Soft Everting Robots for Medical Applications: A Review

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***Abstract*— Soft Everting Robots (SER) are a subclass of soft robotic systems that move by body eversion, enabling highly compliant and adaptive locomotion. These properties make them attractive for medical use, particularly in endoluminal procedures such as colonoscopy or vascular navigation. A structured literature review was performed following the PRISMA methodology. In total, 50 publications were identified that explicitly investigated SER in medical contexts. The publications were categorized by application area, technical design aspects, and reported challenges. Recurring issues include safe interaction with delicate tissue, prevention of leakage, miniaturization to anatomical constraints, sterility and reusability concepts, and reliable navigation in tortuous pathways. SER are additionally compared against related technologies – as these often surface in SER-related searches and can be confused with SER approaches – and the commercialization landscape is briefly outlined. By consolidating these findings, the review provides a structured overview of the state of the art and outlines guidelines for design, control, and the potential future clinical implementation of SER.**

***Index Terms*— medical robotics, soft robotics, colonoscopy, endoscopes, robot control**

I. Introduction

A. Motivation

SOFT robotic systems have gained relevance in biomedical engineering due to their intrinsic compliance, adaptability, and ability to interact safely with fragile tissue. Soft Everting Robots (SER) constitute a distinct subclass that advances through continuous eversion or inversion of its body [1], [2]. This growth-like locomotion enables access to narrow, tortuous pathways, as previously demonstrated in industrial inspection and search-and-rescue scenarios [3], [4].

In medicine, SER research is only beginning to consolidate into a systematic body of knowledge. Their compliant body and pressure-driven propulsion make them promising for endoluminal procedures such as gastrointestinal endoscopy (GI), bronchoscopy, and vascular navigation. Conventional flexible endoscopes and catheter-based robotic systems often struggle to combine atraumatic advancement and reliable maneuverability under strict anatomical constraints. In colonoscopy for example, shaft looping during insertion has been reported to account for up to 90 % of pain episodes and increases the risk of tissue damage and perforation [5]. Similarly, fibreoptic ductoscopy has seen limited adoption because existing platforms are unwieldy and insufficiently flexible to safely navigate the fragile mammary ducts [6]. SER, in contrast, advance without the need for pushing forces from the proximal end and adapt naturally to anatomical variability. Early comparative studies indicate that such characteristics may reduce interaction forces and procedural discomfort [7]–[9], potentially lowering sedation needs and decreasing operator workload – all factors that could translate into more consistent procedure quality and a smoother learning curve for clinicians [10].

Despite this potential, significant hurdles remain before clinical translation is feasible. Present prototypes face challenges in miniaturization, controlled navigation within complex anatomy, maintaining safe pressure thresholds, preventing

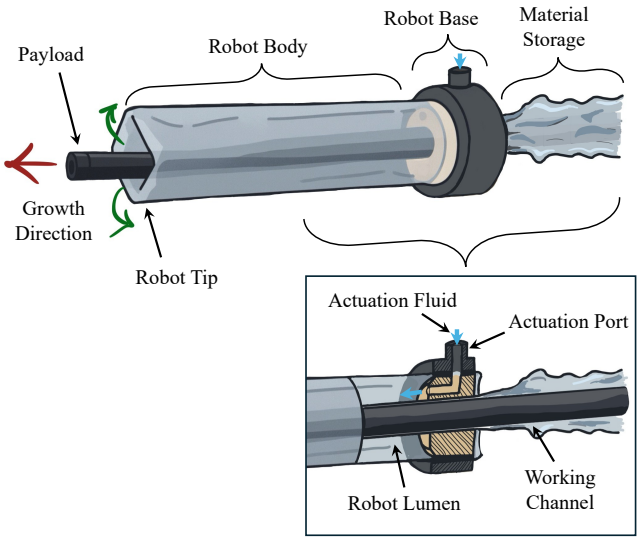

Fig. 1: Working principle of Soft Everting Robots (SER), shown in a schematic representation of an exemplary SER design illustrating eversion-based growth and the terminology used throughout this work. For clarity, the pressure chamber is omitted, although a majority of SER designs employ a pressure chamber containing the actuation components and preventing fluid leakage.

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leakage, and robust concepts for sterility and biocompatibility. Moreover, the dynamics of SER are highly nonlinear, demanding advanced models and control strategies. Although broad reviews on soft robotics and tip-growing robots exist, no systematic analysis has yet focused specifically on SER for medical use, leaving a relevant gap in the literature.

B. Objective

This review addresses the current lack of a dedicated synthesis on SER for medical use. It provides an overview of existing designs and experimental studies with a focus on medical applications and examines the technical, clinical, and translational challenges that currently limit progress. In addition, SER are discussed in relation to other soft robotic technologies, including balloon-assisted and capsule-based systems, to outline both their specific advantages and their limitations. The aim is to establish a structured foundation for future research and to support the further development of SER toward clinically viable solutions.

II. Background on Soft Everting Robots

A. Working Principle of SER

SER are a subclass of (soft) continuum robots that achieve locomotion through eversion, a process in which the robot's body material is turned inside out at its distal tip [2]. Common terms used for SER include *Vine Robots* [8], [11]–[17], *(Soft) Growing Robots* [6], [9], [18]–[22], *Eversion-Growing Robots* [19], [23], [24] and *Tip-Extending Robots* [25]. Less frequently used designations include *Everting Tubes* [26] and *Inverted Tubular Element Locomotion* [27]. The term *Toposcopy* for SER devices dates back to the mid-20th century but is no longer commonly used today [1], [28], [29]. In contrast to traditional continuum robots, where the entire body is pushed forward, a SER grows only at its tip, extending its length without relative movement between its outer surface and its surrounding environment. The robot body typically is made of a thin walled, flexible tube that is initially inverted in itself [2]. Although flexibility is required to enable smooth eversion, the tube material must also exhibit sufficient tensile stiffness to withstand the internal pressure during growth and maintain the structural shape of the outer body [12].

One end of the inverted foil is mounted at the stationary robot base (see Figure 1). Additional foil material passes through the base and is stored on the side facing away from the growth direction. This configuration creates a cavity on the side in growth direction that can be pressurized. When pressurized with a fluid, the inner layer unfolds at the distal end and becomes the new outer surface, causing the robot to extend forward from its tip. The already everted section experiences minimal relative motion, allowing the robot to advance smoothly while adapting its shape to environmental constraints and interactions. Due to this growth principle, SER can reach lengths many times greater than their initial packed configuration, allowing compact systems to explore large or tortuous spaces [2].

Because only the tip moves relative to its surroundings, SER can navigate through confined and tortuous pathways with minimal friction and shear forces [2]. This makes them particularly suitable for delicate environments such as the colon, airway, or vascular system, where conventional instruments pose a risk of tissue trauma. The eversion motion is fully reversible and is called inversion. Reducing internal pressure and applying a pulling force at the proximal end of the inlying material enables retraction of the robot body [30].

In addition to their inherently compliant and safe locomotion, SER can be equipped with features that enable controlled navigation and interaction with their environment. Depending on the design, this may include mechanisms for directional steering or integrated sensing to support precise and minimally invasive movement [2].

B. Terminology of SER

As described before, the general architecture of SER can be divided into several functional subcomponents. To ensure consistency throughout this work, the following terminology is defined and schematically illustrated in Figure 1. These definitions establish a common framework for discussing the structural components, operating principles, and comparative analysis of different SER systems.

The *robot body* refers to the thin-walled, flexible tube that forms the primary structure of the robot when inverted. The *robot base* denotes the stationary proximal section where the inverted body is anchored and the *actuation fluid* is supplied through an *actuation port* to the *robot lumen*. The robot base serves as the fixed reference point of the system and defines the growth direction, which extends distally from the base toward the environment. Additional material for growth of the robot body is stored behind the base, this section acts as *material storage* that determines the maximum reachable length of the robot and enables compact packing prior to deployment. At the distal end, the *robot tip* is the region where eversion occurs and new material unfolds, resulting in forward growth. Inside the body, a central *working channel* runs along the robot's longitudinal axis and remains separated from the pressurized robot lumen, enabling the transport or deployment of *payloads* – that is, devices, tools, or instruments used for diagnostic, therapeutic, or sensing purposes, such as endoscopic instruments, optical fibers, or fluid delivery systems.

III. Methods

A. Search Strategy

The review process was performed following the general principles of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which provide a standardized framework for conducting and reporting systematic reviews [31]. Search terms were grouped into three categories: (i) descriptors of the locomotion principle (everting, vine, soft growing), (ii) a device-related term (robot), and (iii) medical or clinical keywords (*oscopy, medical). Each search string consisted of exactly one term from each category, combined using the Boolean operator AND (i AND ii AND iii). Consequently, all possible term combinations across the three categories were systematically applied. Given the

interdisciplinary scope of medical technology, which spans engineering and clinical research, Google Scholar (Google LLC, USA) was used as the only search engine. The search included publications available up to October 2025. In total, more than 550 publications were initially identified and subsequently screened for inclusion according to the criteria described in subsection III-B. The reference lists of all included papers were then reviewed using the same criteria. Whenever new relevant studies were identified, their references were examined iteratively until no additional eligible publications were found. The entire selection process, including the number of records identified, reviewed, and ultimately included, is summarized in the PRISMA flow diagram, which can be found in Figure 2.

B. Inclusion and Exclusion Criteria

To keep the review focused on clinically relevant developments, clear inclusion and exclusion criteria were applied. Publications were included when they explicitly dealt with medical applications of SER in their design, experimental evaluation, or intended use. Typical examples were prototypes or design studies aimed at procedures such as endoscopy or vascular navigation. Publications were excluded if they mentioned medical use only as a possible future application without adapting the design or providing experimental evidence. Studies on other endoluminal robotic platforms such as continuum robots, balloon-assisted devices, or capsule endoscopes were not considered unless they provided a direct comparison with SER.

C. Classification

The publications that met the inclusion criteria were analyzed along three main dimensions. First, they were grouped by type of medical application. Second, they were examined in terms of technical design aspects, including actuation principles, materials, deployment mechanisms, and strategies for miniaturization or functional integration as well as control and navigation strategies. Finally, the challenges reported in each study were extracted.

IV. Results

In total, 50 publications were identified that met the inclusion criteria (see Table 1.1 and 1.2).

A. Medical Application Areas

The development of SER for medical use has been driven by the demand for safe navigation through tortuous, confined, and delicate anatomical structures while minimizing patient discomfort and tissue trauma [1], [9], [28], [50]. Based on the reviewed literature, the main medical application domains for SER can be grouped as follows (see Figure 3):

1) Upper and lower GI endoscopy
2) Endovascular procedures
3) Intraductal breast interventions
4) Airway management and bronchoscopy
5) Neurosurgical and spinal applications

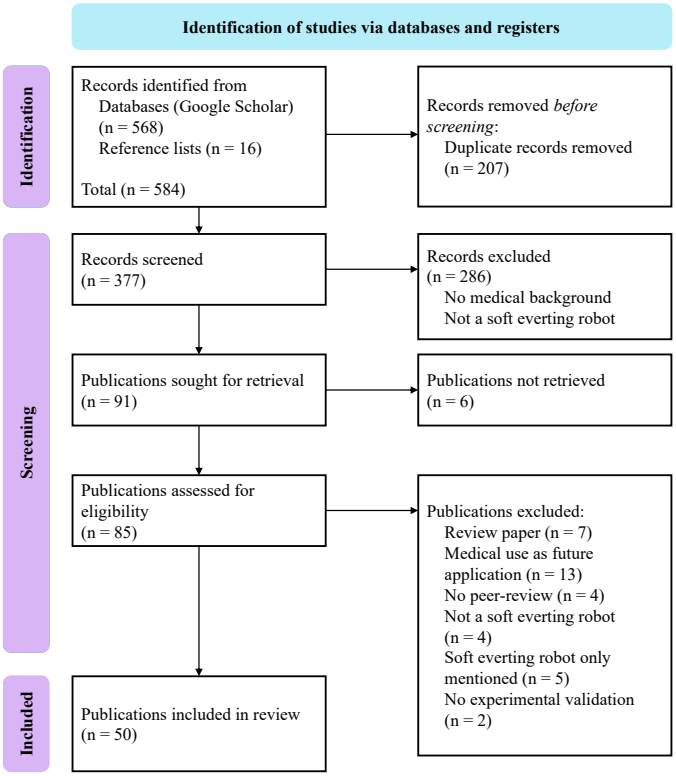

Fig. 2: PRISMA flow diagram for the systematic literature review conducted.

6) Other medical use cases

Each of these applications imposes specific anatomical and procedural constraints that SER would need to address. Many endoscopic and catheter-based procedures require instruments to follow small radii and complex 3D loops.

In colonoscopy, the sigmoid and transverse colon contain multiple sharp bends with centerline angles smaller than 90° [57], often combined with tight curvature, which in conventional systems can lead to looping, increased friction, and patient discomfort [12]. Beyond navigation alone, GI endoscopes must also provide access for diagnostic and therapeutic tools – such as biopsy forceps, needles, or snares – through a working channel typically 2–4.2 mm in diameter, while the overall device diameter commonly ranges between 5 and 15 mm [58]. Reasons for the greater overall device diameter are the needed incorporation of imaging, suction channels and the mechanism required for distal tip steering. To support these clinical functions, SER for GI applications would need to preserve a channel throughout eversion, enabling simultaneous imaging, insufflation, and tool delivery while minimizing wall stress and tissue strain. In miniaturized applications, for example in vascular, mammary, or spinal spaces, the required lumen size reduces substantially, demanding proportionally smaller working channels suitable for guidewires or microinstruments without compromising eversion performance.

Safe clinical operation requires precise control of internal pressure and tissue contact forces. Pressure ranges enabling a stable eversion and locomotion are described in subsection IV-B. However, several designs emphasize that operating pressure

TABLE 1.1: Reported work on Soft Everting Robots (SER) for medical applications. Publications are grouped thematically according to areas of application; the affiliation refers to the first author. Status of development and evaluation: Laboratory prototype (1; proof-of-concept testing under laboratory conditions), technical phantom testing (2; evaluation in artificial or anatomically representative phantoms), ex vivo biological testing (3; experiments on excised biological tissue), and clinical testing (4; in vivo evaluation).

Cat.	Reference	Affiliation	Medical Application	Material, thickness (in µm)	Dimensions (in mm); diameter ⌀, l length, $//w$ flat width	Pressure (in kPa)	Actuat. medium	System Design if available: system name, chamber/no-chamber design, steering method, payload/working channel, other features	Status
Upper and lower GI endoscopy	Borvorntanajanya et al., 2024 [32]	Imperial College London, GBR	Colonoscopy	PE, 60	⌀24	50	gas	pressure chamber, no payload, tip-cap with electromagnetic sensor for tracking	1,2
	Borvorntanajanya et al., 2025 [7]	Imperial College London, GBR	Colonoscopy	SCRN	⌀18	12.5-20	see [32]	pressure chamber, tip-mounted (intraluminal) pneumatically actuated steering device, no payload, tip-cap with pneumatic sensing pouches for measuring forces and providing haptic feedback	1,2
	Shi et al., 2025 [33]	Imperial College London, GBR	Colonoscopy	SCRN	⌀18, l 1600	10-17	see [32]	pressure chamber, see [7], no payload (but considered in design), see [7]	1,2
	Ahmed et al., 2025 [10]	Imperial College London, GBR	Colonoscopy	SCRN	⌀18, l 1600	20	see [32]	pressure chamber, see [7], no payload (but considered in design), see [7]	1,2
	Weinmann et al., 2024 [34]	Univ. of Stuttgart, DEU	Colonoscopy	LDPE, 50	⌀31.5, l 1500	14–30	gas	no pressure chamber, payload	1,2
	Dinkel et al., 2024 [35]	Univ. of Stuttgart, DEU	Colonoscopy	see [34]	⌀31.5	33	see [34]	no pressure chamber, payload	1,2
	Dinkel et al., 2025 [36]	Univ. of Stuttgart, DEU	Colonoscopy	see [34]	see [35]	n/a	see [34]	no pressure chamber, payload	1,2
	Dinkel et al., 2025 [37]	Univ. of Stuttgart, DEU	Colonoscopy	see [34]	see [35]	n/a	see [34]	no pressure chamber, steering via PAMs, payload	1
	Saxena et al., 2019 [27]	Pennsylvania State Univ., PA, USA	Colonoscopy	LDPE, 50/ 100/ 150	⌀48.5	0.4–3.5	gas	no pressure chamber, no steering, no payload, pressure supply in sealed robot body	1,2
	Saxena et al., 2020 [38]	Pennsylvania State Univ., PA, USA	Colonoscopy	PE, 51/ 76/ 102	⌀25.4, 38.1, 50.8	6.2–29.6	gas	no pressure chamber, no steering, no payload, pressure supply in sealed robot body	1,2
	Bell et al,. 1999 [29]	Sunderland Univ., GBR	Colonoscopy	PE	⌀30–40	< 69	liquid	pressure chamber, payload	1,2
	Pore et al., 2022 [14]	Univ. of Verona, ITA	Colonoscopy	latex and polymers	⌀38	15	gas	EndoVine, pressure chamber, no steering, payload	1,2
	Giri et al., 2025 [12]	Univ. of California, CA, USA	Colonoscopy	strecholon, 38	⌀27	12.4	gas	no pressure chamber, tip-mounted (intraluminal) pneumatically actuated steering device	1,2
	Kim et al., 2025 [9]	Korea Advanced Inst. of Science and Techn. (KAIST), KOR	Colonoscopy	n/a	⌀19–31 (25)	4–5	gas	pressure chamber, steering via fPAMs, payload	1,2
GI/Endovascular	Zeimer, Simkin, 1966 [1]	The National Physical Laboratory of Israel, Hebrew Univ. Campus	Gastroscopy, Colonoscopy	cellophane dialyzing tubes	⌀6.35–17.46	39.2–98.1	liquid	Toposcope, pressure chamber, payload	1,2,3
	Benjamin et al., 1986 [39]	Univ. of Louisville, KY, USA.	Endoscopic gastrointestinal dilation (esophagus, pylorus)	PE	⌀4, l 200	275.8	liquid	no pressure chamber, payload	1,4
	Manoj et al., 2023 [16]	TKM Inst. of Techn., IND	Gastroscopy	silikon based	n/a	n/a	gas	pressure chamber, tip-cap for endoscopic imaging	1,2
	Goldstein et al., 1983 [40]	National Inst. of Health, MD, USA	originally endovascular procedure, future idea: use for GI	LDPEUE, 60	⌀1, l 300	203	liquid	see [41]	1,2,4
	Shook et al., 1986 [42]	National Inst. of Health, MD, USA	Endovascular Procedures, Endoscopic retrograde cholangiopancreatography (ERCP)	LDPEUE, 64/ 84/ 103	⌀1, 1.3, 1.7, $l > 400$	65–101	liquid	see [41]	1,2,4
	Girerd et al., 2024 [20]	Univ. of California, CA, USA	Colonoscopy, Endovascular procedure	Dyneema, 21	⌀12.9, l 1500 / ⌀5.2, l 340	13.1–55	gas	no pressure chamber, payload, body material scrunched in tip	1,2
Endovascular procedures	Doppman et al., 1979 [41]	National Inst. of Health, MD, USA	Endovascular Procedures	LDPEUE, 70	⌀1, l 300	n/a	n/a	low-durometer aromatic polyester urethane elastomer (LDPEUE), toposcopic catheter, pressure chamber, everting body bonded to conventional catheter	1,2,4
	Goldstein et al., 1980 [28]	National Inst. of Health, MD, USA	Endovascular Procedures	LDPEUE, 70	⌀1	152–203	liquid	see [41]	1,2,4
	Li et al., 2021 [25]	Univ. of California, CA, USA.	Endovascular Surgery	PUCRN, 100	⌀3.5–5	200–300	liquid	VINE catheter, no pressure chamber, pre-shaped, payload	1,2
	Kim et al., 2025 [43]	Univ. of California, CA, USA	Endoluminal navigation / miniature vascular access	TPU	⌀5, l 300	18.2–34.5	gas	no pressure chamber, liquid cristal elastomer (LCE)-actuator based steering, no payload, control of robot body length via string	1,2
	Mangan et al., 2025 [21]	Univ. of California CA, USA	Endovascular emergencies	TPU, 20	⌀2.67, l 445	35–40	liquid	pressure chamber, payload, combined SER and notched continuum robot	1,2
	Krishna et al. [44]	University of California, CA, USA	Endovascular Procedures	TPU, 38	l 200	n/a	n/a	modeling of LCE-actuator based steering for a SER-system	n/a
Intraductal breast interventions	Berthet-Rayne et al., 2021 [6]	King's College London, GBR	Mammary duct endoscopy	LDPE, 35	⌀2.9, l 80	140	liquid	MAMMOBOT, pressure chamber, payload (steerable catheter for navigation)	1,2
	Wu et al., 2023 [19]	King's College London, GBR	Mammary duct endoscopy	see [6]	⌀3, l 140	110–150	see [6]	Physics-based model of MAMMOBOT [6], pressure chamber, payload (steerable catheter), duty-cycle growth,	1,2
	Wu et al., 2023 [45]	King's College London, GBR	Mammary duct endoscopy	see [6]	see [6]	105–135	see [6]	modelling, control, and autonomous steering of MAMMOBOT [6], payload (steerable catheter)	1,2
	Larrea et al., 2021 [46]	Univ. of Bath, GBR	Mammary duct endoscopy	see [6]	see [6]	0–150	see [6]	Modeling of MAMMOBOT [6], model validation based on experimental data	n/a
	Vartholomeos et al., 2024 [23]	Univ. of Thessaly, GRC	Mammary duct endoscopy	see [6]	see [6]	110–150	see [6]	modeling and model validation based on MAMMOBOT [6]	1
	Vyas et al., 2022 [47]	Imperial College London, GBR	Mammary duct endomicroscopy	see [6]	see [6]	see [6]	see [6]	endoscopic imaging unit used with MAMMOBOT [6]	1,2,3

TABLE 1.2: Reported work on Soft Everting Robots (SER) for medical applications. Publications are grouped thematically according to areas of application; the affiliation refers to the first author. Status of development and evaluation: Laboratory prototype (1; proof-of-concept testing under laboratory conditions), technical phantom testing (2; evaluation in artificial or anatomically representative phantoms), ex vivo biological testing (3; experiments on excised biological tissue), and clinical testing (4; in vivo evaluation).

Cat.	Reference	Affiliation	Medical Application	Material, thickness (in µm)	Dimensions (in mm); diameter ⌀, l length, $//w$ flat width	Pressure (in kPa)	Actuat. medium	System Design if availabe: system name, chamber/no-chamber design, steering method, payload/working channel, other features	Status
Airway management and bronchoscopy	Hwee et al., 2022 [8]	Univ. of Washington, WA, USA	Emergency airway management	LDPE, 50	⌀25.4	12–17.5	gas	pressure chamber, pre-shaped to anatomy, material on motorized spool	1,2
	O'Connor et al., 2024 [48]	Univ. of Washington, WA, USA	Emergency airway management	TPU, 50/100	⌀20	7.2–21.6	gas	pressure chamber, optional sealing cuffs, straight and anatomically pre-shaped versions, no payload	1,2
	Lewis et al., 2024 [49]	Univ. of Washington, WA, USA	Emergency airway management	LDPE, 50, TPU, 50/100	⌀13/20/25	10–25	gas	pressure chamber, optional sealing cuffs, pre-shaped TPU tubes for tracheal navigation	1,2
	Davy et al., 2025 [50]	Univ. of Leeds, GBR	Bronchoscopy	TPE, 38	⌀5, l 145	35	liquid	steering via internal magnetic fluid and external magnet, payload	1,2
	Davy et al., 2024 [13]	Univ. of Leeds, GBR	Bronchoscopy	LDPE, 20	⌀8, l 250	12	gas	magnetic silicone coating, external magnetic steering	1,2
Neurosurgical and spinal applications	Slade et al., 2017 [51]	Stanford Univ., CA, USA.	Nonspecific, Neurosurgery	LDPE, 13	⌀4, l 20	15.5–31	gas	no pressure chamber, pre-shaped robot body, payload (catheter, surgical wire)	1,2
	Song et al., 2023 [52]	Ecole Polytechnique Fédérale de Lausanne (EPFL), CHE.	Electrocorticography	PDMS	l 15, w 6	n/a	liquid	Polydimethylsiloxane (PDMS), multi-legged deployable Electrocorticography array	1,2,3
	Dimas et al., 2024 [22]	Univ. of Thessaly, GRC	Neurointerventional navigation (spinal subarachnoid space)	n/a	n/a	n/a	n/a	simulation based on the MAMMOBOT platform by Berthet-Rayne et al., 2021 [6]	n/a
	Wu et al., 2025 [53]	King's College London, GBR	Neurointerventional navigation (spinal subarachnoid space)	PTFE, 20	⌀20	100–125	liquid	pressure chamber, payload (endoscope, NiTi steerable tip, force sensor)	1,2
Other medical use cases	Putzu et al., 2019 [26], [54]	Queen Mary Univ. of London, GBR	Minimally invasive surgery	n/a	⌀18, l 1000	n/a	gas	no pressure chamber, payload (camera, tools)	1,2
	Kim et al., 2025 [15]	Korea Advanced Inst. of Science and Techn. (KAIST), KOR	Nonspecific endoluminal applications	SCRN, 60	⌀25	0–30	gas	pressure chamber, magnetic tip (camera, localization) and external permanent-magnet steering, payload	1,2
	Seo et al. 2024 [18]	Korea Advanced Inst. of Science and Techn. (KAIST), KOR	Nonspecific, frequent tool replacements	SCRN, 60	⌀130, l 200	0.6–4	gas	6 sub-vines, arranged in a circle creating a working channel structure, steering by differential sub-vine growth	1,2
	Watson, Morimoto, 2020 [17]	Univ. of California, CA, USA	nonspecific	SCRN	⌀12, l 645	170–200	gas	no pressure chamber, magnet at tip for localization with external sensor array	1,2
	Alvarez et al. 2025 [11]	Univ. of California, CA, USA	Transdermal drug delivery	TPU, 50–200	⌀6–24, 12, l 5–400	3–62	gas	pressure chamber, payload, model and validation of high-speed eversion	1,2
	Al Harthy et al., 2024 [24]	King's College London, GBR	Nonspecific, neuro-interventional, endovascular	LDPE, 30	⌀6.4, l 60	10–35	liquid	pressure chamber, payload (steerable catheter), low melting point alloy as actuation fluid	1,2
	Kishino et al., 2025 [55]	Chuo Univ., JPN	Cystoscope insertion (urethra, prostate, bladder)	LDPE, 60	⌀6, l 200	70–90	gas	optional pressure chamber, payload (cystoscope)	1,2
	Gong et al., 2025 [56]	Univ. of Washington School of Med., WA USA	Rapid Wound Packing	TPU, 50	w 30-80	6.1–20.7	gas	pressure chamber, no payload	1,2

must remain below a safe level, yet clinical safety thresholds for intraluminal pressure are not quantified and remain to be validated [6], [8], [50]. Across applications, safe tip-force limits are highly application-dependent. In vascular settings, forces above 2 N may risk arterial rupture [25], whereas conventional colonoscopes often generate substantially higher insertion and tip forces (typically 5–20 N), especially in the sigmoid colon and rectum [7], [9], [10]. Preliminary studies suggest that the compliant, pressure-driven nature of SER could inherently enable operation within these physiological limits [7], [9], [10].

Time-critical procedures such as airway management or hemorrhage control demand fast and repeatable deployment. Hwee et al. demonstrated that everting airway devices can autonomously navigate through airway anatomy [8], while Gong et al. showed that everting tamponades rapidly conform to and pressurize irregular wound cavities [56]. Such self-deploying behavior could minimize specialized operator training and enable use in emergency or low-resource settings.

B. Design and Technical Aspects

1) Dimensions: Reported SER dimensions span a wide range aligned with their target anatomies. Miniaturized systems for ductal or vascular access operate at 1–5 mm outer diameter [41], [43], [45], intermediate designs for catheter-like GI or airway navigation fall within 4–10 mm [13], [43], [50], and large prototypes for colonoscopy or wound packing reach 15–50 mm [8], [9], [12], [34]. Across studies, a qualitative scaling trend can be observed. Systems with smaller outer diameters tend to exhibit shorter achievable eversion lengths from a few hundred millimeters [6], [19], [55], whereas larger-diameter prototypes more frequently demonstrate meter-scale deployments (about 1500–1600 mm) [10], [33], [34]. This is partly due to the corresponding medical application, the system size and the potentially limited material storage volume, as well as lower wall stiffness with smaller diameters (subsubsection IV-B.4).

2) Materials and Manufacturing: Across the literature, SER bodies are predominantly made from thin films – most commonly low-density polyethylene (LDPE) [6], [8], [13], [34], thermoplastic polyurthane (TPU) [11], [43], [56], thermo-

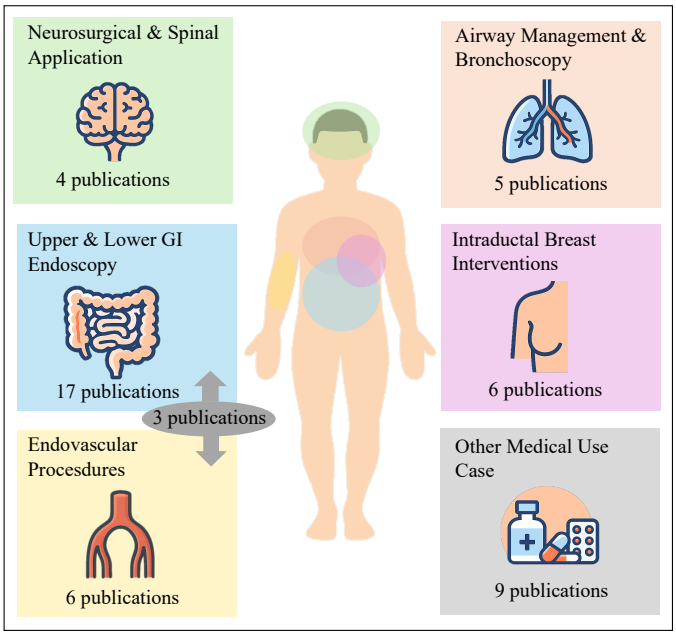

Fig. 3: Identified medical application areas of Soft Everting Robots (SER) and number of identified publications.

plastic elastomer (TPE) [50], silicone or polyurethane-coated ripstop nylon fabric (PUCRN/SCRN) [7], [15], [25] – selected for low compliance, high flexibility, and compatibility with simple thermal manufacturing processes.

Reported film thicknesses cluster around 20–60 µm across all scales and the thickness is inherently coupled to SER size, with smaller diameters requiring thinner membranes to preserve flexibility and enable reliable low-pressure eversion. Miniaturized systems use e.g. 35 µm thick LDPE foil [6], whereas larger protoypes tend to use thicker films of 50 µm [34], [49].

Manufacturing of SER remains dominated by manual or semi-manual processes. Recent work has introduced partially automated fabrication methods – such as 3D-printer-based thermal bonding [37], [56], laser welding [7], and heat-sealing presses [6], [9], [48] – to improve repeatability and enable complex geometries. With these techniques, thin polymer sheets are fabricated to tubular geometries, using fin or lap seams that differ in strength and compliance [6], [48].

Biocompatibility is generally inferred from the use of established commodity polymers, though formal certification and validated sterilization pathways remain largely unaddressed [33]. Thin LDPE films are considered to be suitable only for single-use operation.

3) Structural Architecture and Payload Integration: SER architectures fall into two main groups: systems based on a *pressure chamber* and chamber-less designs. A majority of the reported SER employ a chamber that contains actuation components and material storage, accounting for 25 out of the 39 publications that specify this feature. Chamber-less designs therefore represent a minority within the current literature (e.g., Weinmann et al. [34]). Among chamber-based setups, some place all components inside the pressurized domain, while others keep the working channel externally accessible and separated from the pressure region. These architectural decisions directly shape material storage and payload handling. When the material is stored entirely inside the pressurized region, it is typically rolled [1] or scrunched [15], and any payload must be co-stored and co-conveyed. If the working channel remains open to the outside, payloads can be introduced externally without pre-rolling, enabling more flexible tool use and exchange [6], [14], [35].

4) Actuation: SER rely on pressure-driven actuation to initiate and maintain tip extension. In the publications considered, pneumatic systems represent the dominant actuation strategy, accounting for 29 out of the 47 publications that specify an actuation medium [9], [34], [55], while the remaining systems are hydraulically actuated [6], [21], [25], [53]. For both actuation media, most systems operate in a relatively narrow pressure range between the onset of eversion and material failure. The correlation between the eversion pressure requirements and the robot dimensions across the considered studies is synthesized in Figure 4. The data indicates that miniaturized SER for vascular use (<5 mm) consistently require higher pressures of approximately 100–200 kPa to exhibit stable eversion [11], [24], [34], [43], [48]. In contrast, larger GI-scale robots (20–50 mm) require initiation pressures above 5 kPa and operate at lower ranges from 5–35 kPa, though they face greater challenges in buckling stability [6], [28]. As further illustrated by the color-coded wall thickness t in Figure 4, this characteristic shift is driven by the ratio between wall thickness and diameter (t/d). While GI-scale robots can afford higher t/d ratios to ensure membrane robustness, smaller SER are pushed towards minimal ratios to maintain bending flexibility in tortuous vessels, which in turn increases the risk of rupture due to the high actuation pressures needed.

Across scales, these narrow operational windows underscore the need for accurate pressure regulation and integrated overpressure protection. Systems using low-melting-point alloys additionally couple actuation with stiffness modulation, requiring coordinated control of pressure and temperature [24]. No systematic correlation was observed between the choice of actuation medium and the presence or absence of a pressure chamber architecture.

5) Steering Mechanisms: To faciliate cross study comparison, the 19 publications that mentioned hardware concepts enabling directional steering in SER were examined with regard to their stated performance indicators and measurement methods. Across these approaches, steering mechanisms can generally be categorized according to the location at which they act:

1) Attached or embedded directly on the robot body,
2) positioned inside the robot lumen,
3) or applied through the working channel.

These concepts fundamentally determine achievable curvature, steering range, scalability, and system complexity, which are typically quantified using metrics such as maximum bending angle, curvature, or bending radius (Table 2). The quantitative analysis of these steering methods reveals a heterogeneous landscape of performance metrics. Steering locations reveal a clear dependency on the robot's scale and its intended clinical application. For larger GI-scale SER, the internal

volume allows for the integration of intraluminal steering modules, such as pneumatically actuated bending segments. These systems typically achieve high bending angles between 130° and 201.8° [12], [33], which are essential for sharp bends of the intestine. In contrast, the limited internal space in miniaturized applications (e.g. endovascular or bronchoscopic applications) with decreasing device diameters requires a shift to alternative strategies. These include pre-shaped SER bodies that have been adapted in advance to the desired anatomy [25], [51], or payload-controlled steering [6], [13]. While these miniaturized approaches often specify performance in terms of minimum bending radii (38.5–49.5 mm) or specific curvatures, they reflect a design trade-off in which the challenge of control is shifted from the robot to the payload or environment in order to maintain scalability. Performance is frequently first evaluated in tip deflection tests under idealized conditions, and subsequently assessed in anatomical phantoms to better approximate in vivo constraints [6], [12], [15], [43], [50].

Given the central importance of directional steering for SER functionality, the underlying mechanisms, representative examples, and associated control concepts are discussed separately in subsection IV-C.

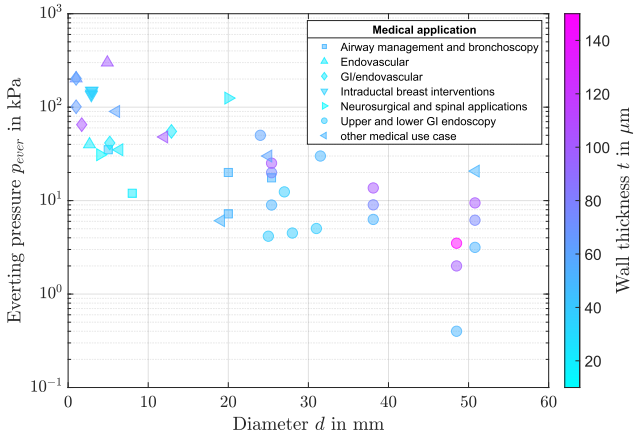

Fig. 4: Soft Everting Robots (SER) design space and clinical scaling. Scatter plot illustrating the synthesis of maximum eversion pressure p_{ever} versus robot diameter d. Marker shapes categorize the studies by the medical application area, while the color gradient indicates wall thickness t in μm. Individual studies may contribute multiple data points, representing various tested design configurations.

6) Functional Integration / Sensing: Functional tool integration tailored to specific medical procedures remains limited, and no comprehensive solution has yet been established. The challenge in this area lies in the migrating distal SER tip inherent to the eversion mechanism. Additional mechanisms are required to enable fixation of cameras, instruments, and sensors for position or force measurements at its tip. One approach is to use passive intraluminal tubes as payloads in the SER for tool or fluid delivery [20]. These tubes can be equipped with dedicated tip caps to maintain alignment between the tube and robot body during retraction [9], and allow the integration of wired sensors [50]. Alternatively, ring structures positioned within the robot lumen can travel along the inner robot body layer originating from the material section [17]. External distal tip mounts and caps with integrated tools and sensors have also been proposed. These are rigid elements that guide the robot body through them and mechanically define the distal tip of the robot [7]. The chosen integration strategy determines the available sensing modalities and thus directly constrains system observability and feedback control, as discussed in subsubsection IV-C.2.

C. Navigation and Control

In the following, we refer to *navigation* as the entirety of the task-level goal to move the SER tip to a desired target, which is a combination of perception, path planning, and execution. We distinguish control as the low-level algorithms to achieve this desired growth and direction from high-level navigation.

Navigation through environments by tip-extension comes with challenges, as both the amount and direction of growth need to be controlled. Since growth is actuated by pressure, controlling the latter is not only essential for motion but also for safety: exceeding threshold pressures leads to buckling or damage. Additionally, control of growth and steering is not always decoupled and heavily depends on the technical specifics of the prototype used. For certain applications, such as airway interventions [8] or wound packing [56], manual steering is sufficient. In this section, we review navigation and control strategies organized by increasing levels of autonomy, starting from foundational modeling to shared-control teleoperation. Note that fully autonomous SER remain largely future work.

1) Modeling: Modeling is the foundation for predicting the robot's behavior and inform path planning and control. Modeling approaches for SER range from simple analytical models to computationally intensive numerical simulations, each addressing different aspects of the robot's behavior.

On a time-axis, we distinguish *quasi-static* and *dynamic* models. The foundational quasi-static force balance model from Blumenschein et al. characterizes the relationship between internal pressure and growth [59] and enables simple real-time planning when assuming slow motions. Dynamic extensions account for high velocity operations with inertial effects, including force-balance extensions [11] and Lagrange-based formulations [60], [61].

On a physics-axis, purely geometric *kinematic* models map inputs to robot shape, which is especially useful for path planning and teleoperation, whereas *energy-based* models capture complex deformations and tissue contact. In the context of SER, kinematic models relate pressure to robot position in space [62] and can also model simple interactions of SER with a planar environment [63], [64]. They allow for efficient path planning even when more complex robot architectures are involved [65], are ideal for teleoperation, but are blind to forces or payloads. In contrast, energy-based models include forces via solving an underlying optimization problem and allow for the integration of multiple energy domains. Larrea et al. combine plant cell expansion theory with actuation and hydraulic modeling [46], while Wu et al. use physics-based finite element simulations to predict growing and interaction

TABLE 2: Overview of the steering methods described in the literature reviewed with regard to their placement in the Soft Everting Robots (SER) and the associated quantitative performance indicators (maximum bending angle, minimum bending radius and curvature, where available) as achieved in phantom or free space evaluations. The values correspond to the ranges specified in the respective publications. Due to inconsistent reporting standards, the metrics are not directly comparable, and individual lines may contain multiple system variants.

Steering Location	**Steering Method**	**Maximum Bending Angle**	**Minimum Bending Radius** (in mm)	**Curvature** (in m^{-1})	**Medical Application**	**References**
Robot body	Pre-shaped	90–180	≥ 5	n/a	endovascular, airway management and bronchoscopy, neurosurgical and spinal applications	[8], [25], [49], [51]
	PAM	90	n/a	6.08	upper and lower GI endoscopy, other medical applications	[9], [18], [37]
	Magnetic skin	72	n/a	n/a	airway management and bronchoscopy	[13]
	LCE-actuator	>100	n/a	13.9–57.9	endovascular	[43]
Inside robot lumen	Pneumatically actuated bending module	130–201.8	n/a	n/a	upper and lower GI endoscopy	[7], [10], [12], [33]
	Magnetic Fluid	70	n/a	n/a	airway management and bronchoscopy	[50]
Applied through working channel	Tendon-steered catheter	n/a	40	11.2	intraductal breast interventions, neurosurgical and spinal applications	[6], [19], [24], [53]
	Payload with magnetic tip	>90	38.5–49.5	n/a	other medical use case	[15]

capabilities [19]. Such models offer higher accuracy than purely kinematic models [45], but come with significant computational cost, usually unsuitable for intraoperative control.

For real-time control, one distinguishes *control-oriented* models suitable for onboard execution versus *high-fidelity* models for offline use. Here, lumped-parameter dynamic models can capture mixed energy domain dynamics while remaining computationally feasible [23], whereas more accurate finite element models mainly serve preoperative (offline) planning [45].

2) Sensing and State Estimation: While models provide the analytical baseline for algorithm design, knowledge of the robot's configuration is necessary for closing the loop in control. However, as mounting sensors along the robot body for full shape reconstruction is challenging, sensing information is usually either unavailable or limited to a single point, such as the tip. Most existing prototypes incorporate only basic imaging, using miniature cameras or fiber-based microendoscopes mounted at the distal tip or carried in the working channel [9], [50]. Such fiber-optic endoscopes can provide visual feedback for control, though this is sensitive to lighting conditions [45]. More recent prototypes demonstrate localized sensing capabilities, such as pneumatic force-sensing pouches integrated near the tip [7], or magnetic elements for tip tracking [17]. To augment sparse measurements and make them usable for feedback control, state estimation algorithms combine mathematical models with available sensing to localize more points along the robot backbone. For example, geometric model-based methods for teleoperated steering using joystick control incorporate feedback from inertial measurement units to estimate the robot configuration [66].

3) Low-level Growth Control: Low-level growth actuation is often governed by duty-cycle control, which modulates between high pressure for eversion and low pressure for catheter advancement and steering. This approach maintains position during growth through cyclical pressurization, growth, depressurization, and retraction phases [6], [50]. Model-based tracking control can account for pressure dynamics through sliding-mode control and nonlinear observers to compensate for external forces [32]. Pressure modulation strategies improve locomotion efficiency by addressing payload outrunning (see subsubsection IV-D.4) [35], whereas storing scrunched material at the tip of the SER can be used to overcome initial friction during growth and improve pressure efficiency [20]. An alternative control paradigm uses variable stiffness, where temperature-based control of low melting point alloys enables switching between stiff and compliant states for steering and force exertion [24].

4) Steering and Path Following: Once low-level growth control for advancing the robot is established, the directional motion and path execution become feasible through dedicated steering strategies. For instance, first prototypes exploit the basic pneumatic eversion with discrete pre-formed bends. Here, closed-loop visual feedback from a tip-mounted camera tracking a light source is achieved via selective pressurization [2]. However, such pre-formed bends produce permanent, non-reversible changes and depend on up-front planning. The introduction of series pneumatic artificial muscles (sPAMs) along the robot body enables steering through asymmetric contraction, decoupling growth from direction and allowing for simultaneous extension and steering independent of environmental contact [62]–[64]. Visual servo control laws enable growth to designated locations [62], while interaction-model-based path planning exploits beneficial obstacle contact for navigation [63]. Multi-segment selective actuation via magnetic valves and cylindrical pneumatic artificial muscles (cPAMs) further enhances steering control [65]. For closed-loop control, Shi et al. place a position sensor at the robot tip and

design an adaptive control to follow predefined paths [33]. An additional tip-mounted camera allows for image-guided lumen detection via shape-from-shading. Other image-based path planning using preoperative imaging (e.g., MRI scans) combined with extended A* algorithms to compute collision-free paths that include obstacle avoidance [22]. Subsequent innovations address the challenge of steering without full-body actuation: inchworm-inspired devices nested within SER enable controlled steering along curved paths and retraction in colonoscopy [12], while serially-connected robot systems pair tendon-actuated steering robots with hydraulically-actuated growing robots [21]. Alternative actuation paradigms employ magnetic guidance, where external magnets control robot bending and creasing behavior [13]. Magnetic steering typically uses joystick-based manipulation of magnet position [50], offering a control modality distinct from pressure-based systems yet still compatible with duty-cycle operation principles for growth.

5) Teleoperation and Shared Autonomy: Teleoperation with visual or sensory feedback drives many clinical implementations to put the human in the loop, achieving shared autonomy where the human oversees the high-level decisions while the robot handles the low-level execution. Hybrid controllers switch between open-loop model-based guidance (via inverse constant curvature kinematics) for distant configurations and closed-loop proportional control near the target to minimize steady-state error [45]. Haptic feedback systems that rely contact forces from tip-mounted pneumatic sensing pouches to the operator via haptic joysticks improve teleoperation effectiveness [7]. Advanced teleoperation systems also integrate microendoscopes and force sensors at the tip for precise tip positioning in complex anatomies, such as the spinal subarachnoid space [53].

D. Translational Challenges and Open Issues

Despite the promising advances demonstrated across various prototypes, several challenges remain before SER can transition from research concepts to clinically viable medical devices. These challenges span multiple domains, including interaction forces, miniaturization, manufacturing reproducibility, sensing and control, sterility and reusability, and user integration.

1) Manufacturing and Reproducibility: The fabrication of SER currently relies predominantly on manual processes such as hand-cutting, heat-sealing, and custom bonding. Several studies report that these methods introduce variability in wall thickness, seam quality, and leak tightness, which directly affects eversion pressures and overall mechanical performance [48], [51]. Thin-walled designs are particularly sensitive to small construction defects, such as pinholes or uneven seals, and more complex geometries tend to increase the likelihood of fabrication inconsistencies [48]. Because membrane stiffness and pressure resistance strongly depend on uniform film thickness and reliable seam formation [51], handcrafted processes make it difficult to produce consistent prototypes or compare results across studies.

2) Miniaturization with Clinically Viable Materials: Reducing the diameter proportionally lowers the tip cross-sectional area and thus the available actuation force for a given pressure [43], [50]. Thinner walls are required at smaller robot diameters to maintain sufficient flexibility, enable the large deformations needed for eversion, reduce bending stiffness, and lower both friction and the pressure required for growth. However, this comes at the cost of reduced burst-pressure resistance and potentially lower fatigue life, making the balance between compliance, durability, and safe operating pressure a central design challenge [19], [20], [24].

At small scales, the everting body often requires the simultaneous translational motion of the internal payload to support forward movement [6]. In such configurations, propulsion depends on the combined movement of both components. This coupling significantly limits the reachable length of the robot and constrains diagnostic or therapeutic actions to a specific deployment position, rather than enabling continuous access along the entire body.

Material selection of the robots body strongly influences system limitations. Repeated eversion and inversion cycles impose cyclic tensile and bending stresses [24], which can lead to wrinkling, delamination, or puncture of the robots body thin polymer films. Achieving high fatigue resistance while maintaining compliance is therefore essential.

3) Modeling and Control: SER control is constrained by limited sensing, incomplete interaction models, and strong coupling between eversion, steering, and environmental forces [33]. In current implementations, teleoperation with visual or limited sensor feedback is used, as robust low-level closed-loop controllers remain challenging to implement due to incomplete state information, model uncertainties, and the difficulty of sensing the robot's continuously changing shape. Accurate navigation requires reliable tip or shape estimation, yet approaches such as magnetic localization, online Jacobian adaptation, or embedded strain sensing remain difficult to integrate into thin-walled structures.

Autonomous lumen tracking has been demonstrated in controlled phantoms, but performance decreases in highly curved or compliant anatomies where steering authority becomes insufficient [32]. Coordinated control of growth and steering remains largely untested, and comprehensive assessments of robustness, autonomy, and failure handling are still missing.

Controlled retraction of SER poses a particularly challenging problem. During reverse motion, the thin-walled body loses axial tension, leading to buckling, wrinkling, and material accumulation that prevent predictable shape control [14], [19]. Existing systems rely on motorized spools or mechanical assistance to retract and rewind the everted body [33], [34], yet stable, shear-free reverse motion has not been demonstrated in current designs.

4) System Architecture and Payload Integration: Reliable material storage and sealing of SER remain fundamental challenges in the development. Existing systems show that even minor construction defects or leakage-prone transitions can destabilize pressure conditions and impair consistent eversion [33], [35], [48]. Material storage concepts further introduce friction-related disturbances that may cause backup,

clogging, or stuttering eversion (uneven pressure propagation or intermittent halting of the growth process) when local friction, non-uniform unfolding, or temporary sticking of the stored membrane occur [20], [35]. These effects reduce controllability and can increase mechanical load on the thin-walled structure.

Furthermore, carrying internal payloads is essential for most medical SER applications. But similar disturbances occur when a payload is integrated, since additional friction or asymmetry along the eversion path is expected to affect the smoothness of the growth process. Integrating a payload leads to an effect where the internal channel advances faster than the everting body – here referred to as *payload outrunning*, and previously described in the literature as *spitting* [50]. This effect can be mitigated by reducing internal friction, for instance by encasing the catheter or working channel in polytetrafluoroethylene (PTFE) to facilitate smooth sliding within the robot body [24]. Alternatively, iterative pressure-modulation strategies, as demonstrated in our previous work, can temporarily lower friction and synchronize the relative motion between body and payload [35].

5) Steering: Steering performance in SER is primarily constrained by the pressure-stiffness relationship of the everting body. Higher internal pressures increase axial stiffness and reduce achievable bending angles, yet such elevated pressures are often required to sustain growth, whereas operating at lower pressures may fail to generate sufficient force for reliable eversion. Miniaturization inherently reduces steering authority, as smaller diameters provide less actuation area and must overcome higher relative bending stiffness [20], [43].

Rigid or tip-mounted components increase internal drag and mechanical resistance and compromise the compliant, shear-free behavior central to everting locomotion [9], [33]. Approaches such as magnetic skins or fluidic steering layers may enhance curvature while maintaining compliance [13], [50], yet they remain untested in anatomically realistic conditions.

6) Sensor Integration: Integrating reliable, fatigue-resistant, and clinically compatible sensors into thin-walled everting structures without compromising eversion performance remains an open challenge. Sensors in thin-walled everting bodies increases internal tension and must accommodate large bending angles [43], while practical medical use further demands fatigue-resistant, clinically compatible sensing that tolerates frictional loads at the everting tip and repeated eversion-inversion cycles. Conventional sensor technologies – such as wired strain gauges, inertial measurement units, optical fibers, or embedded magnetic markers – introduce stiffness, increase wall thickness, or create discontinuities that compromise sealing integrity and burst resistance; such discontinuities, added layers, or stiff components are known to hinder miniaturization and impair soft-body characteristics.

Recent approaches such as pneumatic force-sensing pouches [7], magnetic skins [13], [50], or tethered sensor mounts [9] demonstrate the feasibility of embedded sensing, but they also increase manufacturing complexity and remain unvalidated under sterilization or biocompatibility constraints.

7) Sterility, Reuse, and Workflow integration: Sterility and reusability of materials used for the robots body are still poorly explored in current SER research. Commonly used materials still lack regulatory approval for clinical use and have not been validated for sterilization or long-term biocompatibility, which is essential for safe intraluminal deployment. None of the publications provide a detailed justification or design rationale for a sterile single-use concept. Some works note the use of low-cost or disposable materials [34], [54], but do not explicitly frame the device as a clinically intended single-use system. No published system provides an established strategy for sterile use or reuse, marking a critical gap toward preclinical and clinical translation.

Clinical implementation will depend on intuitive control interfaces and user acceptance. Early benchtop studies indicate that simplified interfaces can reduce the learning effort and are perceived as easier to use than conventional endoscopic or catheter-based tools [10]. Recent SER systems demonstrate joystick-based teleoperation and autonomous navigation [33], but their integration into existing clinical workflows – including compatibility with standard pressure-supply infrastructure – is largely untested.

8) Standardized Evaluation: Although eversion theoretically minimizes shear forces, a quantitative understanding of SER-tissue interaction is lacking. Only few studies have characterized contact or normal forces during in-vitro navigation.

Furthermore, current evaluations rely almost exclusively on benchtop phantoms that differ substantially in geometry, stiffness, and surface friction – from rigid guides and commercial training manikins to soft textile or silicone-rubber colon models [7], [33], [36]. While these setups enable safe early-stage testing, their heterogeneous and only partially physiological properties complicate direct comparison of reported pressures and forces across studies and limit the transferability of proposed “safe” operating ranges.

E. Alternative Soft Robotic Approaches to Endoscopy

A number of robotic colonoscopy concepts have been proposed that may appear, at first glance, related to SER, as they also aim to achieve atraumatic and self-propelled advancement through the colon. However, these systems do not fall within the class of SER as defined here, since their locomotion mechanism fundamentally differs from tip eversion, even though they are also driven by fluid pressure.

Inchworm-type robots, such as the Endotics System [67] or the Soft Pneumatic Inchworm Double-Balloon (SPID) robot [68], move by alternating anchoring and extension cycles that mimic peristalsis. These mechanisms produce stepwise motion that depends on local friction or fixation against the mucosa.

The Aer-O-Scope system employs a two-balloon configuration that enables gentle advancement through controlled gas pressure gradients [69], [70]. This approach shares certain conceptual similarities with inchworm-like motion but remains fundamentally pressure-driven and does not involve body eversion as in SER.

The Sightline ColonoSight system is a sleeve-based device that propels the endoscope by pneumatic advancement of a disposable sleeve, whose folded material is stored near the

distal tip and unfolds along the colon wall [71]. Advantages include reduced tissue friction and reduced contamination risk.

Also featuring sleeve material storage in the tip region is the system described by Dehghani et al. [72]. It is a pneumatically driven colonoscopy robot that advances by axial elongation of a compliant latex tube connected to an external fixture. This approach reduces looping and wall stress compared to conventional colonoscopes.

The described systems share the goal of reducing interaction forces and thus minimizing trauma to the luminal wall, similar to the targeted advantage of SER. They aim to avoid the pushing forces typical for conventional endoscopy and instead generate pulling forces on the imaging and working channels through active propulsion of the endoscope tip. Comparable effects can also be achieved by capsule endoscopy, though this approach faces major challenges in maneuverability and control.

In contrast, SER enable smooth progression without cyclic gripping or relative motion at the tissue interface. Moreover, SER can gently maintain the lumen in an insufflated-like open state during retraction, improving visibility of anatomical features such as haustral folds.

V. Future Research Directions Towards Clinical Translation

Based on the challenges identified in the preceding sections, this chapter outlines key future directions and design guidelines that appear most relevant for advancing SER toward safe and clinically viable medical use.

1) Scalable and Reproducible Manufacturing: Emerging fabrication strategies (see subsubsection IV-D.1) demonstrate the potential for more precise and scalable manufacturing. In this work, establishing standardized, automatable workflows is considered essential to ensure reproducibility across prototypes, enable valid comparisons between studies, and ultimately support regulatory pathways.

2) Miniaturization with Clinically Viable Materials: Miniaturized SER require thin-walled structures without compromising burst resistance. It is derived that materials should allow wall thicknesses in the low-micrometer range, maintain high tensile strength and low extensibility to prevent rupture under operating pressures, and tolerate repeated eversion-inversion cycles without fatigue. Material concepts should combine low friction to the environment and low resistance against the eversion process with resistance to fatigue and sterilization processes. Incorporating lubricious coatings may further reduce tissue interaction.

3) Validated Models for Safe Pressure-Driven Growth: Developing suitable models of the eversion process supports understanding and control of the coupled dynamics between pressure, deformation, and environmental interaction. Validated models capturing the relations between pressure, eversion velocity, and external constraints, including transitions between growth and retraction are key to predictive control and the avoidance of instabilities such as buckling or pressure threshold. Combining model-based and sensor-based feedback holds promise for merging physical insight with real-time data, enabling safe, adaptive motion in variable anatomies. Integrated pressure, flow, or imaging feedback may further enhance state estimation and procedural safety.

4) Steering Architectures and Payload Integration: The choice of the directional steering concept should reflect the required curvature and angular range dependent on the targeted applications: tight turns over short distances favor localized tip steering or tendon-driven actuation, while large directional changes with moderate curvature can be achieved by distributed steering. When the steering mechanism must also accommodate payloads such as imaging catheters or instrument channels, the resulting composite bending stiffness must be considered in the steering design and actuation strategy. However, avoiding active components at the robot tip leads to previously described challenges such as payload outrunning, for which solution concepts are summarized in subsection IV-D. Future designs should treat steering architecture, payload integration, and compliance tuning as interdependent parameters to ensure precise yet atraumatic navigation.

5) Reliable Sensor Integration: Functional components must be integrated without impairing eversion, increasing stiffness, or compromising sterility. Imaging, working channels, and sensors should therefore remain low-profile, flexible, and fatigue-resistant. SER also offer a unique opportunity for distributed sensing along their body surface: the large and compliant contact area enables in-situ measurement of tissue properties such as impedance, temperature, or local biochemical conditions. Such sensing concepts may allow comprehensive mapping of the intestinal environment and support diagnostic procedures as well as adaptive control strategies.

6) Sterility, Workflow Integration, and Modular System Design: Sterility and workflow integration remain key challenges for clinical translation. The close coupling of pressure generation and actuation complicates a clear separation between sterile and non-sterile domains. It can be concluded that concepts for single- or multi-use operation and for integrating sterilization into the design process remain to be developed. Fully enclosing drive components within the pressurized region risks contamination and impedes material exchange, whereas external or modular solutions increase technical complexity and cost. Future developments should aim to balance practicality, hygiene, and system integrity.

7) Standardized Evaluation and Clinical Benefit Metrics: Standardized evaluation methods are essential for assessing safety, navigation, and overall SER performance. Developing standardized, anatomically realistic, and mechanically well-characterized intestinal phantoms therefore represents an important prerequisite for obtaining comparable interaction data, validating embedded force-sensing concepts, and ultimately defining clinically relevant safety thresholds for SER propulsion and steering. Beyond benchtop validation, demonstrating patient benefit requires metrics that link technical performance to clinical outcomes, including reduced wall forces, minimized tissue deformation, shorter procedure times, and lower operator workload.

From a technical perspective, we identify directional control, reliable payload transport, and the clear separation be-

tween contaminated and non-contaminated compartments as key challenges that must be addressed to advance the clinical applicability of SER.

VI. Commercialization

Several commercialization efforts have been undertaken to translate the utilization of everting motion for medical applications into clinical products. Patent applications describing this concept date back to 1974 and 1980 [73], [74]. In Germany, the Invendoscope was developed [75], [76], while the company originally engaged with this technology, STM Medizintechnik Starnberg GmbH (Weinheim, DEU), had already filed related patents in the early 1990s [77], [78]. The system was later further developed by Invendo Medical GmbH (Kissing, DEU), which was acquired by Ambu A/S (Ballerup, DNK) in 2017 [79]. Multiple generations of the Invendoscope were released, some of which achieved both CE mark and FDA 510(k) clearance [80]. The general suitability was demonstrated in a prospective clinical study reported in 2007, although technical improvements were deemed necessary [81].

The number of patents on this locomotion approach for medical applications has risen sharply in recent years. Early adoption may have been hindered by limited user acceptance, but growing confidence in medical robotics may now shift this perception. Future research should therefore address not only technological refinement but also operation modes, user interfaces, and workflow integration to ensure intuitive use and full procedural control by physicians.

VII. Discussion

The scope of this review was defined by a systematic literature search focusing on explicitly medical applications of SER. While this ensured clinical relevance, it may have excluded technical studies on non-medical prototypes that could inform future designs. In addition, the heterogeneity of experimental setups and performance metrics prevents quantitative comparison across studies. Publications released after completion of the literature search were not considered.

Focusing exclusively on SER with explicit medical application is considered appropriate, as clinical translation imposes domain-specific constraints, that are rarely addressed in general SER research. Where relevant, non-medical work was referenced selectively when its methods directly inform these constraints.

Clear trends can be observed across the identified literature. Research is shifting from conceptual prototypes toward application-driven designs with miniaturized structures, integrated working channels, and sophisticated control approaches. In addition, an increasing number of studies include validation in anatomically realistic environments. However, standardized testing of safety, reliability, and tissue interaction remains lacking, limiting comparability.

The proposed design and control guidelines are broadly applicable but must be tailored to the anatomical and procedural setting respectively. In colonoscopy, large bending angles and variable lumen diameters demand high compliance, whereas vascular navigation requires extreme miniaturization.

From a translational perspective, major barriers persist at the interface between engineering and clinical practice. Reliable sterilization concepts, intuitive control modes, and seamless workflow integration will determine clinical acceptance. Regulatory compliance further requires reproducibility, safety validation, and manufacturing consistency, which are not yet established. Nevertheless, the growing number of application-oriented prototypes indicates that SER technology is approaching readiness for preclinical evaluation.

VIII. Conclusion

SER represent an emerging and highly promising class of soft robotic systems for medical interventions. This review systematically consolidate current developments in SER designed for medical application, outlining key advances in design, actuation, and control alongside remaining challenges in safety, miniaturization, sterility, and navigation. Recent progress toward application-specific prototypes demonstrates the strong potential of this technology to achieve truly atraumatic and intuitive procedures. Future research should therefore prioritize the integration of sensing and functional modules, validated control strategies, and clinically compatible sterility and workflow concepts. With continued interdisciplinary effort, SER are well positioned to evolve from experimental platforms into reliable instruments. Despite earlier commercialization attempts, the current climate of technological openness and rising technology acceptance offers a renewed opportunity for SER.

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