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Advances in Transanal Quasi-single-port Surgery Robotic Systems: A Comprehensive Review

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***Abstract*—This review highlights the advantages of taQSPS and offers a comprehensive analysis of the development, current applications, and future trends of robotic systems utilized in transanal Quasi-Single-Port Surgery (taQSPS). Timely surgical intervention is crucial for optimal outcomes in rectal cancer treatment, with techniques evolving from open surgery to endoscopic surgery and, more recently, to taQSPS. This innovative technique accesses lesions via a transanal route while utilizing instruments and methods similar to those in Single-Port Surgery (SPS). Building on this foundation, SPS robotic surgical systems have emerged as a promising advancement for taQSPS, offering enhanced precision and maneuverability. However, despite their progress, general-purpose SPS robotic systems are often limited by their bulky design and lack of adaptability to the rectal cavity. In contrast, specialized taQSPS robotic systems are tailored to transanal procedures' unique anatomical and operational demands, making them highly suitable for such surgeries. This review highlights the potential of specialized taQSPS robotic systems, serving as a valuable reference for researchers and clinicians, and aims to promote further development and adoption of these systems in clinical practice.**

***Index Terms*—Rectal Cancer; Early-stage Cancer Therapy; Transanal Quasi-single-port Surgery; Single-port Surgery Robotic System; Specialized Transanal Quasi-single-port Surgery Robotic System.**

I. INTRODUCTION

According to the statistical data released by the International Agency for Research on Cancer (IARC) in 2022, colorectal cancer, a malignancy affecting the colon or rectum, constituted 9.6% of all globally reported cancer cases in terms of incidence, placing it as the third most common cancer after lung and breast cancers [1]. Specifically, rectal cancer is characterized by malignant neoplasms that originate in the rectum, typically evolving from a recognizable and treatable preclinical stage termed adenoma [2]. Early-stage rectal cancer screening and timely treatment are essential for preventing further progression, alleviating patient suffering, and improving survival rates [3]. According to the TNM classification [4], early-stage rectal cancer is categorized as T1-T2 and node-negative. As illustrated in Fig. 1-a, “Tis” denotes intramucosal adenocarcinoma (a tumor confined to the mucosal layer), “T1” indicates submucosal infiltration (extension into the tissue

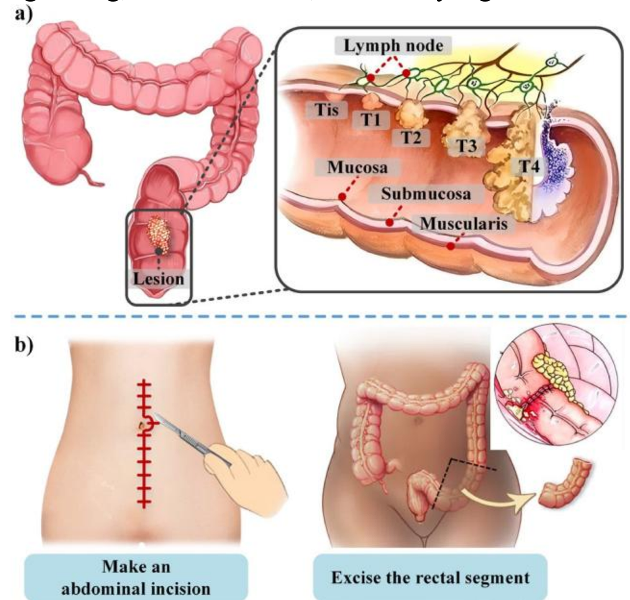

Fig. 1. a) Rectal cancer and its staging; b) Radical excision procedures.

beneath the mucosa), and “T2” signifies extension to the muscularis propria (the muscle layer of the rectal wall). With the increasing implementation of early cancer screening programs, the detection rate of early-stage rectal cancer is anticipated to continue rising, thereby leading to a growing demand for timely and effective treatment among patients [5].

Despite the significant advancements in nonoperative treatment options, such as radiation therapy, chemotherapy, and immunotherapy, surgical intervention continues to be a cornerstone in the management of rectal cancer. Among various surgical procedures, local resection is widely considered to be a more suitable option for treating early-stage rectal cancer. Unlike radical excision, as depicted in Fig. 1-b, which involves removing a considerable amount of healthy tissue [6], local resection emphasizes the removal of only the tumor and its surrounding tissue. This approach preserves unaffected rectal segments while ensuring sufficient oncological control, thereby minimizing surgical trauma and enhancing quality of life [7]. Based on variations in surgical techniques, tools, and the degree of patient trauma, the evolutionary stages of local resection procedures can be systematically categorized into open surgery, endoscopic surgery, and taQSPS, as illustrated in Fig. 2.

Open surgery techniques, such as the Kraske approach and

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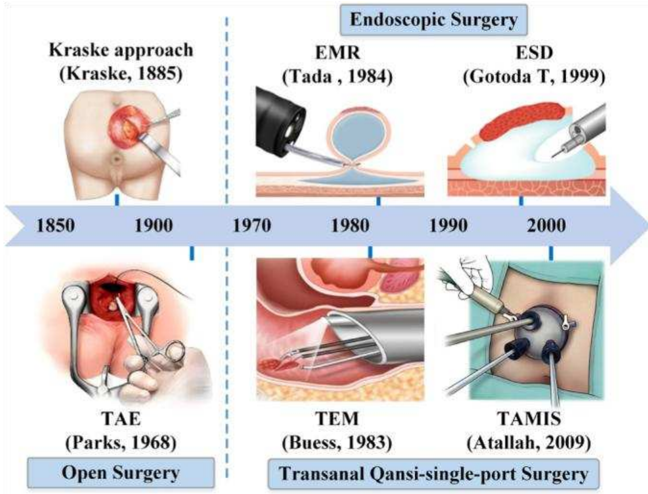

Fig. 2. Evolution of the surgical management of early-stage rectal cancer through local resection [10], [13], [18], [19], [30], © 2022 Elsevier, © 2017 Cleveland Clinic and © 2019 Lippincott

Transanal Excision (TAE), represent the earliest category of local resection procedures. The Kraske approach was first described by Kraske in 1885 [8]. As illustrated in Fig.3-a [9], [10], this procedure requires a paracoccygeal incision to adequately expose the surgical field, thereby ensuring accurate and precise tumor resection. Although it offers certain advantages, this approach has limited clinical acceptance because of the high recurrence rate and considerable risk of complications [11]. In contrast, modern TAE, which was popularized by Parks et al. in the 1960s, has become the predominant technique for local resection [12]. As illustrated in Fig. 3-b [13], during TAE, anorectal retractors are employed to dilate the anus to an appropriate diameter. Rigid instruments are then utilized to mark and resect the tumor along with the surrounding tissue via a transanal approach [14]. This method circumvents the need for laparotomy and enterostomy, thereby minimizing surgical trauma and accelerating patient recovery. However, the confined space within the rectal cavity imposes significant limitations on access and visibility provided by traditional retractors, making it difficult to achieve adequate lighting and exposure. Moreover, the inadequate flexibility and precision of rigid instruments pose challenges in achieving complete excision of larger lesions, thereby restricting the applicability of local resection in rectal cancer treatment.

In recent years, with the continuous advancement of flexible endoscopic technology, endoscopic surgery based on flexible endoscopes has gradually been applied in the clinical practice of local resection for rectal cancer [15], [16]. Two typical endoscopic surgical techniques are Endoscopic Mucosal Resection (EMR) and Endoscopic Submucosal Dissection (ESD) [17], as depicted in Fig. 3-d [18] and Fig. 3-e [19]. Both techniques involve the use of a flexible endoscope to access the tumor site in the rectum via the anus. A submucosal injection is then performed to elevate the lesion, followed by resection or dissection of the target tissue [20], [21]. Compared with TAE, endoscopic surgery using EMR and ESD provides superior illumination and visualization for upper and middle rectum lesions, enabling more accurate lesion identification and excision [22]. However, in clinical practice, endoscopic surgery may face challenges when dealing with larger rectal tumors, as it is difficult to ensure en-bloc resection and necessitates a piecemeal resection approach [23]. Furthermore, endoscopic surgery may not be effective in completely removing lesions with deep submucosal invasion, leading to potential local recurrence [24].

By comparing the key features of open surgery and endoscopic surgery, it becomes evident that adopting a transanal surgical approach, coupled with advancements in surgical instruments to improve illumination, operational flexibility, and precision, often constitutes a critical factor in improving the treatment outcomes for rectal cancer. Consistent with this notion, one significant advancement is the development of taQSPS, which represents a subtype of SPS. Introduced in 1969 [25], SPS allows for inserting all endoscopic and surgical instruments through a single incision. Building on this foundation, taQSPS employs similar instruments and techniques while accessing lesions via a transanal route, thus eliminating the need for skin incisions. Transanal Endoscopic Microsurgery (TEM), a representative form of taQSPS, was first described by Buess in 1983 [26]. As shown in Fig. 3-g [27], the procedure begins with the transanal insertion of a specialized proctoscope to dilate the anus, followed by the insufflation of carbon dioxide. Enhanced visualization is achieved through either a binocular stereoscopic eyepiece or a forward-oblique telescope, enabling precise excision and suturing. However, despite being in use for over four decades, TEM has not been widely adopted by surgeons, partly due to its steep learning curve and the substantial costs associated with the specialized instruments required for the procedure [28]. Building on the foundation of TEM, Atallah et al. introduced an innovative approach in 2009 by integrating single-port laparoscopic devices into TEM, which was named Transanal Minimally Invasive Surgery (TAMIS) [29], as depicted in Fig. 3-h [30]. This method replaced the expensive, highly specialized instruments used in TEM with single-port laparoscopic instruments. As a result, TAMIS significantly reduced surgical costs while maintaining the excellent oncologic outcomes of TEM. Additionally, it provided surgeons with a more accessible learning curve, further promoting the widespread adoption of taQSPS.

Compared with radical excision and open surgery, taQSPS techniques such as TEM and TAMIS avoid unnecessary surgical trauma, and provide superior visualization of the lesion, thereby reducing the risk of complications and the recurrence rate while enabling more precise and controlled local resection [29]. Moreover, compared with EMR and ESD, taQSPS can achieve complete removal of larger or more invasive rectal tumors, thereby broadening its clinical indication. However, despite the advantages of taQSP, performing surgery in a confined space through a single port with rigid instruments substantially restricts the technique's full potential. In addition to common issues such as a narrow operating space and hand tremors during

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surgery, taQSPS introduces further complications due to its inherent single-port design. The restricted space within the rectal environment makes it difficult to properly deploy surgical instruments, resulting in a lack of instrument triangulation. Moreover, the rigid instruments used in taQSPS offer limited flexibility and can cause mirrored and unintuitive hand-eye coordination due to the fulcrum effect [31]. These factors compromise the dexterity and accuracy of the procedure, increase the difficulty of the operation, and produce a steep learning curve, all of which hinder the rapid adoption of taQSPS. To mitigate these challenges, robotic surgical systems have recently been introduced, providing enhanced dexterity, stability, and motion accuracy [32], [33].

This review highlights the advantages of taQSPS and offers a comprehensive analysis of the development, current applications, and future trends of robotic systems utilized in taQSPS. Section II covers existing robotic systems used in taQSPS, including general-purpose, specialized, and potentially applicable systems. Section III summarizes the achievements in the development of specialized taQSPS robotic systems, elaborates on the key technologies that drive their advancement, and explores future trends in this domain. A systematic search of databases such as Web of Science, PubMed, IEEE Xplore, and Springer was conducted for studies published between 2006 and 2024 using keywords like " early-stage cancer therapy," "robotic transanal minimally invasive surgery," and " single-port surgery robotic system." Duplicate records were removed across databases, and the relevance of articles was evaluated based on their titles, abstracts, and keywords.

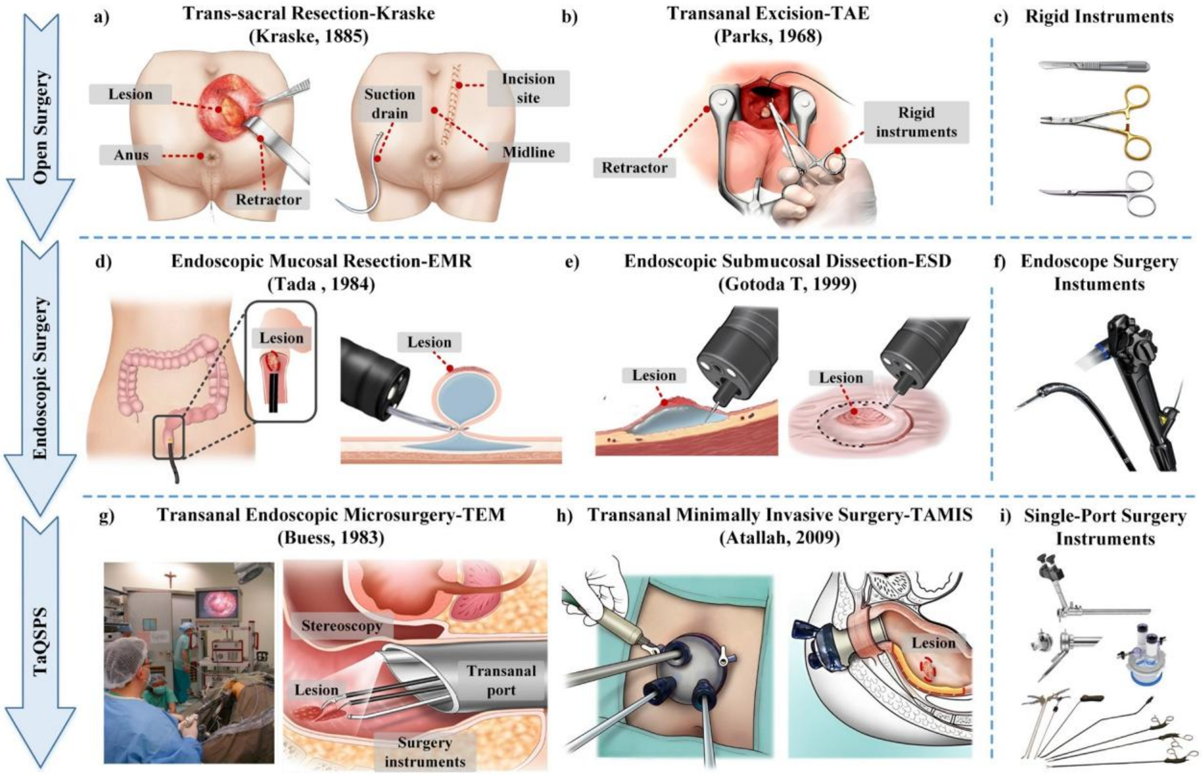

Fig. 3. Typical surgical techniques of local resection: a) Trans-sacral resection (Kraske) [10], © 2022 Elsevier; b) Transanal excision (TAE) [13]; c) Typical instruments of open surgery; d) Endoscopic mucosal resection (EMR) [18], © 2017 Cleveland Clinic; e) Endoscopic submucosal dissection (ESD) [19]; f) Typical instruments of endoscopic surgery; g) Transanal endoscopic microsurgery (TEM); h) Transanal minimally invasive surgery (TAMIS) [30], © 2019 Lippincott; i) Typical instruments of SPS.

II. Development of Surgical Treatments for Earlystage Rectal Cancer

In robot-assisted SPS, the integration of robotic precision with human control addresses numerous challenges associated with conventional SPS. By adopting a digital master-slave configuration, the fulcrum effect is mitigated. Simultaneously, the accuracy of instrument tip manipulation is enhanced by eliminating tremors and applying motion scaling. Based on their scope of application, the current robotic systems utilized in taQSPS can be categorized into two primary types: generalpurpose SPS robotic systems and specialized taQSPS robotic systems. A comparative analysis of several representative robotic systems is provided in Table I.

A. General-purpose SPS Robotic Systems

Since the introduction of the da Vinci SP system into the field of SPS, general-purpose SPS robotic systems have witnessed substantial advancements. These systems typically employ a master-slave configuration [34], comprising a master console and a slave manipulator. As illustrated in Fig. 4-h, the slave manipulator generally includes an endoscope or a 3D camera for stereoscopic vision and two to three long-shafted surgical instruments for performing surgical procedures. These instruments enter the patient's body cavity through the umbilicus or a single skin incision in parallel and are then unfolded and deployed. Based on this design, general-purpose SPS robotic systems have achieved significant advancements in technological innovation, broadened clinical applications, and performance optimization across multiple dimensions.

1) Da Vinci SP

The da Vinci SP, developed by Intuitive Surgical Inc. of Sunnyvale, USA, and FDA-approved in 2014, comprises three primary components: a surgeon console, a patient-side cart, and a vision cart, as illustrated in Fig. 4-a [35], [36]. The surgeon is situated at the surgeon console during surgery, visualizing the site and controlling instruments via two master controllers. The surgeon console also features a touchscreen for settings and a foot switch for mode changes. The patient-side cart is equipped with a slave manipulator that contains four robotic instrument drives, controlling three 7-DoF EndoWrist SP instruments and an endoscope. The EndoWrist SP instruments feature a 5-mm snake-style wrist with an additional "elbow" joint, enabling triangulation at the surgical site through a single port. Since its introduction in 2018, the da Vinci SP has significantly contributed to the clinical adoption of single-port robotic surgical systems [37], [38]. By 2024, it had received CE mark approval for use in Europe for endoscopic abdominopelvic, thoracoscopic, transoral otolaryngology, transanal colorectal, and breast surgical procedures [39]. However, the substantial costs associated with purchasing, operating, and maintaining the system limit its widespread adoption [40]. As the early patents that secured Intuitive Surgical's monopoly have begun to expire, other institutions and companies have developed competing platforms and actively entered the market. This trend has facilitated greater adoption of single-port robotic surgery.

2) Miniature In Vivo Robotic Assistant (MIRA)

The Miniature In Vivo Robotic Assistant (MIRA) system, designed and implemented by Virtual Incision Co., Ltd, Lincoln, USA, received FDA approval in 2020, as depicted in Fig. 4-b [41]. This system consists of a master console, a companion cart, and a dual-armed surgical manipulator [42]. One of the key advancements of the MIRA system is the miniaturization of its dual-armed surgical manipulator, which weighs approximately 2 pounds and features a vertically oriented cylindrical body equipped with two instrument arms and an integrated camera. This compact design substantially reduces overall size compared with conventional systems, enhancing both its usability and maneuverability in the operating room [43]. During surgery, each instrument arm is inserted through a small incision and subsequently assembled within the abdominal cavity, thereby minimizing the risk of injury and infection. Invivo experiments have demonstrated the effectiveness of MIRA compared with traditional laparoscopic instruments [44]. However, the limited number of joints restricts each instrument arm to only 4 DoFs, which may reduce flexibility and pose challenges in ensuring optimal surgical outcomes.

3) Enos (SPORT)

The Enos robotic single-access surgical system, previously known as the Single Port Orifice Robotic Technology (SPORT) surgical system, was developed by Titan Medical Inc., Toronto, Canada, and rebranded in 2020 [45]. The primary objective of this system is to address the inherent challenges associated with minimally invasive SPS, such as inadequate triangulation and limited wrist articulation. The system comprises a master surgeon console and a slave patient-side cart, as illustrated in Fig. 4-c [43], [46]. The patient cart is equipped with a 15-mm diameter surgical port, providing ample workspace and high operational flexibility. The robotic manipulator, which is inserted through the surgical port, comprises a 25-mm tubular device that accommodates two 6-mm multi-DoF instrument arms and a 3D camera. Each instrument arm features a threesegment continuum design, with each segment offering two DoFs for bending. The camera is deployed after insertion into the patient's body to achieve an optimal position for surgical triangulation with the instruments. Currently, the system is progressing toward FDA approval and has undergone trials in general and colorectal surgeries in cadaver models. Preclinical study results indicate that various abdominal procedures can be safely performed using the current prototype [47]. However, the system has not been tested in vivo, and further experimental data are necessary to substantiate its clinical reliability.

4) SHURUI

In 2019, Xu et al. from Shanghai Jiao Tong University in China introduced a versatile modular surgical robotic system known as the SHURUI single-port endoscopic surgical system [48], [49]. This system was designed to support multiport, single-port, and hybrid-port procedures simultaneously. It consists of a master surgeon console with hand controllers, foot pedals, and a slave patient-side cart, as depicted in Fig. 4-d. Each 6-DoF surgical instrument mounted on the slave patientside cart features two distal continuum segments, a tool stem, and a detachable transmission unit. The distal continuum segments are driven by nitinol rods to achieve 4-DoF bending, while the instruments can also translate and rotate around their longitudinal axes. A key feature of this system is the use of dual continuum mechanisms, which simplify the redundant nitinol rod drives and increase the number of rods, thereby enhancing the instruments' payload capability [50]. The approval for its use in urology and gynecology has been granted in China, and it has successfully concluded clinical trials involving urological and gynecological surgical procedures [51], [52]. However, the process of inserting and removing instruments from robotic arms is labor-intensive, and forced connections can render the instruments inoperable and difficult to disconnect, necessitating a system restart [53].

5) EDGE SP1000

The EDGE SP1000 single-port robotic surgical system, developed by Shenzhen Edge Medical Co., Ltd in China, obtained NMPA approval in 2023. This system comprises a

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master surgeon console, a video cart, and a slave patient-side cart, as depicted in Fig. 4-f [54], [55]. The surgeon console is equipped with a 3D image viewer, two master manipulators, a control panel, and multiple foot pedals. The patient-side cart houses an endoscope and three robotic wrist instruments inserted through a 27-mm multi-channel single port. Two of these instruments replicate the real-time movements commanded by the master manipulators, while the third instrument is primarily used for organ and tissue retraction. Each instrument features a design similar to the da Vinci EndoWrist, incorporating a snake-like wrist and an additional elbow joint to facilitate triangulation within the body.

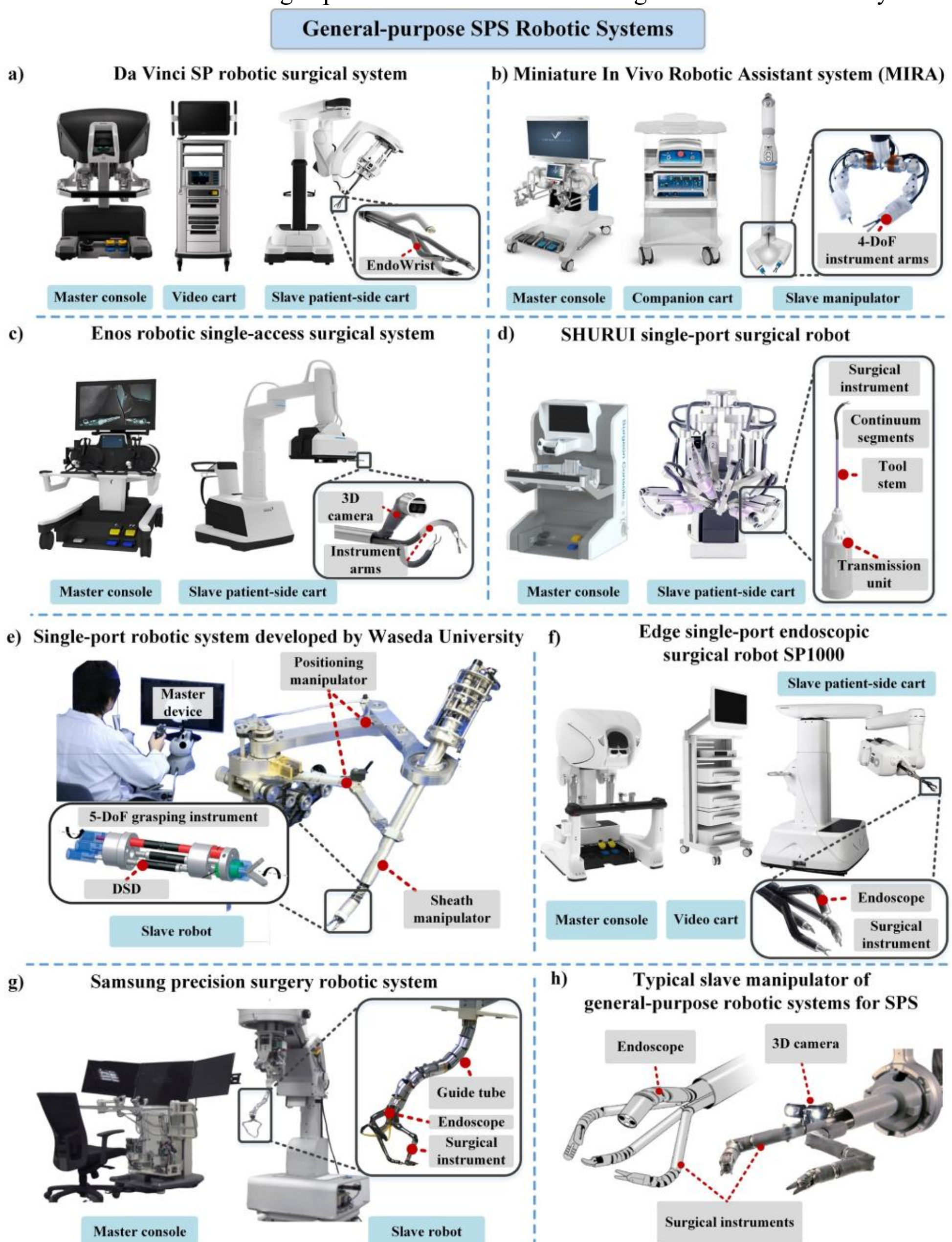

Fig. 4. General-purpose SPS robotic systems: a) Da Vinci SP robotic surgical system [36], © 2024 Intuitive Surgical Inc., Ltd; b) Miniature in vivo robotic assistant system (MIRA) [41], © 2024 Virtual Incision Co., Ltd; c) Enos robotic single-access surgical system [46], © 2024 Titan Medical Inc., Ltd; d) SHURUI single-port surgical robot [48], © 2021 IEEE; e) Single-port robotic system developed by Waseda University [58], © 2010 Wiley; f) Edge singleport endoscopic surgical robot [55], © 2024 SP1000 Shenzhen Edge Medical Co.; g) Samsung precision surgery robotic system [62], © 2015 Springer; h) Typical slave manipulator of general-purpose robotic systems for SPS.

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Additionally, the system also integrates electrosurgical equipment and avoids the intersection of robotic arms to minimize the risk of collisions. The EDGE SP1000 has completed animal experiments and in-human trials, demonstrating its feasibility and safety in transanal total mesorectal excision and various gynecological procedures for both benign and malignant conditions [56], [57].

6) Single-port Robotic System Developed by Waseda University

In 2010, Kobayashi et al. from Waseda University, Tokyo, Japan, introduced an innovative robotic system with dynamic vision control designed to assist in abdominal SPS [58], [59]. The system comprises a master console equipped with two PHANTOM-Omni devices and a joystick, as well as a slave robot featuring a vision control manipulator, two surgical instruments, and a flexible endoscope, as illustrated in Fig. 4-e. The vision control manipulator utilizes a 4-DoF external positioning manipulator and a 2-DoF sheath manipulator to precisely adjust the position and orientation of the internal instruments and flexible endoscope, thereby enabling effective vision field control and tissue manipulation. To enhance the intuitiveness of the slave robot's control, the 5-DoF grasping instruments emulate a simplified human arm, achieving 2-DoF elbow rotations via a double-screw-drive (DSD) mechanism [60]. In-vivo experiments demonstrated that vision control in the stomach and a cautery task by a cautery tool could be effectively achieved [61]. However, surgeons experienced challenges in simultaneously controlling the two tool manipulation controllers and the joystick, which impaired their hand-eye coordination. Additionally, as the experiment progressed, the positions of the end-effectors were progressively displaced as a result of the flexibility shaft-power transmission system.

7) Samsung Precision Surgery Robotic System

Roh et al. from Samsung Research in Seoul, Republic of Korea introduced a flexible SPS robot system in 2015, comprising a master surgeon console and a slave robot [62], as depicted in Fig. 4-g. The master console provides real-time visual feedback and employs a pair of instrument controllers equipped with force/torque sensors (Nano 17, ATI Industrial Automation, Inc., USA) to interpret the surgeon’s commands and control the slave robot. The slave robot consists of a positioning arm, a guide tube, several surgical instruments, and actuation units. The guide tube navigates the instruments using a variable stiffness mechanism that can continuously adjust rigidity to meet stringent safety and payload requirements [63]. Meanwhile, the 7-DoF instruments employ a rigid joint design based on rolling gears to enhance stiffness and load-bearing capacity while reducing the tension in the driving wires. Peg transfer and suturing trials demonstrated the system's feasibility for SPS. However, the rigid joint design of the instruments results in non-continuous bending and nonlinear transmission, potentially compromising movement precision and posing challenges to ensuring the safety of the procedure. Moreover, the coupling effect between the variable stiffness mechanism and wire-driven actuation, both relying on adjusting wire length, complicates control and precise manipulation.

B. Specialized TaQSPS Robotic Systems

Despite the substantial contributions made by research institutions and scientists in advancing general-purpose SPS robotic systems, the majority of these systems are designed for abdominal procedures that require larger working spaces, such as urological [37], [64], gynecological [64], [65], and general surgery [64]. As shown in Table 1, the bulky instrument arms of these systems occupy considerable space within the human body, rendering them cumbersome and ill-suited for the confined rectal cavity. This limitation impedes the ability to meet the precise surgical requirements of taQSPS. Consequently, it is imperative to develop specialized taQSPS robotic systems to ensure both feasibility and effectiveness, thereby facilitating broader clinical adoption. The subsequent sections outline the critical design considerations for these specialized robotic systems.

Size Constraints: The access port of the slave manipulator should have an outer diameter no greater than 40 mm to ensure smooth insertion through the anus. Moreover, each surgical instrument should have a diameter no larger than 12 mm. These stringent size constraints are essential for accommodating the narrow anatomy and minimizing the risk of tissue damage.

Degrees of Freedom: Each instrument should possess sufficient DoFs to ensure high operational flexibility within the confined rectal cavity, enabling precise triangulation for both visualization and operations.

Flexibility and Rigidity: Instruments should exhibit adequate flexibility to safely navigate the narrow rectal cavity and reach target lesions while maintaining sufficient rigidity to support the required loading and ensure precise manipulation during the operational interaction stage.

Workspace: Given the dimensions of the rectum, the ideal workspace should be greater than 35mm × 35mm × 60mm. An adequate workspace is crucial for the unrestricted operation of the instruments and effective engagement with lesions.

In response to these design specifications, recent endeavors have been directed toward developing robotic systems that are uniquely adapted for managing taQSPS within the confined and narrow rectal cavity. These efforts aim to engineer robotic systems that can navigate the intricate anatomy of the rectum with precision while accommodating the specific challenges posed by the limited space available for surgical intervention.

1) FLEXMIN

The FLEXMIN, developed by Matich et al. in 2015 at the Technical University of Darmstadt, Germany, is a pioneering

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single-port robotic system designed for transanal rectal resection [66], [67]. As shown in Fig. 5-a1, it consists of a slave robot and a master surgeon interface. The slave robot includes a drive unit, a rigid tool-carrying shaft with a diameter of less than 39 mm, and two 5-DoF rigid instrument arms featuring a parallel structure to enhance positioning accuracy and rigidity. Each arm operates within a workspace of 60 mm × 85 mm, and both arms share a cylindrical workspace with a 50 mm diameter,

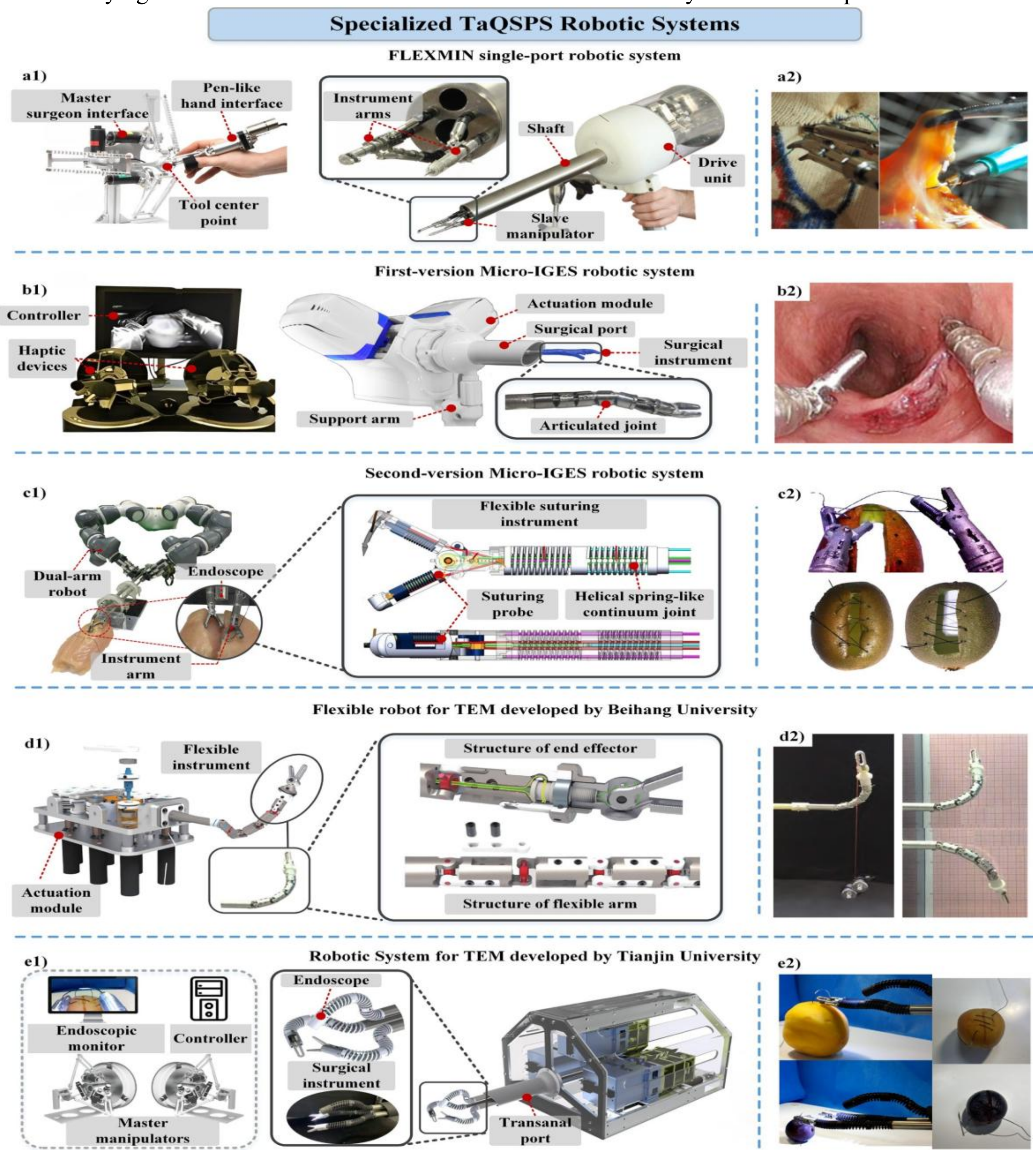

Fig. 5. Specialized taQSPS robotic systems: a1) The master surgeon interface and slave robot of FLEXMIN single-port robotic system [66], [67], © 2015 IEEE and © 2017 IEEE; a2) Experimental testing of FLEXMIN using a porcine model [67], © 2017 IEEE; b1) The master console and slave manipulator of First-version Micro-IGES robotic system [68], [69], © 2017 IEEE; b2) In-vivo tests of first-version Micro-IGES robotic system [69], © 2017 IEEE; c1) The dual-arm robot and suturing instruments of Second-version Micro-IGES robotic system [70], © 2019 IEEE; c2) Suturing and knot-tying experiments of secondversion Micro-IGES robotic system [70], © 2019 IEEE; d1) Flexible robot for TEM developed by Beihang University and its joint structure [72], © 2023 ROBOT; d2) Motion performance experiments of flexible robot for TEM developed by Beihang University [72], © 2023 ROBOT; e1) Master control components and slave manipulator of Robotic System for TEM Developed by Tianjin University [73], © 2024 IEEE; e2) Surgical simulation experiments of robotic System for TEM Developed by Tianjin University [73], © 2024 IEEE.

meeting taQSPS requirements. The master interface, based on a 3-DoF parallel mechanism, controls the tool center point (TCP) and enables precise manipulation of the arms via penlike hand controllers for rotation and gripper movements. Experimental testing on a porcine model demonstrated that FLEXMIN outperforms traditional SPS systems in terms of workspace utilization and dexterity. However, the rigid design of the instrument arms, which are based on a parallel mechanism, limits their adaptability to the curved rectal cavity, risking inadvertent tissue damage during surgical procedures. Additionally, the 4 DoFs per instrument arm restrict the system's operational flexibility, hindering the execution of complex surgical tasks in the confined space of the rectum.

2) Micro-IGES Robotic System with two successive versions

The first-version Micro-IGES robotic system, developed by Shang et al. at Imperial College London, UK, in 2017, was designed to tackle the ergonomic challenges inherent in traditional TEM, such as the fulcrum effect and constrained workspace [68], [69]. As illustrated in Fig. 5-b1, the system comprises two main components: a master console equipped with Omega.7 haptic devices (Force Dimension, Switzerland) and a slave manipulator. The slave manipulator, measuring 350 mm × 500mm × 500mm and weighing 3kg, features a support arm mounted on the operating table to hold a 36mm diameter surgical port for transanal insertion. It is outfitted with two 7DoF articulated surgical instruments, actuation modules, and a stereo endoscope (Olympus EndoEye Flex, Japan). Benchtop, ex-vivo, and in-vivo tests confirmed the system's clinical suitability. However, the articulated joint-based design introduced issues such as increased friction, discontinuous bending, and nonlinear motion transmission, necessitating supplementary algorithmic compensation for motion accuracy. Additionally, the fixed positioning of the endoscope led to conflicts with the instruments, reducing the surgical field of view and impairing visibility.

In 2019, Hu et al. from the same group at Imperial College London further refined the system by developing a second version to overcome these limitations [70]. This updated version incorporates a commercial dual-arm robot (YuMi, ABB, Switzerland) and utilizes two 5-DoF flexible suturing instruments, each 6 mm in diameter, as illustrated in Fig. 5-c1. These instruments feature a helical spring-like continuum joint with circular rolling contacts at each spiral to prevent axial compression and enhance bending stiffness [71]. Additionally, the distal end of these flexible instruments integrates a novel suturing probe that utilizes a pair of crank-slider mechanisms to control the opening and closing of its jaws. Each jaw is equipped with a latch that can securely hold a double-pointed needle with notches on each end, enabling alternately securing the needle between the jaws. This design allows for single-instrument operations such as positioning, suturing, and knottying within the rectal cavity. Suturing and knot-tying experiments in a simulated TEM environment confirmed the system's viability. However, the instruments' performance is limited when suturing cuts are positioned below or perpendicular to the instrument axis, due to each instrument having only two DoFs for bending.

3) Flexible Robot for TEM Developed by Beihang University

Wang et al. from Beihang University, Beijing, China, designed a 5-DoF flexible robot based on universal joints and series rods in 2023 to assist with traditional TEM proctoscopes during surgical procedures [72]. The flexible robot primarily consists of a 5-DoF flexible instrument and an actuation module, as illustrated in Fig. 5-d1. The flexible instrument is composed of rigid linkages connected by universal joints, providing 2DoF bending, which is driven and controlled by four cables. Additionally, the proximal end of the flexible arm incorporates a 1-DoF deployable joint, facilitating triangulation during insertion via a transanal approach. The end effector of the flexible instrument has two DoFs: 1-DOF wrist rotation and the opening/closing of the gripper. Two cables run through the central channel of the instrument arm and are secured within the end effector to control these two DoFs. The flexible robot has been demonstrated to perform complex motions. However, the proposed design based on universal joints and series rods introduces nonlinear transmission issues, resulting in insufficient positioning accuracy (2.7mm) and payload capacity (0.4N). Moreover, the system has not yet been integrated into a complete master-slave surgical robot system, and there is a lack of phantom or animal experiments to validate its effectiveness in surgical settings.

4) Robotic System for TEM Developed by Tianjin University

In 2023, Li et al. from Tianjin University in China developed a master-slave robotic system specifically designed for TEM. This system enhances hand-eye coordination and dexterity within the confined rectal cavity while minimizing visual obstruction [73]. The system comprises two master manipulators and one slave manipulator, each equipped with three instrument arms, as illustrated in Fig. 5-e1. The master manipulators consist of a mobile plate connected to a horizontal base via three branch chains. These branch chains are redundantly actuated by a parallel mechanism, which can be described as 2(RRRS)-RRRSP [74]. This design effectively avoids internal workspace singularities, thereby addressing the limitations of the orientational workspace found in traditional parallel operator interfaces. The slave manipulator includes two 7-DoF surgical instruments and a 5-DoF endoscopic arm, each fitted with a modular hybrid coaxial continuum unit (HCCU). The HCCU incorporates an outer dual-helix structure to enhance torsional stiffness and a notched central backbone to improve compressive stiffness. Modular interfaces facilitate the assembly of multi-DoF distal joints, while the proximal associated continuum segment (PACS) enables the instruments to deform into an S-shape, thereby enhancing triangulation in the rectum and simplifying the kinematic control algorithm. Surgical simulations, including peeling grape skins and suturing apricot pits, demonstrated the system's broad field of view and operational intuitiveness. However, the system has not yet undergone animal or human trials, and further testing is required to validate its clinical safety and efficacy.

C. Other Robotic Systems with the Potential to Perform TaQSPS

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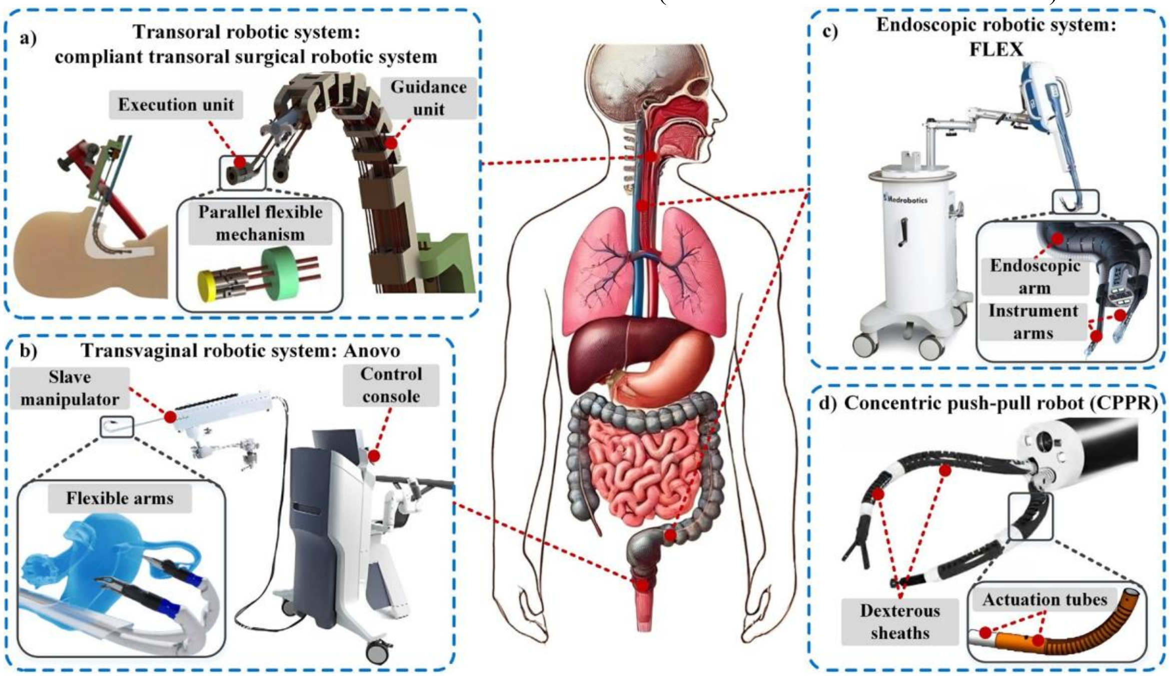

Fig. 6. Other robotic systems with the potential to perform TaQSPS: a) Transoral robotic system: compliant transoral surgical robotic system, and simulation of its surgical scene [79], © 2019 Springer; b) Transvaginal robotic system: Anovo, and its flexible arms [82], © 2024 Momentis Surgical, Inc., Ltd; c) Endoscopic robotic systems: FLEX, and its endoscope arm [86], © 2024 Robotics Surgical Co., Ltd; d) Concentric push-pull robots (CPPR), and its principle structure [87], [88], © 2022 IEEE and © 2024 IEEE.

Several robotic systems designed for other anatomical regions exhibit significant potential for adaptation to transanal procedures due to their quasi-single-port configuration. These systems are frequently employed in shallow environments similar to the rectum, such as those encountered in transoral and transvaginal surgeries [75], [76]. Despite variations in size tailored to specific anatomical applications, these systems share fundamental design principles and structural similarities with specialized taQSPS robotic systems. Therefore, after appropriate modifications to fit the dimensions of the rectal cavity, these systems can potentially be adapted for taQSPS. Additionally, certain innovative features from these systems can serve as valuable references for advancing the development of specialized taQSPS robotic systems.

For instance, Gu et al. developed a compliant transoral surgical robotic system in 2019 based on a parallel flexible mechanism [77], [78], [79], as illustrated in Fig. 6-a. This system incorporates a guidance unit with a continuum structure for smooth navigation through the oral cavity and an execution unit featuring a 3-DoF parallel flexible mechanism actuated by Ni-Ti rods, ensuring precise end-effector positioning. This hybrid design combines the flexibility and load capacity of parallel mechanisms [80] with the compactness and compliance of continuum robots, which can be utilized to enhance the load capacity and positioning accuracy of instrument arms in taQSPS systems. Furthermore, Momentis Surgical, Inc. (Lauderdale, Florida, USA) introduced the Anovo™ surgical robot for gynecological procedures, which subsequently received FDA approval in 2021 [81], [82] (Fig. 6-b). By employing a three-layer nested articulated tube structure, each flexible arm maintains a compact profile while enabling joints to bend beyond 180 degrees, thereby enhancing surgical maneuverability. This design can inspire the development of more flexible and dexterous instrument arms for taQSPS robotic systems.

Beyond the aforementioned robotic systems, the design principles of other surgical robots offer considerable potential to broaden the application spectrum of specialized taQSPS robotic systems, enabling them to address higher rectal and even colonic lesions, as well as advanced rectal cancer. For instance, recent advancements in flexible endoscope technology have led to the development of therapeutic flexible endoscopic robotic systems, particularly for ESD. These systems demonstrate a broader range of surgical capabilities compared with conventional endoscopic tools, positioning them as promising candidates for taQSPS in treating higher rectal or colonic lesions. One such system is the FLEX Robotic System, developed by Robotics Surgical Co. (Raynham, MA, USA), which was initially designed for transoral procedures and received FDA approval in 2015 [83], [84]. Its application was later extended to transanal colorectal surgery, with FDA approval granted in 2017 [85], [86]. As shown in Fig. 6-c, the system's slave manipulator consists of a robotic endoscope arm and two 4-DoF instrument arms. The endoscope arm employs a follow-the-leader motion strategy with concentric, snake-like structures to navigate complex pathways and includes two external accessory channels for exchanging flexible instrument arms. The system's efficacy in performing colonic ESD has been demonstrated using ex-vivo bovine models.

Additionally, concentric push-pull robots (CPPR) have emerged in the field of surgical robotics [87], [88], introducing

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a novel design paradigm for specialized robotic systems aimed at enhancing potential applications in advanced rectal cancer treatment. The CPPR mechanism comprises a pair of nested NiTi actuation tubes that are asymmetrically laser-patterned. The top ends of these tubes are rigidly connected, forming a flexible joint that bends in response to the translation of the actuation tube bases. Unlike cable-driven continuum robots, which can only withstand tension, CPPR tubes can endure both tension and compression, enabling bidirectional active bending and enhancing the flexibility of instrument arm motion. The multitube structure also increases manipulator stiffness, thereby improving load-bearing capacity for tasks such as tissue traction. These characteristics render CPPR an up-and-coming solution for developing specialized taQSPS robotic systems. For instance, in 2023, Dang et al. developed a flexible bimanual robotic system for colorectal cancer ESD utilizing CPPR technology [89], as illustrated in Fig. 6-d. This system exhibited high axial and torsional stiffness while maintaining low bending stiffness, meeting the stringent surgical requirements.

III. Conclusion and Outlook

This review traces the evolution of local resection techniques for early-stage rectal cancer, with a particular emphasis on taQSPS and its comparison to open and endoscopic surgeries. It provides a comprehensive analysis of specialized taQSPS robotic systems, emphasizing the advantages of these systems over large, bulky, and complicated general-purpose SPS robots. Unlike general-purpose systems that are typically designed for larger abdominal procedures, specialized taQSPS robotic systems are optimized for the confined dimensions of the rectal cavity, offering a more compact and efficient design. These advancements not only enhance the feasibility and effectiveness of taQSPS but also have the potential to improve treatment outcomes and increase adoption rates in early-stage rectal cancer surgery. Notwithstanding the significant developmental potential and promising clinical applications of specialized taQSPS robotic systems, which are still in the nascent stages of exploration, the number of such systems and associated studies remains relatively sparse. The majority of these systems are currently in the experimental validation phase, with none having attained commercial application thus far. Furthermore, comprehensive clinical studies reporting standardized outcome metrics for specialized taQSPS robotic systems, such as success rates, complication rates, or cost analyses, remain limited at this stage. Therefore, sustained and heightened attention from the research community is imperative to catalyze advancements in this domain and to bridge the gap between experimental validation and clinical implementation.

Furthermore, despite the significant achievements made by research institutions and scientists, several key technical modules of specialized taQSPS robotic systems remain immature and have yet to fully integrate into a unified design framework. This challenge is particularly evident in the design of slave instrument arms, the integration of force and shape sensing, and the realization of surgical autonomy, all of which are intrinsically linked to the future trends of surgical robotic systems and the practical clinical requirements of surgeons.

While various slave instrument arms based on continuum [90], [91] and articulated-joint [69], [72] mechanisms have been developed, a universally applicable design methodology remains elusive. Given the spatial constraints within the rectal cavity, surgical instruments should maintain an external diameter not exceeding 12mm. This requirement complicates the design by balancing compactness and sufficient DoFs for operational dexterity. Additionally, the slender and flexible nature of these arms results in lower payload capacity compared to laparoscopic robots, further highlighting the need for research to enhance both motion flexibility and payload capacity within the confined rectal cavity. To address these challenges, innovative structural designs for various parts of the instrument arms are being investigated to establish a design methodology that satisfies anatomical constraints while ensuring adequate operational dexterity and payload capacity. Regarding the end effector, most flexible instrument arms are limited to traditional tools such as needles and forceps [73]. Due to their limited motion flexibility and payload capacity, surgeons typically encounter challenges in generating sufficient clamping force and achieving dexterous manipulation, particularly in tasks such as suturing. To address these issues, Hu et al. introduced a novel suturing probe in the second version of the Micro-IGES system, enabling single-arm operations for suturing and knot-tying [70]. Similarly, Cao et al. developed a 5-DoF suturing instrument featuring a latching mechanism that allows for selective needle attachment to either jaw, enhancing precise needle control and enabling single-arm operations [92].

Moreover, in robotic-assisted taQSPS, surgeons have limited direct perception of the interaction forces between the instrument arms and human tissues. This limitation may result in either excessive or insufficient force application, thereby increasing the risk of surgical errors. Integrating force sensors into the distal ends of the robotic system's instrument arms can provide surgeons with a more intuitive and natural surgical experience, thereby enhancing their perception of interaction forces. This improvement can significantly improve surgical safety and overall outcomes [93]. Current mainstream force sensors are primarily designed based on strain gauge [94], capacitive [95], [96], and optical fiber technologies [97], [98], [99], [100]. However, as of now, only a few commercially available force sensors can achieve robust integration with surgical instruments, thereby limiting their widespread clinical application [93]. Moreover, in robotic systems equipped with flexible instrument arms, ensuring the accuracy and reliability of motion control depends on efficient and precise real-time shape sensing[101]. Accurately modeling the shape of flexible instrument arms remains challenging due to their slender structure, nonlinear deformation characteristics, and the complexity of multi-point tissue contact during insertion into narrow human cavities [102]. To address these challenges, researchers have developed several shape-sensing technologies that include fiber Bragg grating (FBG) sensing [103], [104], electromagnetic (EM) tracking [105], [106], and intraoperative imaging [107]. Furthermore, by leveraging information such as the length and driving force of the drive wires at the proximal end of flexible instrument arms, emerging technologies such as deep learning (DL) networks can also facilitate precise shape information acquisition [108], [109].

With the continuous advancement of artificial intelligence (AI), surgical autonomy has emerged as a critical trend in developing next-generation specialized taQSPS robotic systems. By integrating perceptual data from force and shapesensing technologies, these AI-enhanced systems demonstrate significant improvements in intelligent diagnosis and surgical autonomy through DL and computer vision (CV) [110], effectively reducing reliance on surgeons' experience while enhancing procedural accuracy, stability, and safety. Based on the extent of surgeons' involvement during surgery, the autonomy levels of surgical robotic systems can be categorized into stages ranging from no autonomy, such as the master-slave configuration employed by most robotic systems for taQSPS, to high-level autonomy [111]. The fundamental technical frameworks for surgical autonomy can be categorized into three main areas: First, within medical image processing, algorithms such as convolutional neural networks (CNN) and generative adversarial networks (GAN) have been instrumental in advancing key capabilities, including image reconstruction [112], [113], tissue image segmentation [114], [115], and lesion detection [116], [117]. These methods supply the precise anatomical data required for automated surgical procedures. Second, in terms of surgical navigation and planning, progress in simultaneous localization and mapping (SLAM) as well as dynamic path planning has strengthened real-time environmental awareness and supported personalized surgical strategies [118], [119]. Third, in terms of human-robot interaction control and autonomous control, advancements in impedance/admittance control and reinforcement learning have not only improved the safety of robot-assisted operations but also empowered robots to autonomously perform complex tasks, such as suturing and cutting [120], [121].

Furthermore, embodied AI techniques, including generative scene simulation, policy learning, and endoscopy video analysis, which serve as key representatives of autonomous control, are increasingly recognized as the primary research challenges for enhancing the autonomy of surgical robotic systems. Yang et al. developed an efficient data-driven scene simulation method that leverages robotic surgery videos and incorporates physicsembedded 3D Gaussian models, which is expected to play a crucial role in surgical education and simulator-based robot learning [122]. This method enables efficient reconstruction and simulation of surgical scenes from endoscopic videos while achieving realistic tissue deformation under various external forces. Moreover, Wang et al. proposed a foundation model named EndoFM-LV [123], which was developed using a minute-level pre-training framework specifically designed for the analysis of long endoscopy video sequences. This model has been evaluated across four types of endoscopy tasks: classification, segmentation, detection, and workflow recognition. The experimental results demonstrate that this framework significantly outperforms previous video-based and frame-based approaches, making it highly suitable for various automated medical applications, including lesion segmentation, lesion detection, and workflow recognition. Through comprehensive integration with aforementioned AI technologies, the next generation of specialized surgical robotic systems will evolve from localized automation of specific complex procedures towards full surgical automation, ultimately becoming an intelligent system capable of addressing multiple stages of rectal cancer.

Moreover, beyond early-stage rectal cancer, the quasi-singleport architecture and compact form factor of specialized taQSPS systems render them particularly well-suited for other minimally invasive procedures in similarly constrained, shallow cavities. For instance, the small-diameter shafts, highly dexterous instrument arms, and integrated force and shape sensing capabilities can be readily adapted for transvaginal robotic surgery in gynecological applications and transoral robotic surgery for oropharyngeal lesions, where single-orifice access offers significant advantages. While clinical studies validating these cross-domain applications remain limited—consistent with the nascent stage of specialized taQSPS research—the transferable design principles of compact structure, robust sensing, and multi-DoF dexterity suggest a broader trend toward natural-orifice minimally invasive surgery.

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