the input power (a 2 mm diameter fiber achieves a maximum displacement of 3.21 mm at 1.12 W power, with a step precision of 30 μm) [6].Its core advantages are as follows: No mechanical components, avoiding precision attenuation caused by instrument wear; Fast thermal actuation response speed (rise time: 8.6 s, steady-state speed: 0.8 mm/s) with a hysteresis error of only 87 μm; A central 1.15 mm channel that can integrate CO_2 laser fibers, mass spectrometry sampling tubes, etc [6]. In porcine laparoscopic experiments, Fiberbots equipped with CO_2 laser fibers completed circular (5 mm diameter) and spiral (2 mm pitch) ablation trajectories on liver and cecal tissues, with

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an ablation precision error of <50 μm [6]. In addition, helium cooling (50 psi) controls the fiber surface temperature below 60 °C, and pathological examination of in vitro tissues showed no thermal damage [6]. This technology provides a new tool for minimally invasive tumor ablation (e.g., small intrahepatic metastatic lesions) [6].

2.5. Functional expansion of robotic systems dedicated to gastrointestinal ESD

In addition to the above general-purpose systems, a variety of dedicated robotic systems have entered the research and development stage targeting the particularity of gastrointestinal ESD [4, 5, 8, 12]. For example, the Master and Slave Transluminal Endoscopic Robot (MASTER) realizes synchronous traction and cutting operations on the gastric mucosa through a dual robotic arm cooperative design, and completed 5 cases of early gastric cancer resection in human gastric ESD clinical experiments with a 100% en bloc resection rate [4, 5]. The ESD CYCLOPS system focuses on visual field optimization for intestinal ESD; through multi-degree-of-freedom adjustment of the endoscope tip and directional control of the light source, it solves the problem of intestinal fold occlusion, increasing the mucosal exposure rate by 40% in in vitro porcine colon experiments [4, 5, 8, 12]. The common feature of such systems is functional specialization—optimizing the mechanical structure and control logic around the core steps of ESD (marking, injection, incision, and dissection), further improving surgical efficiency and safety [4, 5, 8, 12].

In summary, surgical operation and therapeutic robots have achieved multi-dimensional breakthroughs in technical principles, structural design, and preclinical validation: LMPA actuation solves the dilemma of rigid-flexible balance [1]; intraluminal robots lower the technical threshold of ESD [2, 9]; and STRAS and Fiberbots achieve precise adaptation to colorectal and narrow space operation scenarios, respectively [3, 6, 8]. These advances provide new solutions for the minimally invasive treatment of diseases such as early gastrointestinal tumors and small liver lesions, and some technologies have shown potential for clinical translation [1-6, 8].

3. Sensing and feedback technology

Sensing and feedback technology is the core support for flexible endoscopic robots to achieve precise operation and improve surgical safety, mainly including three directions: force sensing, shape sensing, and tactile feedback [7, 9, 10]. By real-time acquisition of mechanical signals and spatial attitude information during surgery, it provides a decision-making basis for operators or directly supports closed-loop control [7, 9, 10]. The following content is elaborated in detail in combination with relevant literature.

3.1. Force sensing technology

Force sensing technology is used to monitor the interaction force between instruments and tissues, avoiding tissue damage caused by excessive traction or cutting [7]. At present, the mainstream solutions include three categories: optical fiber sensing, tension feedback, and mechanical modeling derivation [7, 9, 10].

3.1.1. Fiber Bragg Grating (FBG) sensing

The research team from Tianjin University proposed integrating an FBG force sensor at the distal end of the robot [7]. By embedding quasi-distributed optical fibers or adopting an Optical Frequency Domain Reflectometer (OFDR), full-distributed strain sensing is realized, which can capture both

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operational force and structural deformation simultaneously, providing data support for closed-loop control. This scheme has been verified feasible in flexible joint experiments and will be further miniaturized to adapt to endoscopic integration in the future [7].

3.1.2. Tension feedback sensing

The variable neutral-line manipulator indirectly obtains the distal force by monitoring tendon tension [10]. In the tension range of 20–60 N, the stiffness is linearly correlated with tension ($R^2 \approx 0.99$) [10]. A texture analyzer (precision: 0.001 N) was used in experiments to calibrate the force-displacement relationship [10]. Although there is a hysteresis error caused by friction ($\leq 2.34\%$), the error can be reduced by optimizing the wire path with Teflon coating [10].

3.1.3. Mechanical modeling derivation

Based on the Cosserat rod theory, the parallel continuum robot deduces the distal internal force and torque by solving the static equilibrium equation, and constructs an output stiffness matrix (K= [17, 17, 122] N/mm) in the neutral configuration, which can map the distal displacement to the applied force to realize sensorless force feedback with a maximum force calculation error of $\leq 5\%$ [9].

3.2. Shape sensing technology

Shape sensing technology is used to obtain the real-time spatial attitude and bending trajectory of the robot's distal end, ensuring that the instrument accurately reaches the lesion area and adapts to the complex anatomical path of the gastrointestinal tract [7, 9, 10].

3.2.1. Vision-assisted shape sensing

In in vitro experiments, the hybrid pneumatic continuum joint marks the distal centerline through images captured by the endoscopic camera and calculates the displacement deviation under different stiffness states. The deviation is only 4.61 mm in the rigid state (accounting for 4.26% of the total length) and 15.48 mm in the flexible state. This method requires no additional sensing modules and has low cost but relies on visual clarity [7].

3.2.2. Structural deformation modeling

The parallel robot adopts a multi-segment Cosserat rod model coupled with boundary conditions, and predicts the bending shape of each flexible leg through numerical integration [9]. In 14 groups of experimental configurations, the maximum position prediction error is 11.74 mm (percentage error: 2.89%), and the maximum angle prediction error is 3.14°, which can meet the requirements of surgical attitude feedback [9].

3.2.3. Optical fiber shape sensing

Multi-core Fiber Bragg Gratings are adopted to reconstruct the 3D shape of the robot by monitoring the strain at each point of the optical fiber, with a resolution of up to 0.1 mm, adapting to the detection of micro-deformations. In the future, it will be integrated with force sensing to realize synchronous sensing of multiple physical quantities [11].

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3.3. Tactile feedback technology

Tactile feedback technology helps operators judge tissue hardness, lesion boundaries and other information by simulating tissue tactile sensation, reducing the difficulty of surgical decision-making [5, 12]. At present, master-slave tactile transmission is the main implementation method [5, 12].

3.3.1. Bidirectional tactile feedback

The ETRS robot is equipped with a bidirectional tactile feedback function [5, 12]. The master unit can feed back the contact force at the endoscope tip (e.g., tissue resistance) to the operator and simultaneously transmit the force applied by the operator to the distal end in equal proportion [5, 12]. All endoscopic operations can be completed with one hand. In porcine gastric ESD experiments, operators accurately distinguished mucosal and submucosal tissues through tactile feedback, improving dissection precision [5, 12].

3.3.2. Stiffness tactile mapping

The hybrid pneumatic joint indirectly provides tissue hardness feedback for operators by adjusting air pressure to change structural stiffness—when the instrument contacts hard tissue, the stiffness can be increased by raising air pressure, and the operator perceives the load change through the master controller [7]. This scheme requires no additional tactile sensors and has strong synergy with the stiffness adjustment function [7].

3.4. Feedback control strategies

Feedback control strategies realize precise attitude and force control of the robot based on sensing data [7, 9, 10]. At present, they are mainly based on open-loop compensation and the embryonic form of closed-loop control, and are gradually developing towards autonomous optimization [5, 12].

3.4.1. Open-loop friction compensation

Aiming at the hysteresis problem caused by wire friction, the variable neutral-line manipulator establishes a friction model through experiments and introduces a compensation term into the control algorithm, reducing the force feedback error from 8.8% to 3.2% and improving operational consistency [10].

3.4.2. Closed-loop attitude control

Based on the inverse kinematics model, the parallel robot compensates for the distal attitude deviation by adjusting the length of each flexible leg. In motions such as torsion and tilt, the attitude control precision is $\leq 2°$, which can effectively offset the deformation caused by tissue reaction force [9].

3.4.3. Exploration of autonomous optimization

It is proposed to draw on the classification standard of autonomous driving to construct the autonomy level of surgical robots [5, 12]. First, autonomous optimization of the surgical field of

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view will be realized (e.g., automatically adjusting the endoscope angle to ensure a clear operational area) [5, 12]. In the future, combined with sensing data, semi-autonomous execution of basic operations such as marking and incision will be achieved [5, 12].

3.5. Current progress and challenges of sensing and feedback technology

At present, the sensing and feedback technology of flexible endoscopic robots has realized the basic perception of force-shape-tactile sensation, but still faces three major challenges: first, the high difficulty of miniaturized integration, and the spatial conflict between sensors such as FBG and endoscopic instrument channels has not been completely resolved [7]; second, the insufficient precision of synchronous sensing of multiple physical quantities, with a time synchronization error of ≥10 ms between force and shape sensing [7, 11]; third, poor adaptability to the clinical environment, as body fluids and temperature changes affect the stability of optical fiber sensing signals [11]. In the future, it is necessary to promote the maturation of the technology through material innovation (e.g., biocompatible sensing materials), algorithm optimization (e.g., multi-sensor data fusion) and clinical validation [5, 7, 11].

4. Structural and performance optimization

Structural and performance optimization is the key for flexible endoscopic robots to adapt to the clinical needs of gastrointestinal surgery [5-7, 9, 10]. Centered on the three core goals of structural lightweighting, performance precision, and clinical adaptability, it balances flexibility, operability and safety through mechanical structure innovation, parameter iteration and clinical demand-oriented design [7-10].

4.1. Structural design optimization

Structural design directly determines the spatial adaptability and operational convenience of the robot, with optimization directions focusing on three paths: continuum joint innovation, parallel structure improvement, and modular integration [7-10].

4.1.1. Multi-degree-of-freedom optimization of continuum joints

The hybrid pneumatic-cable driven continuum joint proposed by Tianjin University adopts a combination of a helical spring-like continuum structure and a super-elastic nitinol backbone [7]. Four circumferentially uniformly distributed cables enable 2-degree-of-freedom bending (±90°) with a bending curvature error of ≤2.55%, solving the problem of insufficient degrees of freedom of traditional single-channel endoscopes [7]. Its unique flat trachea embedded design integrates the stiffness adjustment function without increasing the outer diameter (18 mm), realizing independent control of bending and stiffness [7].

4.1.2. Stability optimization of parallel structures

The parallel continuum robot based on the Stewart-Gough platform adopts 6 spring steel compliant legs connected in parallel, and improves structural stability by optimizing the layout of leg end connection points (87 mm in radial direction, spaced at 120°) [9]. In the neutral configuration, the torsional stiffness reaches 17 N/mm, which is 40% higher than that of traditional series structures,

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and no buckling failure occurs under a 1 kg load, solving the problem of structural sloshing in long-stroke operations [9].

4.1.3. Modular and integrated design

The ETRS robot adopts a modular design, integrating the Endoscopic Operation Robot (EOR) with the instrument drive system [5, 12]. A single console realizes the full-process actions such as endoscopic movement and instrument operation (grasping, cutting, injection), without the need for repeated equipment replacement [5, 12]. Its third-generation EOR is equipped with a bidirectional tactile feedback function, and all operations can be completed with one hand, simplifying the clinical operation process [5, 12].

4.1.4. Miniaturized structural innovation

The variable neutral-line hyper-redundant manipulator connects rigid connecting rods with rolling joints (rod thickness: only 2 mm) and realizes stiffness adjustment through the asymmetric arrangement of tendons. The overall outer diameter can be controlled within 13 mm, adapting to narrow gastrointestinal channels (e.g., the duodenum and deep colon) [5, 10].

4.2. Core performance optimization

Core performance optimization focuses on four key indicators: flexibility, stiffness regulation, load capacity and operational precision [5-7, 9, 10]. Through structural parameter iteration and actuation method improvement, it achieves precise matching between performance and clinical needs [5-7, 9, 10].

4.2.1. Flexibility optimization

With bending angle, degrees of freedom and response speed as the core indicators, the Anubiscope platform adopts a clamshell-type distal design[3,8]. Through two 4.3 mm working channels and one 3.2 mm auxiliary channel, it realizes 5-degree-of-freedom instrument motion [3, 8]. In the porcine colon model, the bending angle can reach ±90° with a response delay of ≤200 ms, improving the surgical efficiency by 42% compared with traditional endoscopic surgery (the average surgical time is shortened from 55.87 min to 32.3 min) [3, 8].

4.2.2. Stiffness regulation range optimization

To meet the dual demands of flexible navigation and rigid operation, the hybrid pneumatic scheme realizes a continuous stiffness change from 120.32 N·cm² to 389.93 N·cm² through air pressure adjustment (0–500 kPa), with a stiffness ratio of 3.2:1 and a rigid-flexible conversion time of <3 s, meeting the demand for rapid switching during surgery [7]. The variable neutral-line scheme achieves a linear stiffness change range of 0.242–0.529 N/mm through tendon tension adjustment (20–60 N), adapting to the operational loads of different tissues [7, 10].

4.2.3. Load capacity optimization

The load upper limit is improved through material selection and structural reinforcement [5, 7]. The hybrid pneumatic joint meets the requirements of gastrointestinal tissue traction (required load ≤2.26

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N). In the neutral configuration, the parallel robot has an axial load capacity of 50 N, which is 67% higher than that of traditional continuum structures, and can cope with complex tissue dissection scenarios [7].

4.2.4. Operational precision optimization

Positioning precision is improved through error compensation and structural calibration [4, 5]. The MASTER robot adopts master-slave exoskeleton control combined with a tendon-sheath friction compensation algorithm, with a distal positioning error of ≤2 mm [4, 5]. In porcine gastric ESD surgery, the en bloc lesion resection rate reaches 100% without damage to surrounding tissues [4, 5]. The dual-instrument channel robot realizes an instrument operational precision of ±0.5 mm and a dissection margin error of ≤1 mm through channel layout optimization (two 3.2 mm instrument channels with a 90° included angle), meeting the clinical requirements for tumor resection boundaries [5, 6, 12].

4.3. Clinical adaptability optimization

Centered on patient safety, physician convenience and scenario compatibility, clinical adaptability optimization involves customized design according to the anatomical characteristics of the gastrointestinal tract, surgical procedures and clinical specifications [3-5, 7, 8, 12].

4.3.1. Outer diameter and channel layout adaptation

Balancing minimally invasiveness and multi-functionality, the hybrid pneumatic joint has an outer diameter of 18 mm, integrating 1 3.8 mm camera channel, 2 3.2 mm instrument channels and 1 2 mm air-water channel, adapting to the needs of two-handed operation [7]. The outer diameter of commercial endoscopes is usually 9–15 mm [7]. Through material lightweighting (nylon 3D-printed structure + nitinol backbone), this design adds a stiffness adjustment module and dual instrument channels without a significant increase in outer diameter, resulting in the same patient trauma as traditional endoscopes [7].

4.3.2. Surgical procedure adaptation

Simplifying operational steps and reducing the learning curve, the Anubiscope platform adopts a surgical triangulation positioning design, eliminating the need for frequent instrument replacement [3, 8]. Surgeons with no ESD experience can complete the surgery within 32 min, shortening the learning curve by 60% compared with traditional endoscopic surgery [3, 8]. The ETRS robot integrates full-process functions such as marking, injection, cutting and hemostasis, and can be operated by a single physician, reducing the difficulty of surgical team coordination [5, 12].

4.3.3. Clinical environment adaptation

Meeting the specifications of sterilization and imaging compatibility, the variable neutral-line manipulator adopts an EPDM sheath + steel mesh layer design, supporting low-temperature liquid sterilization and avoiding damage to sensors and drive modules caused by high temperature [5, 10]. The parallel robot has no magnetic components in its structure, compatible with intra-operative imaging equipment such as MRI and CT, and can realize precise operations under real-time image guidance [9].

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4.3.4. Patient comfort optimization

Reducing surgical trauma and discomfort, the dual-instrument channel robot controls the tissue traction force within 0.47 N through a flexible backbone and precise force control, avoiding gastrointestinal perforation caused by excessive force. In in vitro experiments, the pain score of the patient simulation model is 30% lower than that of traditional endoscopes [5, 8].

4.4. Optimization achievements and existing challenges

At present, remarkable achievements have been made in structural and performance optimization: structurally, the integration of multi-degree-of-freedom, small outer diameter and modularization is realized [5, 7-10]; in terms of performance, adjustable stiffness, meeting load requirements and controllable precision are achieved [5, 7-10]; in clinical adaptability, the demands of minimally invasiveness, convenience and safety are satisfied [3, 5, 6, 8, 10, 12]. However, three major challenges still exist: first, the balance contradiction between structural lightweighting and stiffness, as the outer diameter of some high-stiffness designs (e.g., parallel structures) is difficult to be further reduced to below 13 mm [7, 9, 10]; second, insufficient flexibility under complex anatomical paths, as the bending radius of existing robots still needs to be optimized (target $\leq$5 mm) for curved intestinal parts (e.g., the splenic flexure and hepatic flexure) [3, 6, 7]; third, the reliability of long-term clinical application, as repeated sterilization of modular structures may cause component wear and affect operational precision. In the future [5, 10, 12], continuous breakthroughs are needed through new materials (e.g., carbon fiber composites), topology optimization algorithms and self-healing structural design [7-10].

5. Conclusion

Flexible endoscopic surgical robots represent a pivotal advancement in minimally invasive therapy, designed to overcome the limitations of traditional rigid instruments within complex anatomical lumens [1-3, 5, 6, 8]. This review highlights significant multi-dimensional technological progress. Innovations such as low-melting-point alloy (LMPA) actuation solve the rigidity-flexibility dilemma [1], while dedicated intraluminal and master-slave robots (e.g., for ESD procedures) lower technical thresholds and enable precise operations in challenging environments like the colorectum [2-5, 8]. Supporting breakthroughs in sensing/feedback (force, shape, tactile) and structural optimization (lightweighting, variable stiffness) are crucial for enhancing precision, safety, and clinical adaptability [5, 7-10].

Preclinical and initial clinical validations demonstrate the potential of these systems to improve key outcomes, including higher lesion detection rates, reduced complication rates such as perforation, and shortened procedure times [2-6, 8]. However, several challenges remain for clinical translation, including sensor miniaturization, the trade-off between structural flexibility and stability, and the need for larger-scale, long-term clinical data [1, 5, 7, 8, 11].

Future development depends on the convergence of materials science, intelligent control algorithms, and rigorous clinical trials. The continued evolution of these robotic platforms promises to provide more accessible, precise, and safe solutions for the diagnosis and treatment of early gastrointestinal tumors and other conditions [1-6, 8, 12].

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