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NARRATIVE REVIEW

Robotics in interventional endoscopy—evolution and the way forward

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Abstract
The integration of robotics into gastrointestinal (GI) endoscopy represents a transformative advancement and bears the potential to bridge the gap between traditional limitations by offering unprecedented precision and control in diagnostic and therapeutic procedures. This review explores the historical progression, current applications and future potential of robotic platforms in GI endoscopy. Originally designed for surgical applications, robotic systems have expanded their reach into endoscopy, potentially enhancing procedural accuracy and reducing ergonomic strain on practitioners. Natural Orifice Transluminal Endoscopic Surgery (NOTES) emerged as a promising technique, leveraging natural orifices to perform minimally invasive surgeries. Despite its initial potential, several factors, including limitations of the available instrumentations and lack of reliable closure techniques, hindered its widespread adoption and progress. Conventional endoscopic tools often fall short in terms of triangulation, traction and degrees of freedom, necessitating the adoption of robotic interventions. Over recent decades, robotic endoscopy has significantly evolved, focusing on both diagnostic and complex therapeutic procedures such as endoscopic sub-mucosal dissection (ESD) and endoscopic full-thickness resection (EFTR). Various robotic platforms demonstrate enhanced safety and efficiency in GI procedures. As the field progresses, the emphasis on clinical validation, advanced training and the exploration of new applications remains crucial. Continuous innovation in robotic technology and endoscopic techniques promises to overcome existing limitations, further revolutionizing the management of GI diseases and improving patient outcomes.

Keywords Endoscopic surgical procedures · Gastrointestinal endoscopy · Medical device innovation · Minimally invasive surgical procedures · Natural orifice endoscopic surgery · Robotic · Therapeutic endoscopy

Introduction

The field of gastrointestinal (GI) endoscopy has undergone transformative changes since the introduction of the first flexible gastro-endoscope in 1957 by Basil Hirschowitz. This pioneering development laid the foundation for the expansion of diagnostic and therapeutic capabilities in gastroenterology. Over the decades, the role of endoscopy has evolved significantly, shifting from a predominantly diagnostic tool to a critical therapeutic modality [1]. The advent of therapeutic procedures such as endoscopic sub-mucosal dissection (ESD), endoscopic full-thickness resection (EFTR) and natural orifice transluminal endoscopic surgery (NOTES) marked key milestones in the field. These procedures, characterized by their technical complexity and substantial training requirements, traditionally remained within the purview of a select group of highly skilled endoscopists. The challenges posed by the limitations of conventional endoscopic tools—lack of necessary articulation and triangulation of surgical instruments—have been significant barriers, making complex procedures particularly challenging [2, 3]. Current endoscopic platforms have limitations, including outdated designs that have not seen substantial changes in the past several decades, leading to ergonomic issues that contribute to musculoskeletal symptoms among practitioners and a design that is not well-suited for female endoscopists or those with smaller hands.

The integration of robotics into therapeutic endoscopy represents a pivotal advancement in overcoming these barriers. Robotic systems have the potential of extending the capabilities of therapeutic endoscopy by enhancing precision, dexterity and control, thus broadening the scope of procedures that can be performed. Notably, robotic

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platforms have introduced enhanced surgical field visualization, improved ergonomics and tremor filtration, significantly impacting patient outcomes by reducing hospital stays and minimizing adverse events. As we continue to leverage the benefits of robotics, the field of endoscopy stands on the brink of a new era, poised to further revolutionize the approach to GI diseases.

This review aims to elucidate the trajectory of robotic platform development within GI endoscopy, exploring the myriad technological innovations that continue to reshape this vital medical field.

Methods

To compile a comprehensive review on the topic of "Robotics in Therapeutic Endoscopy," we employed a meticulous search strategy using the following primary search terms: "robotic endoscopy," "robot-assisted endoscopy," "therapeutic endoscopy robotics," "natural orifice transluminal endoscopic surgery (NOTES)," "endoscopic sub-mucosal dissection (ESD)," "endoscopic full thickness resection (EFTR)," "robotic platforms in GI surgery," "innovations in endoscopic technology." These terms were used in various combinations to ensure a thorough exploration of the topic. The following databases were utilized: PubMed, Embase and Google Scholar.

Evolution of robotics in gastrointestinal endoscopy

The evolution of robotics within the realm of GI endoscopy signifies a paradigm shift, initially rooting in surgical applications before branching out into broader medical domains. The Automated Endoscopic System for Optimal Positioning (AESOP) emerged as a pioneering robotic surgical platform approved by Food and Drug Administration (FDA) in 1994 followed by the widespread adoption of the da Vinci robotic platform (Intuitive Surgical Inc., Sunnyvale, CA, USA) [4, 5]. This system, renowned for its versatility across various organ systems, exemplifies the quintessential integration of robotic platforms into surgery. The advantages of incorporating robotic platforms into the field of surgery are multifaceted, addressing many limitations inherent in laparoscopic surgeries. Among these are enhanced surgical field visualization, precision, control and surgeon ergonomics—including tremor filtration and improved haptic feedback [6, 7]. This technological advancement has resulted in significant patient-centric outcomes, including reduced hospitalization durations, fewer adverse events and an overall enhancement in the quality of life.

The concept of natural orifice transluminal endoscopic surgery (NOTES) heralded in the 2000s which redefined the boundaries of conventional intra-luminal GI endoscopy. NOTES, a novel hybrid procedure, utilizes a flexible endoscope to facilitate minimally invasive surgeries within the abdominal cavity via natural orifices namely trans-oral, trans-colonic, trans-uretheral or trans-vaginal routes [8, 9]. However, the prevailing limitations of conventional endoscopes—such as lack of triangulation (essential for optimal spatial orientation between the surgical and viewing instruments towards the target area), lack of traction and counter-traction (crucial for facilitating seamless tissue dissection) and limited degrees of freedom (the extent of unrestricted movement across independent planes) and sub-optimal insufflation to improve visualization—underscore the inadequacy of current technologies for NOTES [2, 10, 11].

In response to these challenges, recent decades have witnessed the advent of robotics in endoscopy, aimed at refining the efficacy, safety and reliability of established procedures. Furthermore, this evolution seeks to broaden the horizon of feasible interventions, marking a significant milestone in the continuous advancement of GI endoscopy. Through meticulous development and integration, robotic technologies promise to usher in a new era of precision and possibilities in endoscopic surgery [12].

Types of robotic endoscopic platforms

Several robotic endoscopic devices were developed in the past decade but only a few have reached to pre-clinical and clinical stages. The robotic endoscopic platforms can be grossly divided into the following two categories:

I. Robot-assisted endoscopic devices—multitasking platforms

   a. Direct Drive Endoscopic System (DDES)
   b. EndoSAMURAI
   c. Master and Slave Transluminal Endoscopic Robot (MASTER)
   d. Endomaster EASE System
   e. FLEX Robotic colorectal system
   f. Single-access Transluminal Robotic Assistant for Surgeons (STRAS)
   g. K-FLEX
   h. EndoLuminal Surgical System (ELS)
   i. Endoscopic Therapeutic Robot System (ETRS)

II. Robotic add-on devices

   a. Robot for surgical endoscope (RoSE)
   b. Endoscopic module for on-demand robotic assistance, (EndoMODRA)
   c. Revolute Joint-Based Auxiliary Transluminal Endoscopic Robot (REXTER)

d. Portable endoscopic tool handler (PETH)

Robot assisted endoscopic devices—Multitasking platforms

The multitasking robotic platforms were developed to overcome the limitations of conventional endoscopy while performing complex procedures such as triangulation and "traction and counter traction." Most robotic endoscopy multitasking platforms follow "master–slave concept" of robotic platforms and are designed for telemanipulation. These come with an operator console and a flexible endoscope with at least two robotic arms to perform precise manipulation of tissues [13]. Indeed, many robotic systems initially developed for interventional pulmonary procedures are expected to expand into GI applications. Systems such as Auris Health's Monarch and Intuitive Surgical's Ion, designed for precise navigation and intervention in the lung, offer technological advancements that can be adapted for GI endoscopy. Of note, some of the robotic platforms such as DDES, EndoSAMURAI and MASTER have been discontinued over the years due to various reasons such as technical challenges, market demand and advancements in technology.

The fundamental concept is similar to that of surgical robots used for NOTES such as the da Vinci robotic platform (Intuitive Surgical Inc., Sunnyvale, CA, USA).With the robotic endoscopy, the degree of freedom (DOFs) is increased, thus improving the manoeuvrability [9] (Fig. 1).

The direct drive endoscopic system Direct Drive Endoscopic System (Boston Scientific, Natick, Mass., US) is a manually driven, multitasking platform created for endoluminal and NOTES applications [14]. The unit consists of a rail platform and a flexible articulating guide sheath that can be locked into the desired straight or articulated position. The prototype sheath is 22 × 16 mm in size with three lumens that accept a small caliber endoscope (6 mm) and two 4-mm instruments. This platform provides seven DOFs. In the benchtop and animal model evaluation, DDES was

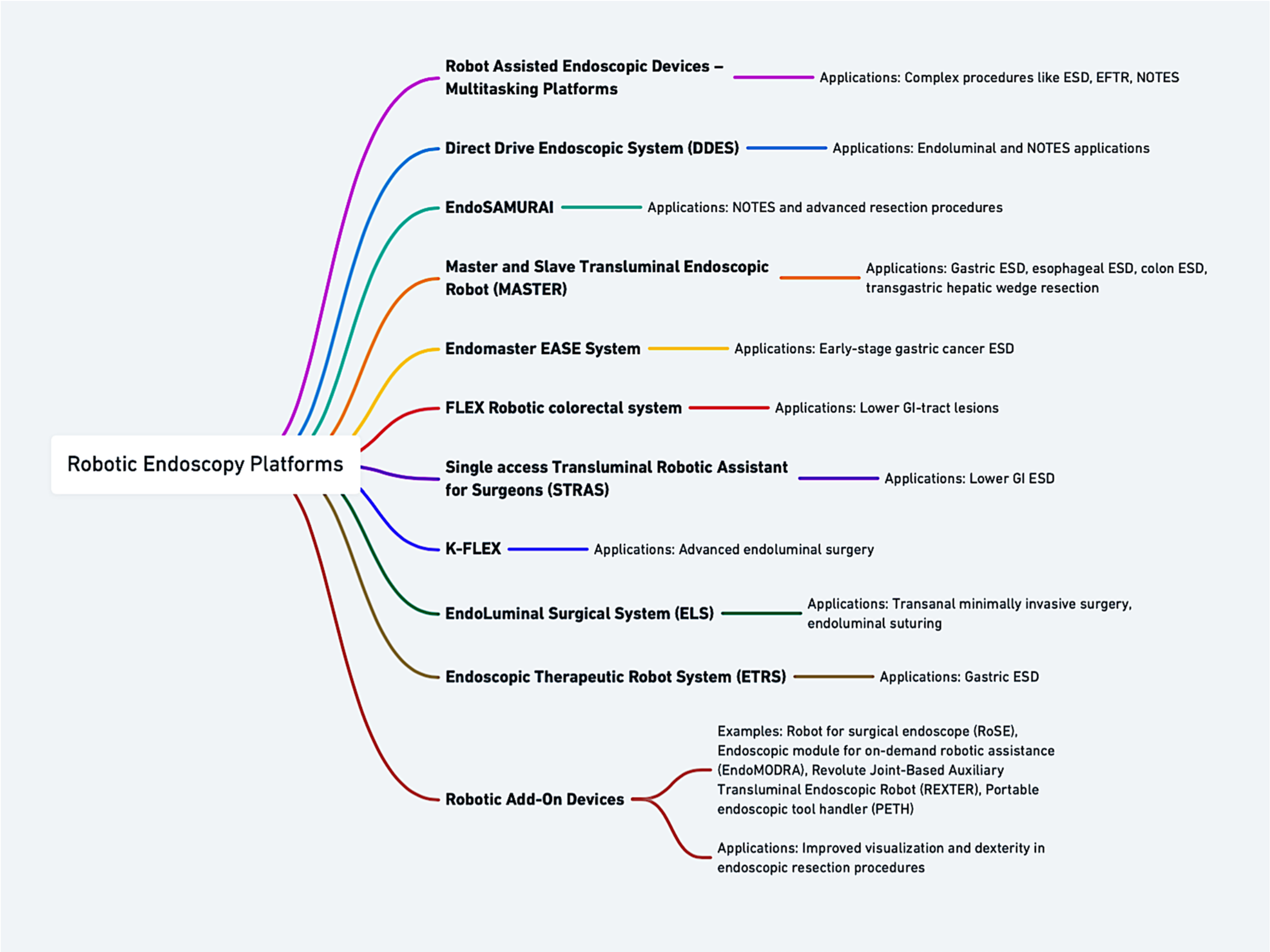


Fig. 1 Overview of different types of robotic endocscopy platforms

capable of triangulation, cutting, grasping, suturing and knot tying [14, 15]. DDES is no longer actively available in the market.

EndoSAMURAI EndoSAMURAI (Olympus Medical Systems, Tokyo, Japan) system has two articulated arms and five DOFs mounted on the tip of a 15-mm caliber endoscope with an accessory channel [16]. The manipulation of the system requires two operators one each for maneuvering the endoscope and the articulated arms, respectively [17]. Animal studies suggest the feasibility of EFTR and NOTES using this platform. In addition, suturing could be effectively performed, a must have feature for advanced resection procedures [18]. There have been no recent updates on the EndoSAMURAI system and it appears to be discontinued (Fig. 2).

Master and slave trans-luminal endoscopic robot Master and Slave Robotic Endoscopy System (EndoMaster Pte Ltd., Singapore) is a robotic endoscopy system equipped with two arms, one featuring a mounting grasping forceps and the other an electrocoagulation hook. These arms are designed to be delivered through the channels of a wide-calibre endoscope, enabling a high degree of manoeuvrability and precision in endoscopic procedures [19]. The operation of the MASTER system necessitates two operators: one to manoeuvre the endoscope and another to control the robotic arms via a remote master console. This dual-operator setup underscores the complexity and sophistication of the system, allowing for precise control during procedures.

The feasibility and effectiveness of ESD using the MASTER system have been demonstrated in ex vivo and in vivo trials in porcine stomach models [20, 21]. In an ex vivo porcine study, the use of MASTER enabled the novice without endoscopy experience to complete the ESD procedure [22]. One of the landmark achievements was its application in a pivotal pilot clinical trial in 2012, which involved five cases of early-stage gastric cancer [23]. This marked the first instance of robotic ESD being performed on humans, showcasing the system's potential for enhancing surgical outcomes in GI oncology. Beyond gastric ESD, the versatility of the MASTER system has been explored in other procedures such as EFTR, esophageal ESD, colon ESD and transgastric hepatic wedge resection, in animal studies [24]. These applications suggest a broad potential impact of the MASTER system across various domains of GI surgery.

The first generation of the MASTER system had notable limitations such as the inability to exchange devices during procedures. To address these limitations, an updated version known as EndoMaster EASE (Endoluminal Access Surgical Efficacy) has been developed. The EndoMaster EASE aims to enhance the system's functionality and usability, making it a more versatile tool for endoscopic surgery.

Endomaster EASE system The Endomaster EASE System (EndoMaster Pte., Singapore) was the first robot to clinically implement ESD for early-stage gastric cancer. It is a traction wire-driven system mounted on a double-channel endoscope (GIF 2T240, Olympus, Tokyo, Japan) [20]. It has two robotic arms with nine DOFs and a separate working channel for standard endoscopic instruments [25]. This is a dual-operator system for controlling the robotic arms from the console and regulating insufflation and suction from an independent endoscopic platform [2]. The left arm has been designed for retraction and the right arm for dissection using endoscopic instruments with different end effectors (i.e. grasper, electrocautery hook, needle holder) [26].

Initial animal studies have concluded technical feasibility in gastric full-thickness resection, hepatic, gastric and colorectal ESD [21, 22, 27]. In humans, a multicentre prospective study showed that ESD was effectively carried out in five patients with early-stage gastric neoplasia within 16 minutes (ranging 3–50 minutes) without peri-operative adverse events and 100% R0 resection [23]. The major limitations of this system is limited manoeuvrability linked to the dimensions of the unit, long assembly time of the robotic system and the inability to exchange instruments [12, 28]. Because of the wire-driven actuation mechanism, hysteresis and non-linear backlash are the concern apart from need for two operators to coordinate movements and inability to sterilize the robotic arms [6, 29] (Fig. 3).

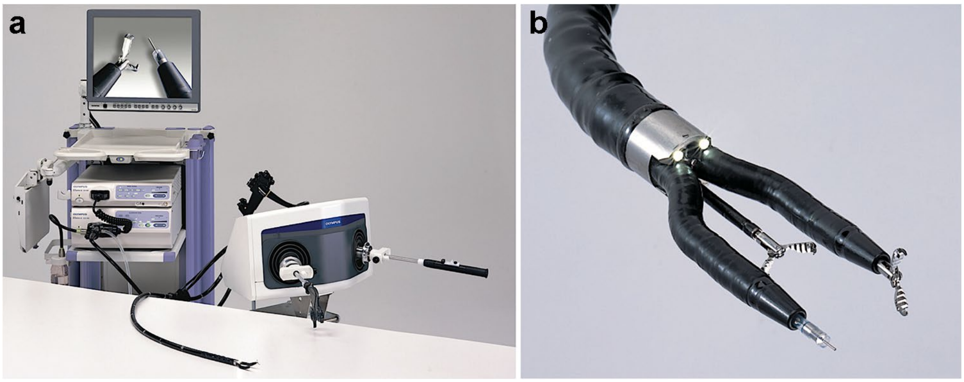


Fig. 2 **a** EndoSAMURAI multitasking robotic platform [16]. **b** The insertion part of the EndoSAMURAI

FLEX robotic colorectal system The Flex Robotic System (Medrobotics Corporation, Raynham, MA, USA) was initially developed for head and neck surgery and subsequently adopted for GI procedures after several modifications [30]. It is the first FDA-approved endoscopic robotic platform in 2017. This system was developed for lesions of lower GI-tract and can access up to 25 cm from the anal margin [31]. The Flex Robotic System is a single operator system, which includes an operational console with joystick controllers and a magnified high-definition display and a mobile cart that holds the Flex colorectal drive. The scope is provided with two 4-mm working channels and several accessories can be used [6, 13, 31, 32]. The University of Kentucky recently acquired this system.

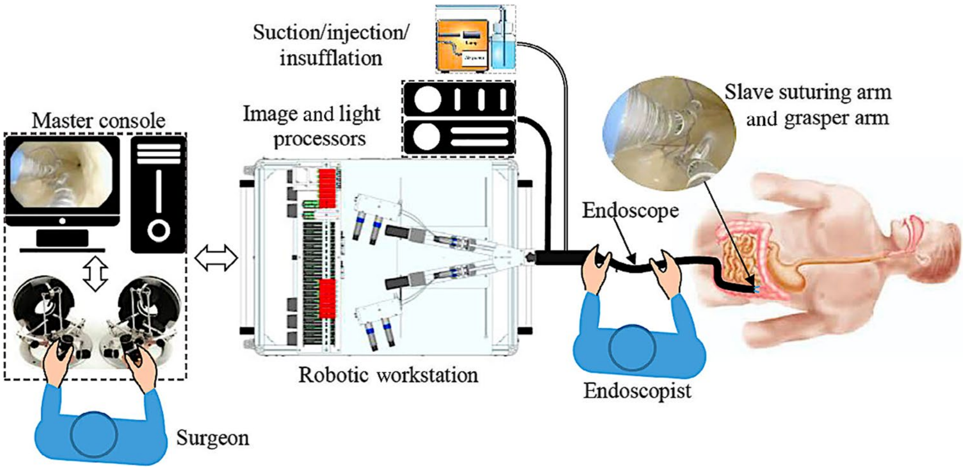
A study on cadaveric models found that the Flex system alone has the ability to provide adequate insufflation, visualization, range of motion and control of movements enabling the operators to perform various types of NOTES [10]. In a recently published pilot randomized controlled study comparing conventional ESD vs. robotic-assisted ESD, the FLEX system was associated with a higher percentage of en bloc resections with a lower procedural time (34.1 vs. 88.6 minutes, $p=0.001$) and a lower rate of perforations (30% vs. 60%, $p=0.18$) [33]. The limitations of this device include large external diameter hindering its insertion into the upper GI tract and inability to access deep lesions in the colon [34] (Fig. 4).

Single-access transluminal robotic assistant for surgeons The Single-access Transluminal Robotic Assistant for Surgeons system (Karl Storz, IRCAD, Tuttlingen, Germany) is the robotic version of the manual Anubiscope, a custom flexible endoscope. EASE is the latest version of STRAS, composed of master–slave system and requires two operators [28, 35]. The system consists of a mobile master console and a detachable endoscope. The endoscope measures 53.5 cm in length and has three working channels (two 4.3 mm for robotic instruments, one 3.2 mm for conventional endoscopic instruments). The master console consists of joysticks and four-way thumb switches to control the endoscope. This system provides 10 DOFs. The operating surgeon is provided with two screens to visualize the endoscopic image as well as the 3D reconstruction image of the operating field. This system has been developed for lower GI ESD [9, 28, 35] (Fig. 5).

In a comparative study on in vivo porcine models, robot-assisted ESDs performed by a laparoscopic surgeon were compared with conventional ESD by an experienced endoscopist. Robot-assisted procedures were associated with a lower risk of perforation (5% vs. 33.3%; $p=0.041$) as well as reduced dissection and procedure duration [36].

Fig. 4 Flex robot system [32]

Fig. 3 Endoluminal Access Surgical Efficacy system (EndoEASE) [25]



K-FLEX K-FLEX (KAIST, Daejeon, Korea) is a robotic platform for advanced endoluminal surgery. This system composed of a master console, driving robot arm and a bendable overtube with two surgical instruments. The robot arm allows two independent bends at an angle more than 100° in each direction allowing precise movements. The master console monitor has a graphic simulator locating the robot arm in GI tract [37, 38]. One limitation of this system is hindernce of the operative by the robotic arms suggesting the requirement of further miniaturization and design modifications.

EndoLuminal surgical system Conceptually, EndoLuminal Surgical System (EndoQuest Robotics., Houston, TX, USA) is similar to other robotic platforms except that it has a separate channel for independent control of a 6-mm endoscope with three DOFs. In addition, it has two instrument channels for wristed robotic instruments, two insufflation channels and one working channel. ELS is specifically designed for trans-anal minimally invasive surgery up to 55 cm from the anal verge. Besides resection, endoluminal suturing can be performed using this device. In a pre-clinical study, Atallah and colleagues demonstrated the feasibility of resection and endosuturing using ELS device [39]. Importantly, the procedure time was substantially shorter in the latter 10 lesions indicating a short learning curve for this system.

Endoscopic therapeutic robot system ETRS is a master–slave type robotic endoscopy system. It allows operation of the regular endoscope and articulated instruments (articulated forceps, an articulated needle knife) remotely via a multitasking console [40]. The main advantage of this system is ability to control the endoscope movements without holding the endoscope itself. Although the system is still at the conceptual modeling level, it has been demonstrated that gastric ESD can be remotely completed without any on-site assistance in ex vivo pig stomach models [40].

Flexible auxiliary single-arm transluminal endoscopic robot system The Flexible Auxiliary Single-Arm Transluminal Endoscopic Robot System (FASTER) system is composed of a robotic arm with three DOFs, drive housing and manipulating console. This system is attached to the tip of the endoscope and has been mainly designed to provide traction during ESD. Manipulation of the endoscope and the robotic arm for traction requires two operators. In vivo animal studies suggest a significant reduction in the sub-mucosal dissection time and less risk of injury to muscularis propria [41, 42].

Da Vinci single port system Da Vinci Single Port (SP) System (Intuitive Surgical, Sunnyvale, CA., USA) has a single port through which two or three working arms as well as a camera can be inserted [43]. The three working arms of the DaVinci SP allows for simultaneous dissection and retraction/counter-traction as well as use of suction. As compared to the multiport system (Da Vinci Xi system), this system allows more mobility during dissection in rectum. This system has been used for intra-abdominal colectomies, proctectomies and more recently trans-anal minimally invasive surgery (TAMS) [43]. Initial studies suggest the safety and utility of Da Vinci SP platform for the management of colorectal neoplasia [43, 44]. A notable limitation of this platform is inability to resect rectal lesions which are very close to the anal verge or the anal sphincter.

Robotic add-on devices

Robotic add-on devices are attached to the conventional endoscopes for better visualization and dexterity while performing endoscopic resection procedures. Some examples of these devices include robot for surgical endoscope (RoSE, Endorobotics, Seoul, Korea), endoscopic module for on-demand robotic assistance (EndoMODRA, Harvard University, Cambridge, MA, USA), Revolute Joint-Based

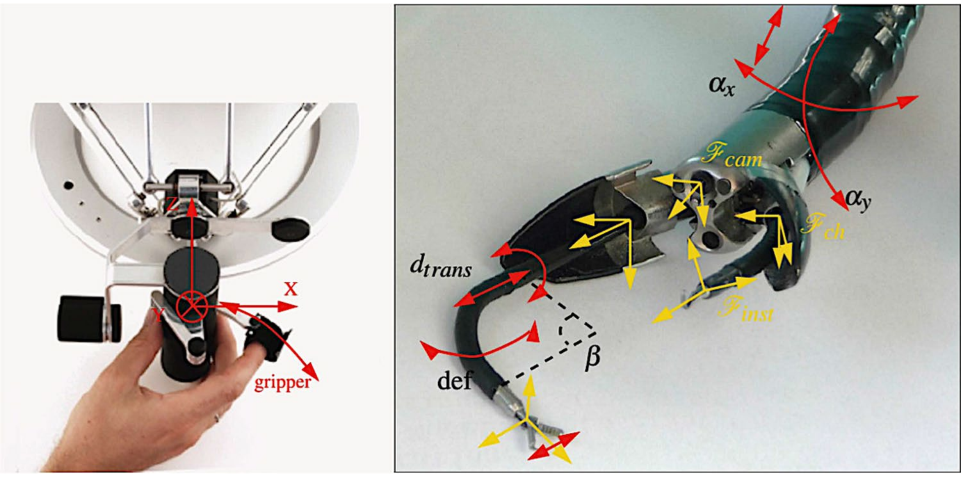


Fig. 5 Single-access Transluminal Robotic Assistant for Surgeons (STRAS) [28]

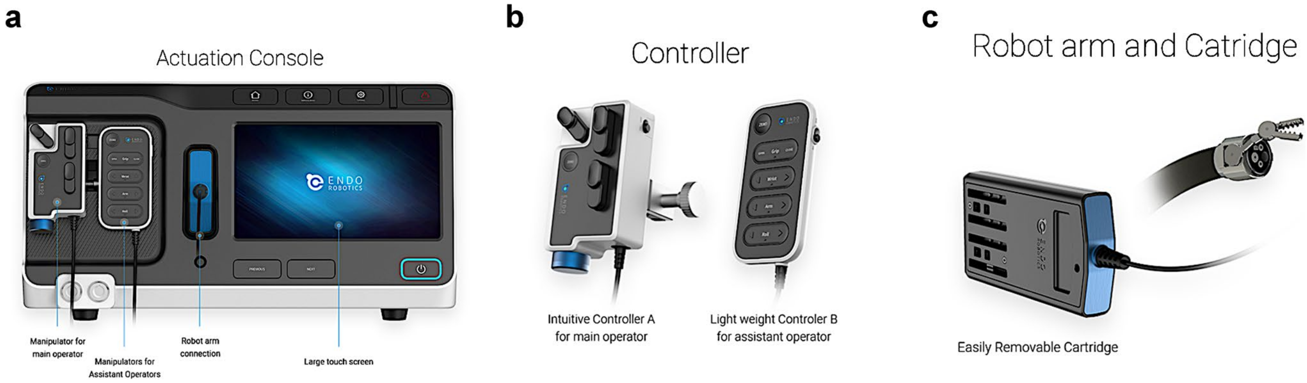


Fig. 6 Robot for surgical endoscope (RoSE). **a** Actuation console. **b** Controller. **c** Robot arm and cartridge

Table 1 Different types of endoscopic robotic multitasking platforms

	Developer	Key features	Clinical trial	FDA approval	Indications	Limitations
EndoSAMURAI	Olympus Medical Systems, Tokyo, Japan	OD 15 mm, DOFs 5, dual operators	In vivo and ex vivo animal	No	EFTR, NOTES	Difficult manoeuvring due to long tip portion, limited accessory devices, no water jet function, time lag due to wired control arms
MASTER	EndoMASTER Pte., Singapore	9 DOFs, two channels, dual operators	Ex vivo, in vivo, human case series	No	ESD, EFTR, NOTES	Lack of ability for instrument exchange, requirement of an overtube to protect the esophagus, large external actuator and bulky control units
Direct drive endoscopy system	Boston Scientific Corp., Natick, MA, USA	OD 22 mm, 7 DOFs, dual operators	In vivo and ex vivo animal	No	NOTES	Large size, does not allow high-flow insufflation or suction/irrigation, parallel channel configuration and torque strength affect procedural efficiency
ISIS-Scope/STRAS system	Karl Storz/IRCAD, Europe	OD 18 mm, 10 DOFs, three channels, dual operators	In vivo animal	No	ESD	Development halted
K-FLEX	EasyEndo Surgical, Daejeon, Korea	OD 17 mm, 14 DOFs, two working channels, single operator	Ex vivo	No	ESD	Visibility of the operative field hindered by robotic arms, further miniaturization and design modifications required
FLEX robotic system	Medrobotics, Raynham, MA, USA	OD 28 mm, two working channels, single operator	Ex vivo and clinical case series	Yes (2017)	ESD, EFTR, NOTES	Limited access in colon due to large size (up to 20 cm)
Endoluminal Surgical system (ELS)	ELS; Colubris MX, Inc., Houston, TX, USA	OD 22 mm, 7 DOFs, single operator	Ex vivo animal	No	ESD	NA

DOFs degrees of freedom, *EFTR* endoscopic full thickness resection, *ESD* endoscopic sub-mucosal dissection, *NA* not available, *NOTES* natural orifice trans-luminal endoscopic surgery, *OD* outer diameter

Table 2 Limitations of the current robotic platforms

1	A majority of the devices tested only in ex vivo or in vivo animal models; real-time efficacy not well known
2	Training required for manipulation of the robotic instruments; learning curve not known
3	Expertise still required in conventional ESD in case conversion is required
4	Optimum indications for the robotic endoscopic procedures remain to be defined
5	Cost-effectiveness data not available
6	Large size and rigidity of many devices hinder access to upper GI tract and proximal colon
7	Although effective resection is possible, efficacy in suturing needs to be evaluated before wider adoption of robotic endoscopy in procedures like NOTES and EFTR

GI gastrointestinal, *NOTES* natural orifice trans-luminal endoscopic surgery, *EFTR* endoscopic full thickness resection, *ESD* endoscopic submucosal dissection

Auxiliary Transluminal Endoscopic Robot (REXTER) and portable endoscopic tool handler (PETH, KAIST; Korea Advanced Institute of Science and Technology, Daejeon, Korea) (Fig. 6).

The benefits of using these add-on devices extend to their cost-effectiveness and straightforward operation, characterized by effortless attachment and detachment procedures. However, they fall short in terms of instrument triangulation and tissue manipulation capabilities when compared to the advanced robotic endoscopic multitasking platform.

Applications of robotic endoscopic platforms

The robotic endoscopy platforms have been predominantly developed to address the challenges associated with advanced therapeutic procedures, including ESD, EFTR and NOTES. While adequate visualization of sub-mucosal plane is crucial during ESD, robust closure techniques are paramount during EFTR and NOTES. In fact, lack of reliable closure methods for GI defects and the complexity of the technique resulted in dampening of the initial enthusiasm generated with NOTES procedure [45]. Endoscopic robotic platforms aim to address the technical difficulties in performing these advanced endoscopic procedures by allowing maintenance of effective traction, providing triangulation of instruments and secure closure with suturing [13, 46]. Benchtop and in vivo studies in animals and to a limited extent in humans have demonstrated the potential of endoscopic robotic platforms in expanding the use of ESD and to a lesser extent NOTES [28, 33, 47]. In addition, several studies have concluded the feasibility of robotic ESD and EFTR in gastric lesions with the advantages of shorter procedural time, less variability around resected margins' depth and laterality as compared to the conventional techniques [48, 49].

Current limitations and future directions

The integration of robotics into endoscopy represents a significant advancement in the field, offering solutions to the limitations of traditional endoscopic procedures. The adoption of the master–slave robotic concept has facilitated complex therapeutic procedures by providing enhanced precision, flexibility and safety. These robotic systems not only aid in reducing the difficulty of performing intricate therapeutic interventions, but also offer novel approaches to managing procedural complications. The end users of endoluminal robotic platforms are likely to be both gastroenterologists (ESD, EFTR, endosuturing) and surgeons (NOTES and full thickness resection) (Table 1).

Despite their intuitive design, these systems exhibit several significant limitations. They are generally large and complex, as well as costly and cumbersome to operate, due in part to the need for frequent docking and undocking during procedures. Additionally, the numerous cables within the robotic endoscope contribute to a considerable amount of hysteresis, leading to delayed responses in the surgical field [13, 26]. One of the main challenges with current robotic endoscope platforms is their limited range compared to flexible endoscopes. Flexible endoscopes have the advantage of being able to navigate through the upper GI tract and colon with relative ease due to their flexibility and manoeuvrability. Robotic endoscope platforms, on the other hand, often face constraints in terms of range and manoeuvrability, particularly when it comes to accessing various parts of the GI tract. This limitation can stem from the need to balance enhanced manoeuvrability with the size constraints of the robotic platform. Reducing the size of these platforms while maintaining or improving their manoeuvrability is indeed a significant engineering challenge. Needless to mention regarding the special considerations for modification of the endoscopy units deploying endoluminal robotics. Since adequate clearance around the robotic system is necessary to allow for the movement of robotic arms and to ensure unobstructed access for staff, the deployment of robotic platforms would demand spacious rooms to accommodate the robotic system and ancillary equipment (Table 2).

Future directions

The future of robotic endoscopy is contingent upon addressing these limitations. In addition, future studies are required with respect to their clinical validation, training and the exploration of new applications. Clinical safety, efficacy and cost-effectiveness must be demonstrated through comprehensive human trials to ensure the viability of robotic systems over traditional methods. Moreover, the development of advanced training opportunities, particularly those incorporating artificial intelligence (AI) and virtual reality, is essential to equip operators with the necessary skills to effectively utilize these technologies. The integration of AI into robotic endoscopy has the potential to revolutionize the field of robotic endoscopy by enhancing precision of the robotic arms, improving diagnostic accuracy and optimizing procedural efficiency. In robotic endoscopy, AI can detect and track surgical instruments, identify surgical phases and recognize tissue planes. AI can potentially support more complicated tasks such as procedural assistance, semi-automated device movements and surgical decision-making assistance [50].

Finally, identifying new clinical applications such as NOTES will be crucial in expanding the utility and impact of robotic endoscopy.

Future directions in robotic endoscopy should focus on overcoming these challenges through innovation in technology, training and clinical research. This includes the continuous improvement of robotic platforms to enhance their functionality and usability, the creation of more comprehensive and accessible training programs and the conduct of rigorous clinical trials to establish the benefits and cost-effectiveness of robotic endoscopy. Additionally, exploring new clinical applications and procedural techniques will further solidify the role of robotics in transforming endoscopic surgery. As the field progresses, collaboration between technology developers, clinicians and researchers will be key in harnessing the full potential of robotics in endoscopy to improve patient outcomes.

Author contribution Zaheer Nabi: conceptualization, methodology, writing—original draft preparation; Manchu Chaithanya: data curation; writing—review and editing; visualization; D. Nageshwar Reddy: supervision, final review of the manuscript. All authors have read and agreed to the published version of the manuscript.

Data availability Yes.

Declarations

Conflict of interest ZN, CM and DNR declare no competing interests.

Human ethics Not applicable (This is a review manuscript).

Consent for publication Not applicable.

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