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TOPICAL REVIEW

State of the art in soft eversion robots for colonoscopy: a review

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Abstract

This review explores the current state of eversion robotics in the context of colonoscopy, given the need for less invasive, more patient-friendly screening technologies. Conventional colonoscopy often leads to discomfort and patient reluctance, contributing to delayed diagnoses and high colorectal cancer mortality rates. Eversion robots, also known as vine robots or soft growing robots are soft, pressure-driven devices that extend by everting from the tip whilst offering a promising option by enabling frictionless advancement and potentially pain-free procedures. We examine the key challenges and opportunities in adapting eversion robots for clinical endoscopic use, focusing on material selection, actuation, steering, and payload delivery. From the literature, thermoplastic polyurethane emerges as the most viable material for the robot's sleeve due to its airtightness, biocompatibility, suitability for heat or ultrasonic welding, and availability in highly flexible thin layers. Tip-steering mechanisms are identified as the most effective strategies for navigation, allowing high flexibility without increasing the wall thickness of the robot, as required in alternative approaches using distributed actuation mechanisms. The review also evaluates strategies for integrating functional tools at the tip of the robot, concluding that cap-free designs provide superior adaptability to the varying colon diameter, preserve compressibility, and keep tip friction to a minimum, unlike cap-based payload delivery methods. By consolidating current research and identifying pathways for innovation, this review supports the development of eversion soft robots as a next-generation solution for minimally invasive colorectal diagnostics and therapy.

1. Introduction

Colorectal cancer is the third most common cancer worldwide, with 1.9 million cases recorded in 2020 [1]. It is also the second leading cause of cancer-related deaths, accounting for 916 000 fatalities [1]. In Europe, colorectal cancer represented 12.7% of all new cancer diagnoses in 2020 and was responsible for 12.4% of cancer-related deaths [2].

Although increasing age remains the most significant risk factor for sporadic colorectal cancer, recent studies indicate a rising incidence in individuals under 50, particularly for left-sided colon and rectal cancers [3]. Its pathogenesis is multi-factorial, including genetic predisposition, environmental exposure, and lifestyle habits [4], while its treatment is determined by histological type, stage of disease, and the relevant medical history of the patient. Early diagnosis, which is significantly determined by increased compliance with screening programs, strongly influences prognosis [5].

Large randomized controlled trials have demonstrated that biennial screening of people between the ages of 45 and 80 years, using routine fecal immuno-chemical tests (FIT), can substantially reduce colorectal cancer mortality [6]. Most healthcare systems have therefore adopted this kind of screening, either opportunistically or through organized programs [7]. Low adherence to screening remains a critical factor contributing to preventable colorectal cancer-related deaths. In the United States, only 62.4% of adults over 50 report having undergone colorectal cancer screening as per guideline recommendations [8]. Perhaps even more concerningly, a recent global survey of 35 fecal immuno-chemical test-based screening programs, by Selby *et al* reported that only 79% of individuals with abnormal FIT results proceeded to undergo colonoscopy [9]. Overall rates of attendance ranged from 39% to 100% [9], while in the UK, 85% of individuals with abnormal test results did proceed with colonoscopy [10].

The primary barriers to colonoscopy include social and logistical factors, but physiological concerns are the most significant [11]. Common concerns include bowel preparation, fear of pain and discomfort, perceived invasiveness, potential complications, and the availability of sedation [11]. Technical aspects of the procedure can also affect outcomes, such as cecal intubation rate, time taken to reach the cecum, patient discomfort, sedation needs, withdrawal time, adenoma detection rate, patient repositioning, and the necessity of applying abdominal pressure by the assistant. A key source of pain during colonoscopy is loop formation in the instrument, causing mesenteric tension, particularly in the sigmoid colon, due to its shape and curvature [12].

Alternative diagnostic approaches include virtual colonoscopy via computed tomography (CT) and wireless capsule endoscopy. However, these methods have significant limitations, with up to 30% of polyps going undetected due to shape or obstruction [13]. Additionally, as these techniques do not allow for tissue sampling, lesion characterization is based solely on visual assessment, leading to potential diagnostic uncertainty [13]. Crucially, unlike traditional colonoscopy, these methods do not enable immediate therapeutic intervention [13]. As a result, colonoscopy remains the gold standard for the reliable detection and treatment of colorectal polyps and cancer.

Several robotic strategies have been actively investigated for colonoscopy. Inchworm-inspired designs employ sequential anchoring and elongation to achieve forward locomotion, often using balloons [14], suction [15], or mechanical legs as anchors [16]. These systems can generate strong propulsion and are relatively well-suited for navigating tubular environments, but their stop-and-go motion can limit traversal speed and patient comfort. Tracked robots represent another approach, adapting flexible tracks or balloon-assisted tracks to conform to the colon's anatomy while providing continuous propulsion [17, 18]. Such systems offer effective traction but may raise concerns about mucosal forces due to their reliance on friction with the colon wall.

Another propulsion mechanism exists in the form of Magnetic Navigation, shown by [19, 20]. The device is a magnetic capsule pulled forward through the colon only by a magnet, externally mounted on a robot arm. This avoids the need for mechanisms such as tracks which can apply stress on the colon as well as the extra wires or pressure lines in the tether required for its function. This leads to an over-all lower profile and lower patient discomfort.

Other assisted endoscope platforms and inflated tube designs have also been proposed. These include balloon-based anchoring systems that reduce looping and insertion forces [21], track-assisted colonoscopes that combine standard form factors with robotic locomotion [22], and balloon-propelled colonoscopes that harness insufflation pressure to advance [23]. While each of these strategies brings unique advantages, they also present specific trade-offs in terms of safety, complexity, and clinical usability. For a more comprehensive overview of these complementary approaches, readers are referred to the review paper by Ciuti *et al* [24] and Dei *et al* [25].

Soft eversion robots may offer a transformative solution to many of the colonoscopy challenges. Eversion robots are constructed from thin, flexible materials and achieve motion by everting—turning inside out—typically through pneumatic actuation. Their movement mimics plant growth, unfolding smoothly and without causing friction to the environment. This frictionless, compliant motion is particularly advantageous in colonoscopy, in which reducing mechanical interaction with the colon wall can significantly decrease patient discomfort and the risk of injury. Due to their inherently soft nature, eversion robots can squeeze through narrow anatomical passages, accommodating variations in the diameter of the colon. Even if seemingly oversized relative to certain segments of the colon, their flexibility allows them to maneuver through it safely and effectively.

Given the affordability of the materials used in their construction (thin plastic or fabric), they potentially offer a low-cost route to inexpensive, disposable devices, making colonoscopy fundamentally more accessible. By improving patient comfort and reducing procedural invasiveness, eversion robots could increase screening uptake, enable earlier detection, and, ultimately, save lives.

The aim of this paper is to assess the feasibility of using eversion robots for colonoscopy applications, and to determine the most suitable eversion robot technologies to achieve this. We begin by examining the clinical and physical challenges of conventional colonoscopy, factoring in important anatomical constraints. We then conduct an in-depth review of eversion robot technologies, focusing on material options, navigation capabilities, and payload delivery methods in the context of colonoscopy requirements. Section three synthesizes these findings to assess the viability of implementing eversion robots in colorectal cancer screening and treatment. Finally, section four concludes the paper with key takeaways while identifying future research directions.

1.1. Colon anatomy

Before any consideration of robotic solutions, a clear understanding of the colonoscopy environment is required—i.e. the colon's typical length, diameter, angles and curvatures. These anatomical parameters, derived from existing models and datasets, serve as a fundamental roadmap for robotic system development.

In a recent systematic review Philipps *et al* reported the total colon length to average around 1.3 m (1312 mm, with a standard deviation (SD) of 134 mm, a minimum length of 1000 mm, and a maximum length of 1590 mm [26]). Utano *et al* measured colon lengths in 295 patients using CT colonography, reporting a mean length of 1.5 m (1503 mm SD 185 mm, with a range from 1097 to 1959 mm). The study also confirmed that female colons tend to be significantly longer than male colons [27]. A recent systematic review by Alqarni *et al* [28] reports the mean colon length as 1483 mm and the maximum length as 2108 mm.

A recent systematic review analyzed colon segment lengths from 31 studies, encompassing cadaver assessments, colonoscopy, and MRI measurements [28]. The sigmoid colon was significantly longer in women than in men, measuring 544 mm (SD 108 mm) vs. 468 mm (SD 159 mm) in the supine position and 535 mm (SD 112 mm) vs. 464 mm (SD 116 mm) in the prone position ($p<0.04$) [29]. Conversely, men exhibited longer descending and ascending colons in both positions ($p<0.001$), and the cecum was significantly longer in men, though only in the prone position ($p<0.001$) [29].

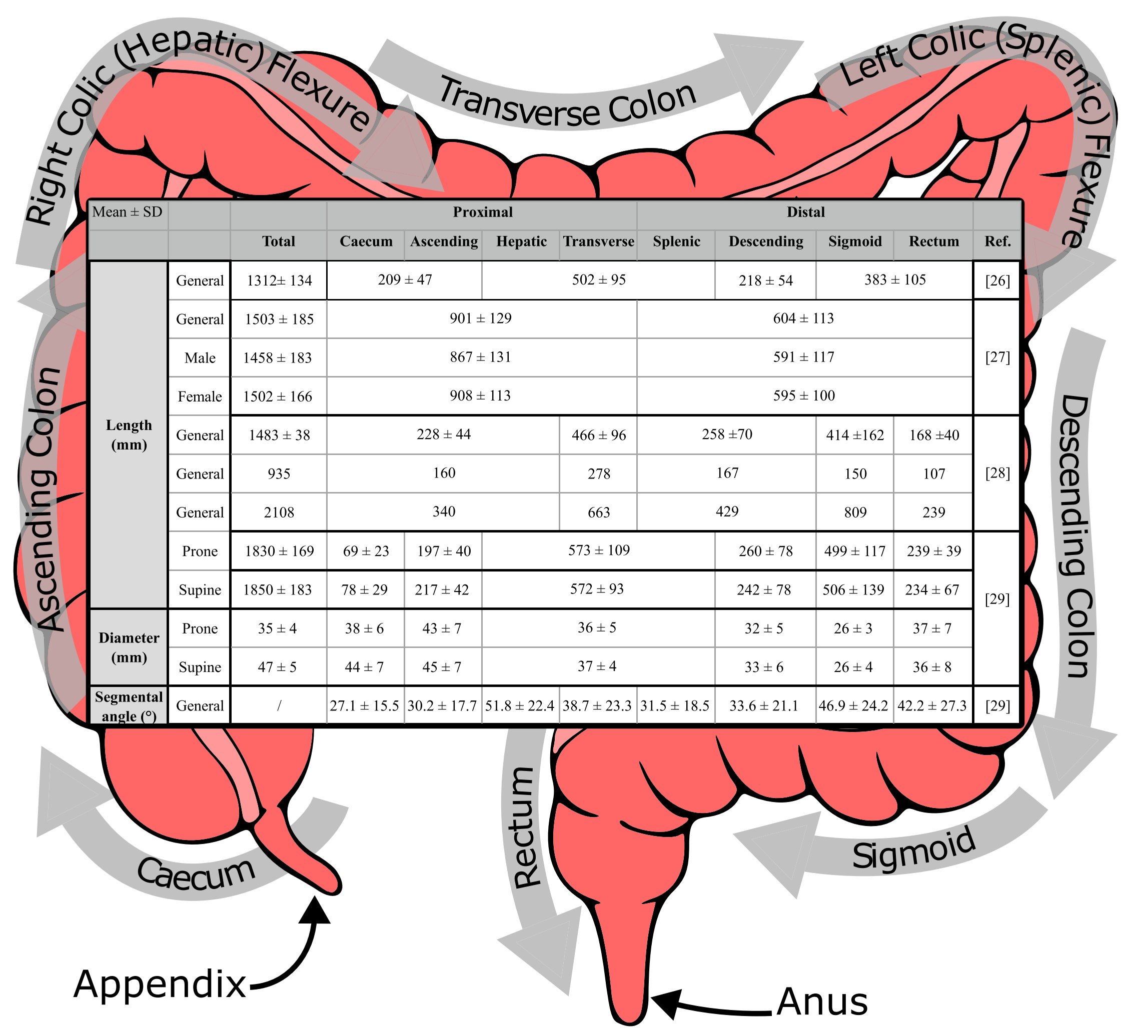
Studies on colonic curvature indicate that it is generally more tortuous in the prone position than in the supine position, except the transverse colon. The descending colon is the most skewed in both positions (supine skewness ratio: 0.84, prone skewness ratio: 0.79), followed closely by the ascending colon [29].

Wall thickness measurements from CT scans suggest a normal range from 3 to 5 mm, with segmental variations from 0 to 8 mm. A fully distended colon exhibits thinner walls (up to 2 mm), whereas in collapsed segments they can measure between 0.5 and 8 mm [30]. A 2020 study examining 132 patients with incidental colonic wall thickening ($\geqslant$3 mm in the colon, $\geqslant$5 mm in the rectum) found malignancies in 28.8% of cases, Crohn's disease in 1.5%, diverticulitis in 13.6%, colorectal polyps in 22.7%, and normal findings in 33.3% [31].

According to results from a study by Alazmani *et al* [29] with 24 participants, the mean values and SDs for diameters of different parts of colon are:

- Rectum: 36 mm (SD 8 mm)
- Sigmoid: 26 mm (SD 4 mm)
- Descending: 33 mm (SD 6 mm)
- Transverse: 37 mm (SD 4 mm)
- Ascending: 45 mm (SD 7 mm)
- Cecum: 42 mm (SD 7 mm)
- Proximal colon (the beginning and middle portions of the colon, specifically the cecum, ascending colon, and transverse colon): 42 mm (SD 4 mm)
- Distal colon (the end of the colon, specifically the descending colon and sigmoid colon): 31 mm (SD 5 mm)
- Total colon 47 mm (SD 5 mm).

The overall diameter of the colon was significantly larger when participants were in the supine position compared to the prone position. This difference was particularly evident in the distal colon, although no significant variations were found between the individual segments within that region. In contrast, every segment of the proximal colon—including the cecum, ascending colon, and transverse colon—showed a significant reduction in diameter when in the prone position. The study also identified gender-based differences: men typically had a larger diameter in the proximal colon, while women exhibited a larger diameter in the distal colon.



Mean ± SD		Total	Proximal				Distal				Ref.
		Total	Caecum	Ascending	Hepatic	Transverse	Splenic	Descending	Sigmoid	Rectum	Ref.
Length (mm)	General	1312± 134	209 ± 47		502 ± 95			218 ± 54	383 ± 105		[26]
	General	1503 ± 185	901 ± 129				604 ± 113				[27]
	Male	1458 ± 183	867 ± 131				591 ± 117				
	Female	1502 ± 166	908 ± 113				595 ± 100				
	General	1483 ± 38	228 ± 44			466 ± 96	258 ±70		414 ±162	168 ±40	[28]
	General	935	160			278	167		150	107	
	General	2108	340			663	429		809	239	
	Prone	1830 ± 169	69 ± 23	197 ± 40	573 ± 109			260 ± 78	499 ± 117	239 ± 39	[29]
	Supine	1850 ± 183	78 ± 29	217 ± 42	572 ± 93			242 ± 78	506 ± 139	234 ± 67	
Diameter (mm)	Prone	35 ± 4	38 ± 6	43 ± 7	36 ± 5			32 ± 5	26 ± 3	37 ± 7	
	Supine	47 ± 5	44 ± 7	45 ± 7	37 ± 4			33 ± 6	26 ± 4	36 ± 8	
Segmental angle (°)	General	/	27.1 ± 15.5	30.2 ± 17.7	51.8 ± 22.4	38.7 ± 23.3	31.5 ± 18.5	33.6 ± 21.1	46.9 ± 24.2	42.2 ± 27.3	[29]

Figure 1. Anatomical diagram of the human colon with a summary table of key morphological parameters, including typical length, internal diameter, and curvature angles of each major segment (ascending, transverse, descending, sigmoid, and rectum). These parameters provide essential design constraints for robotic colonoscopy devices.

Table 1. Key requirements for robotic colonoscopy and representative eversion robot systems that address them. The first column outlines functional or design requirements derived from clinical and anatomical needs. The second provides quantitative values or constraints from colon anatomy literature. The third lists studies demonstrating eversion robot designs that meet these requirements.

Requirement	Reference values	Eversion robots reported
Number of **sharp bends** (>40°)	3 – 7 [29]	[32–35]
Angle of **sharpest bend**	51.8° (SD 22.4°) [29]	[32, 35–39]
Minimum **colon diameter**	26 mm (SD 4 mm) [29]	[38, 40–49]
Total **traversable length**	Mean 1483 mm (SD 38 mm), max 2108 mm [28]	Most eversion robots
Avoid **excessive wall forces**	Relevant data is scarce	Intrinsically compliant, low friction
Enable **tool delivery**	Camera + tools (e.g. snares, forceps)	[50–56]

Colon segments and their respective dimensional ranges are presented in figure 1. Based on this, and data already outlined, a robotic colonoscopy tool must be capable of reaching a depth of two meters, navigating bends sharper than 52°, and either maintaining a diameter of less than 26 mm or having the ability to squeeze through lumens of that size. The robotic requirements for colonoscopy are provided in table 1.

While it would be valuable to include data on the permissible forces that can be applied to the colon wall, such information remains scarce. To date, to the best of authors' knowledge, only a single study has attempted to quantify forces exerted on the rectal wall during trans-anal endoscopic microsurgery [57].

On the basis of these challenges, eversion robots would appear to offer great potential in colonoscopy applications. Designing an eversion robot longer than two meters is unproblematic, and a variety of navigation strategies have been demonstrated that allow the device to negotiate turns exceeding 70°, depending on the bending radius [33]. Furthermore, eversion robots can either be manufactured with a diameter smaller than 22 mm [44] or designed to compress and pass through narrow anatomical pathways, making them excellent candidates for minimally invasive colon exploration.

1.2. Review methodology

This review is guided by the specific requirements of colonoscopy and investigates how eversion robots can effectively address the associated challenges. The paper highlights key advancements in eversion robotics and evaluates their potential to meet the unique demands of colonoscopy procedures. This section outlines the methodology employed in conducting the review, including the databases and search engines used, as well as the keywords applied to identify relevant literature. Furthermore, the criteria and rationale we used for paper inclusion and exclusion in this review are discussed. As an example, studies that focus solely on control or modeling, without hardware development, were excluded, as were studies of other non-eversion-based tip-growing robots.

An eversion robot customized for colonoscopy needs to be highly flexible, able to grow into the colon by working in a dynamic environment of varying diameter and curvatures, and should be able to transport sensors and a range of endoscopic and, surgical tools into the colon. Investigating the literature offers us insight into the materials and technologies used in highly maneuverable eversion robots. This review focuses on several key features of eversion robots, including their constituent materials and construction techniques, their methods of navigation, and the techniques for combining and sealing sheaths to maintain their airtightness. Additionally, state of the art strategies for carrying a payload—such as a sensor or robotic tool—at the tip of the eversion robot are explored. Familiarity with these fundamentals forms the bedrock of understanding necessary to create soft eversion robots with the requisite capabilities for colonoscopy applications.

The keywords and search engines used for the eversion robot literature survey are as follows:

- 117 papers were analyzed from Google scholar with following keywords: 'Vine robot'
- 100 papers were analyzed from Google scholar with following keywords: ('vine' OR 'eversion' OR 'everting' OR 'evert' OR ('soft' AND 'growing')) AND 'robot'
- 83 papers were analyzed from Google scholar with following keywords: 'eversion robot' OR 'everting robot'—'vine robot'
- 126 papers were analyzed from references of recent review paper [58].

All scientific papers related to eversion robots were analyzed. In light of the robotic requirements for colonoscopy outlined in table 1, particular emphasis was placed on papers presenting innovations in materials, hardware development for navigation, or payload delivery methods—areas identified as critical for robotic colonoscopy. In contrast, studies focused exclusively on control and modeling without accompanying hardware development were excluded. This decision was based on the assumption that colonoscopy eversion robots would most likely be tele-operated by the clinician, with minimal reliance on autonomous control. Retraction was not a major focus of this review, as it is generally straightforward to achieve in confined environments such as the colon. Other non-eversion-based tip-growing robots were also excluded.

In reviewing the literature, we extracted and reported key points from each paper. These included the main contribution of the paper, the specific application, materials used, methods for combining sheaths, sealing techniques, robot dimensions, navigation methods, maximum bending capabilities, payload-carrying details, and sensing capabilities.

2. State of the art of eversion robots

2.1. The eversion robot

The eversion robot is a pneumatically or fluid actuated soft robot capable of growing from its tip, mimicking the growth pattern of a plant. It is constructed from flexible sheet materials formed into a tubular shape. Initially, the material is folded inward, and upon inflation with pneumatic pressure, it everts—unfolding from the inside out—causing the robot to extend forward from the tip, as illustrated in figure 2.

This unique motion, known as eversion, allows the robot's body to grow to several times its original length. A key advantage of this mechanism is that it generates virtually no friction between the robot body and the surrounding environment during motion. This frictionless extension makes eversion robots

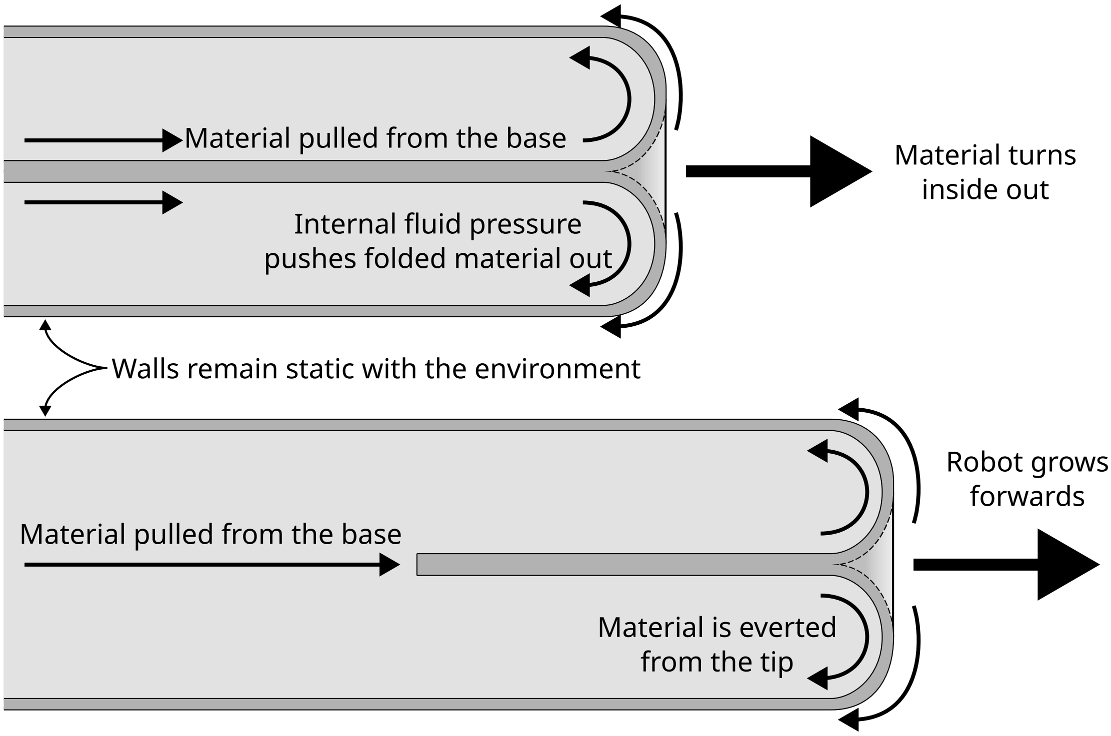


Figure 2. Basic structure of an eversion robot: a thin, flexible, airtight sleeve pressurized from within. Internal pressure unfolds the tip while pulling material from the base, extending the robot forward as its walls remain static relative to the environment.

particularly well-suited for applications in constrained, sensitive, or delicate environments, such as in medical procedures or search and rescue operations.

There exists an optimal pressure range within which an eversion robot can extend smoothly without risking damage to, or rupture of, the sleeve material. Operating within this range ensures reliable eversion, and increasing the pressure (within this safe window) typically results in faster robot movement. In general, the wider this pressure margin, the greater flexibility one has in tuning the robot's motion characteristics.

The sleeve material must meet several critical criteria. It should be airtight enough to contain pneumatic pressure effectively, thin enough to allow smooth unfolding and reduce bending stiffness, and durable enough to withstand repeated inflation at relatively high pressures without failure. Additionally, specific applications impose further constraints—for example, in medical contexts, the material must also be bio-compatible to ensure safe interaction with human tissue.

2.2. Materials

By examining the literature, we identified the materials most commonly used in eversion robotics and evaluated their suitability for colonoscopy applications.

The two most frequently used materials were found to be polyethylene and fabrics (figure 3). However, there is currently a lack of detailed comparative data on the specific differences and benefits of each material type for eversion robot applications.

From the analysis, it appears that fabric-based materials tend to be more durable than polyethylene options. Fabrics can generally withstand higher pressures without sustaining damage, and ripstop fabrics, in particular, stand out for their durability. Another advantage of fabrics is that they can be customized using conventional tools like sewing machines, further increasing their adaptability to a variety of tasks.

Polymer-based robots, in contrast, have traditionally been shaped by heat sealing, a process that limits their potential customization as compared to fabric-based alternatives. However, the introduction of ultrasonic welding has improved the situation in this respect. Additionally, the availability of polymers of minimal thickness may give them a distinct advantage over fabric options, given that low bending stiffness and compact form factors are critical.

Achieving airtightness in fabric materials requires the application of coatings, of which a variety of types can be found in the literature:

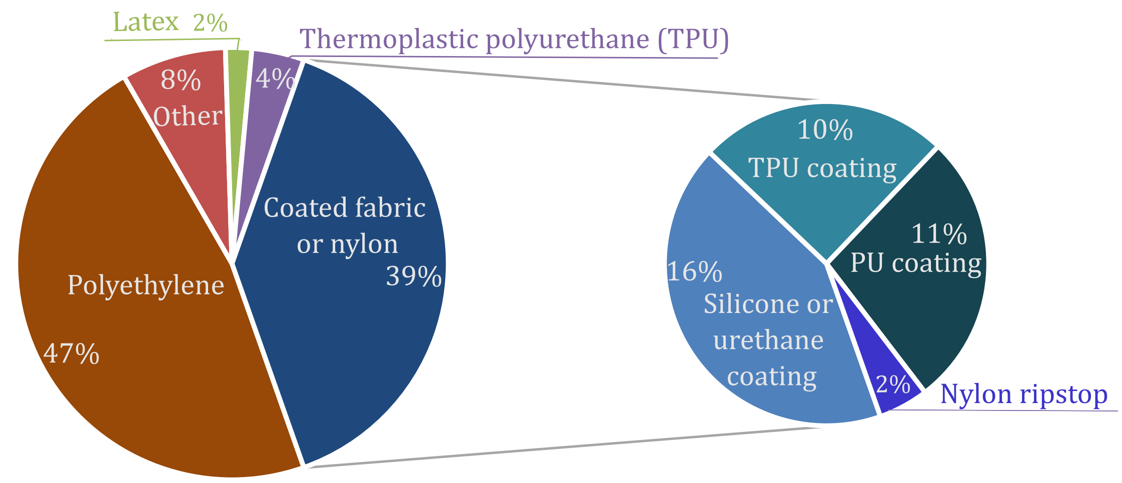


Figure 3. Material selection for eversion robot sleeves reported in the literature. Polyethylene-based materials, especially low-density polyethylene (LDPE), are most common. Coated fabrics such as nylons with silicone or urethane coatings are the second most used. Hyper-elastic options like TPU and latex are less common even though they offer high flexibility and stretchability, advantageous for navigating confined or tortuous environments such as the colon.

- PU coatings [32, 59]
- Silicone coatings [55, 60]
- Thermoplastic polyurethane (TPU) coatings [33, 61].

Despite the options available, the literature lacks sufficient data regarding the comparative performance of these coatings. There is little information on how different coatings influence key factors such as the durability, smoothness, and bending capabilities of eversion robots. This knowledge gap indicates a clear need for further research to better understand the impact of coatings on fabric performance in eversion robot applications. This could lead to more informed material selection and the optimization of soft robotic devices for medical use, particularly in sensitive applications like colonoscopy.

Combination of sheaths and sealing methods

For eversion robots without navigation, a single-layer sheath folded onto itself is typically sufficient. More advanced designs integrate navigation mechanisms into the body, creating multi-layer structures [32], while others attach navigation layers separately [62].

Sealing and bonding methods vary with material type:

Fabric-based Robots: Fabric is widely used for its durability and flexibility, though ensuring airtightness is more challenging. Approaches include:

- **Ultrasonic welding** [33, 51]: Bonds plastic-coated fabrics without perforation, producing durable airtight seams. Requires costly equipment.
- **Heat sealing** [35, 63]: Effective for TPU-coated fabrics but can reduce flexibility, increase eversion pressure, and add thickness.
- **Vinyl application** [54]: Tapes or layers improve airtightness at stitched seams but add stiffness, reducing performance.
- **Silicone glue** [64, 65]: Provides flexible bonds but weaker against high pressures and prone to degradation.
- **Brushing latex** [32, 66]: Improves airtightness over stitched areas, though it becomes brittle and cracks over time, requiring maintenance.

Polymer-based Robots: Polymers are easier to seal due to their compatibility with direct bonding.

- **Heat welding** [40, 44]: Simple and effective for two-layer structures, though less suitable for complex geometries.
- **Ultrasonic welding** [67, 68]: Enables intricate bonding patterns and airtight multi-layer seals, particularly useful for complex polymer-based designs.

Table 2. The materials used for making eversion robots summarized.

Material	Minimum thickness (mm)	Modulus of Elasticity	Bending Stiffness ($\mu N \cdot m$)[a]	Biocompatible Option	Bonding methods	References
Polyethylene	0.02 [40]	221 MPa [69] to 303 MPa [70]	0.175	Available for LDPE [71]	Heat or ultrasonic welding	[34, 40, 42–45, 49, 56, 62, 67, 69, 70, 72–107]
TPU	0.0375 [108]	5 MPa [109] to 371 MPa [110]	0.026	Available [111, 112]	Laser, heat or ultrasonic welding	[46, 108, 110, 113, 114]
PU-coated fabric	No Data	No Data	No Data	Available [115]	Sewing and sealing with vinyl, latex or glue	[32, 52–54, 66, 107, 116–122]
Nylon ripstop	0.06 [65]	No Data	No Data	Available [123]	Sewing and sealing with vinyl, latex or glue	[65, 124, 125]
TPU-coated fabric	0.031 [63]	1.98 MPa [35] to 1.3 GPa [63]	0.006	Available [111, 112]	Heat sealing, ultrasonic welding	[33, 35, 59, 61, 63, 67, 68, 126–129]
Silicone coated fabric	0.05 [38]	74 MPa [130]	0.918	Available [131]	Adhesives	[35, 36, 38, 39, 55, 60, 64, 130, 132–138]

[a] These values are not taken from the literature, but calculated in this paper assuming a Poisson's ratio of 0.4 for all materials.

Table 2 provides a summary of materials that have been used for eversion robot applications, their possible minimum thicknesses and their respective methods of combination.

2.3. Navigation methods

In a colonoscopy application, the robotic tool would need to navigate and scan the entire length of the colon. Eversion robots inherently exhibit a unique motion that, to some extent, allows them to follow environmental pathways. By way of illustration, an eversion robot can navigate through a 45-degree bend within a pipe, but may struggle with sharper, 90-plus degree bends. In free space, they tend to move linearly unless external forces (i.e. obstacles) are encountered.

To improve maneuverability, especially in free space or for sharper turns, additional steering mechanisms need to be incorporated. Navigation strategies are generally of two types: active steering and predetermined steering. Selected examples are given in figure 4.

Active steering methods allow real-time control over the direction and intensity of the robot's movements. Actuators are added to the robot and can be activated or deactivated as required, providing greater navigational flexibility. Active steering methods include:

- **Integration of pneumatic artificial muscles (PAMs):** PAMs are one of the most common active navigation strategies for eversion robots, but their effectiveness depends strongly on how they are implemented. When attached externally to the robot body (figure 4(a)):, PAMs contract upon inflation, bending the robot toward the activated side [59, 81]. This approach is relatively simple, but the achievable bending angles are modest. By contrast, integrating PAMs directly into the robot's body (figure 4(d)) structure removes the need for an extra material layer and leverages the gap between the body wall and the pouch to produce greater bending forces. Although this method is more challenging to fabricate—particularly for long robots—it delivers higher bending angles and improved reliability compared to external attachment [32, 33]. With recent developments by Mack *et al* [107], it has also become possible to fabricate integrated PAMs in a more straightforward and efficient manner.
- **Tip steering mechanisms (figure 4(b)):** Another strategy involves adding internal joints to the tip of the robot, enabling the tip itself to bend. In some cases, this level of steering is sufficient for the robot to maintain its chosen path. However, as the robot continues to evert, the body behind the tip remains in a straight line, which can limit the robot's overall maneuverability when larger bending angles are required. This method is generally suited to scenarios in which only minor directional changes are required, or in which the robot is well constrained by its environment [34–36]. Recent work by Giri *et al* proposed an inchworm-type locomotion strategy for movement inside the colon, employing silicone-based actuators for bending in combination with expanding pneumatic channels to anchor the robot [139]. Although this approach does not render the robot fully compressible, it maintains construction entirely from soft robotic materials that can be pneumatically actuated.

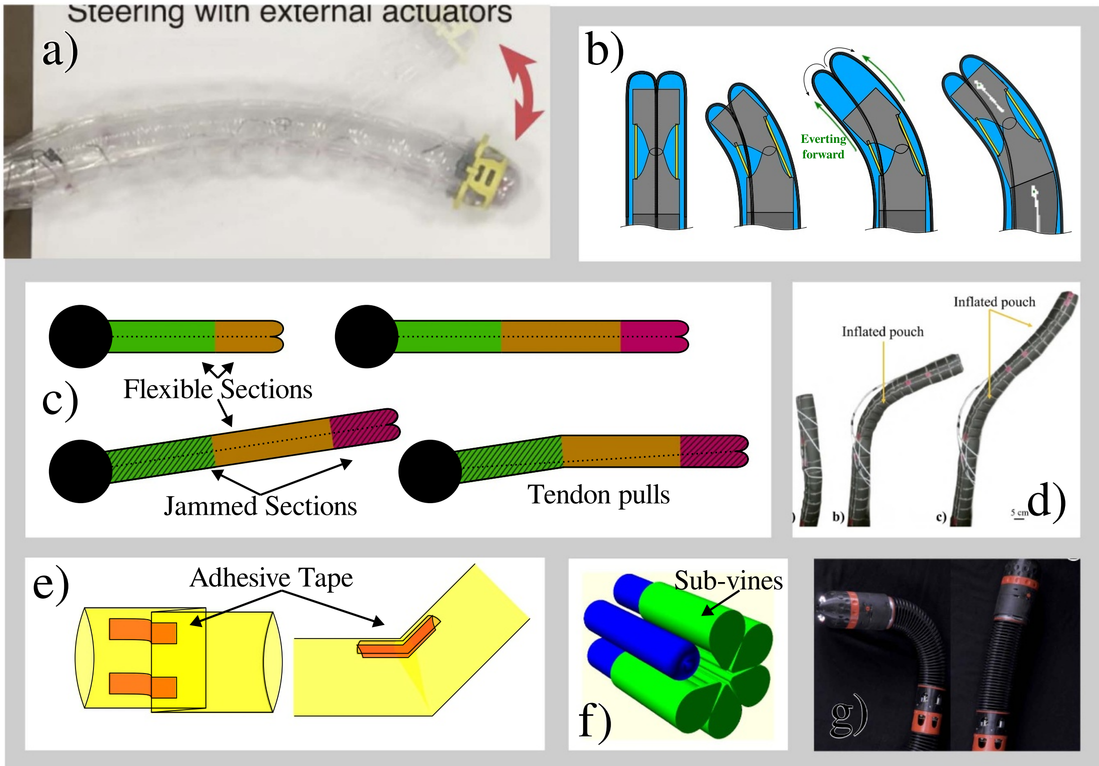


Figure 4. Navigation mechanisms in the literature. (a) External pneumatic artificial muscles (PAMs) [56]. © 2020 IEEE. Reprinted, with permission, from [56]. (b) Tip steering mechanism [34] (c) Stiffness controlled tendon driven navigation [79]. (d) Integrated PAMs [32]. © 2021 IEEE. Reprinted, with permission, from [32]. (e) Predetermined steering using adhesive tapes [43] (f) Sub-eversion robots [60]. (g) Tip mount that steer [51]. © 2021 IEEE. Reprinted, with permission, from [51].

- **Tip mounts that steer (figure 4(g)):** This method involves the creation of a steerable cap or tip mount for the eversion robot. The navigation mechanism is integrated into the robot's tip via an external cap and an internal interlocking system. While the range of bending is relatively limited, this slight steering capability at the tip can influence the robot's choice of path and enable it to make minor adjustments and then to achieve sharper turns [51, 54]. A recent line of research explores tip steering using silicone-based artificial muscles, attached to a cap [137, 138]. This method enables fully pneumatic actuation of the robot. Utilizing this approach, it is reported that the tip steering element can achieve high bending angles (up to 201.8° [137]).
- **Tendons (figure 4(c)):** Tendons are commonly used in continuum robots that are controlled from the base, but face specific challenges with eversion robots due to the friction that accumulates along the tendons—an issue especially when the robot is long. As the robot inverts, tendons can buckle or create resistance at undesired locations. Researchers have attempted to address this problem by combining tendons with other technologies, such as shape-locking mechanisms or through stiffness control, to improve performance [64, 79].
- **Other methods:** Other active steering approaches include the use of magnets [40, 73], photo-thermal phase-change materials [74], fastening belts [61], hyper-elastic materials [37], sub-everting robots [60] (figure 4(f)) and layer jamming [79, 102].

Achieving high bending angles with active steering in open (unconstrained) environments is challenging, as the inflated body of the eversion robot becomes stiff and resists deformation. In some cases, the main air channel can be temporarily deflated to facilitate steering; however, once reinflated, the robot tends to straighten and resume forward movement. However, in confined environments—such as the colon—where physical constraints naturally guide the robot's path, navigation methods tend to be more effective and reliable.

Predetermined steering can be achieved by designing a robot in such a way that it follows a fixed pathway based on predefined bends. Unlike active steering, this approach can achieve effective bending in unconstrained environments, but does not allow for adjustments during operation, as the robot's movement is ”baked in” during the design phase. Some common methods of predetermined steering include:

- **Adhesives (figure 4(e)):** By using adhesives such as tape, sections of the robot's body can be bonded together at specific locations. This creates bends as the robot everts, allowing it to follow a set path. Adhesives offer a simple and effective method of pre-programmed steering, especially in environments in which the required route or pathway is known in advance [43].
- **Altering the body:** Another way to induce predetermined bending is by modifying the robot body during fabrication. For example, polymer-based robots can be welded in specific ways, and fabric-based robots can similarly be sewn up to induce predetermined bending. Such modifications ensure that these robots follow a particular path as they evert, making them well-suited for applications with predictable, pre-mapped routes [82].

These steering techniques allow eversion robots to navigate in either 2D or 3D spaces. By integrating two sets of PAMs cross-sectionally 180 degrees apart, one can enable 2D maneuvering, while three sets at 120-degree intervals allow for 3D movement. However, using these techniques to maneuver against gravity remains challenging, as the inflatable structure of an eversion robot often struggles to hold its shape in a vertical orientation.

Of the existing options, active steering is preferable to predetermined steering within the context of colonoscopy, as in the case of the latter one would need accurate measurements of the shape of the colon—which would need to be acquired through CT scans—prior to complex design and fabrication processes, as even marginal errors could lead to the device getting stuck within the colon. The immediacy of fabrication would amount to a further complexity as extended time between fabrication and use could also lead to problems should the patient's movement cause changes in colon orientation. In contrast, active bending solutions can theoretically traverse colons without requiring any prior knowledge.

Among assorted active steering options, tip steering methods are one of the most promising, as a tip-guided eversion robot can follow more complex pathways. Continuous bending methods could, in principle, assist with tight bend navigation, but have the disadvantage of exerting additional forces onto the colon wall along sections that have already been traversed. Localized bending, effected by continuous sections of inflatable PAMs, could be a partial solution to this problem as bending could be limited to the most distal section but, on the downside, would require more air supply lines. Both continuous and localized bending would also require at least one extra layer of unfolding material, resulting in reduced flexibility. Lesser wall flexibility would increase the pressure required for eversion, which would in turn increase the risk of the robot rupturing and the released air rapidly expanding within the colon.

Tip steering can either be achieved using a device mounted externally on a cap or a mechanism within the robot. Any externally fitted device will increase friction with the colon wall and consequently lead to patient discomfort. An internally integrated device would therefore be preferable, not just for this reason, but also because it can better accommodate power transmission and control as wires or pipes can be passed through the body of the robot, rather than externally between the robot and the colon wall.

Table 3 summarizes navigation methods for eversion robots, providing key information and examples of research papers for each type.

2.4. Payload carrying capabilities

A robotic colonoscopy device should be able to carry three classes of instruments—inspection tools (miniature cameras, illumination and contact sensors), intervention tools (biopsy forceps, snares, grippers) and cleaning/maintenance tools (irrigation, suction, insufflation) — and these tools often need to be delivered by a working channel in the 2.3–3.8 mm span [24]. Inspection tools are used to provide a live video during the operation. Lights brighten the inside, and special contact sensors can touch the tissue to measure properties such as stiffness, which can help identify abnormal areas. Intervention tools are usually used for tissue removal. Biopsy forceps are like tiny pincers that take a small piece of tissue for lab testing. Snares are thin wire loops that can be tightened around a polyp to cut it off safely. Grippers or similar devices can hold or move tissue if needed. Cleaning and maintenance tools are used to keep the view clear and make the procedure safe. Irrigation systems flush the lens or the colon wall with water, suction removes fluid or debris, and insufflation introduces air or carbon dioxide to gently expand the colon so the camera and tools can move more easily. In an ideal procedure, the polyp or tumor is detected and removed on the spot. If the colonoscope is only equipped with inspection tools, such as a camera, a secondary step is required whereby the location of the abnormal needs to be remembered, the inspection tool is to be removed and a new colonoscope equipped with a removal tool needs to be inserted. This overly long approach is to be avoided, with the aim to keep operating times to a minimum.

Table 3. The navigation methods used for eversion robots summarized.

Steering Method	Minimum Bending Radius or Maximum Angle	Advantages	Limitations	References
External PAMs	382 mm	Easier to prototype	Lower performance	[38, 55, 56, 59, 62, 81, 83, 88, 101, 133, 136, 140]
Integrated PAMs	220 mm	Higher performance in bending angle and force output	Harder to manufacture	[32, 33, 66, 107, 117, 121]
Internal tip steering devices	115°	Tip navigation	Does not steer the body of the robot, and might not be able to generate enough forces to overcome pressure of the body of the eversion robot	[34–36, 139]
Tip mounts that steer	63 mm or 201.8°	Can extend and contract by controlling pressure, reduce buckling	Limited maneuvering effectiveness in open spaces, introduces friction to the environment, the robot cannot squeeze through narrow openings	[51, 54, 84, 85, 91, 137, 138]
Tendon driven approaches	76 mm or 60°	Simple manufacturing, larger bending angle for the first bend	Capstan internal friction increase exponentially with total curvature, often has to be combined with stiffening approaches	[39, 64, 68, 79, 93, 127–130, 141]
Pre-determined bending	Any curvature and degree is possible	Simple manufacturing	The trajectory must be known prior to the deployment of the robot	[43, 48, 49, 67, 82, 100, 103]

One of the key challenges in eversion robotics is designing a tip mechanism, or ”cap” that can effectively carry a payload. As the tip of an eversion robot continuously moves forward and inverts, simply attaching a payload to it and expecting it to remain there is not a viable solution. A cap mechanism for an eversion robot must satisfy three primary requirements: it must enable the robot to maintain movement, remain fixed at the tip, and be capable of carrying a payload, such as a sensor or surgical tool.

Various cap designs that meet these requirements have been proposed, each one with its own unique method of securing the cap at the tip and carrying a payload. Some caps are designed to support the control of length and rate of extension, while others passively move with the robot as it inflates. In the following sections we provide an overview of the cap mechanisms best documented in the literature, their advantages, and their limitations. Some of these are illustrated in figure 5.

- **Rigid cap designs:** Several rigid cap designs have been proposed to anchor payloads or navigation mechanisms at the tip of eversion robots, but all introduce significant trade-offs. Friction-based caps rely on resistance between the robot body and the cap to maintain position [59] (figure 5(a)), yet this friction can hinder smooth eversion and increase the risk of jamming, particularly in environments with variable diameters or obstacles. Motorized lead attachment caps use a tether controlled from the base to fix the cap at the tip [50] (figure 5(e)), though this approach requires complex control, introduces additional weight, and reduces maneuverability in longer robots. Magnetic roller caps employ inner and outer rollers held by magnetic attraction to allow relative motion with the robot’s sleeve [135] (figure 5(b)); however, they are highly sensitive to sleeve imperfections and risk either detachment (if magnetic forces are too weak) or entrapment of the material (if too strong). Roller-locking caps integrate passive or active rollers that guide material through the cap [51, 56] (figure 5(d)), offering more precise control but suffering from jamming, vibration, and limited adaptability to diameter changes. Overall, while these rigid cap approaches demonstrate creative engineering, they compromise

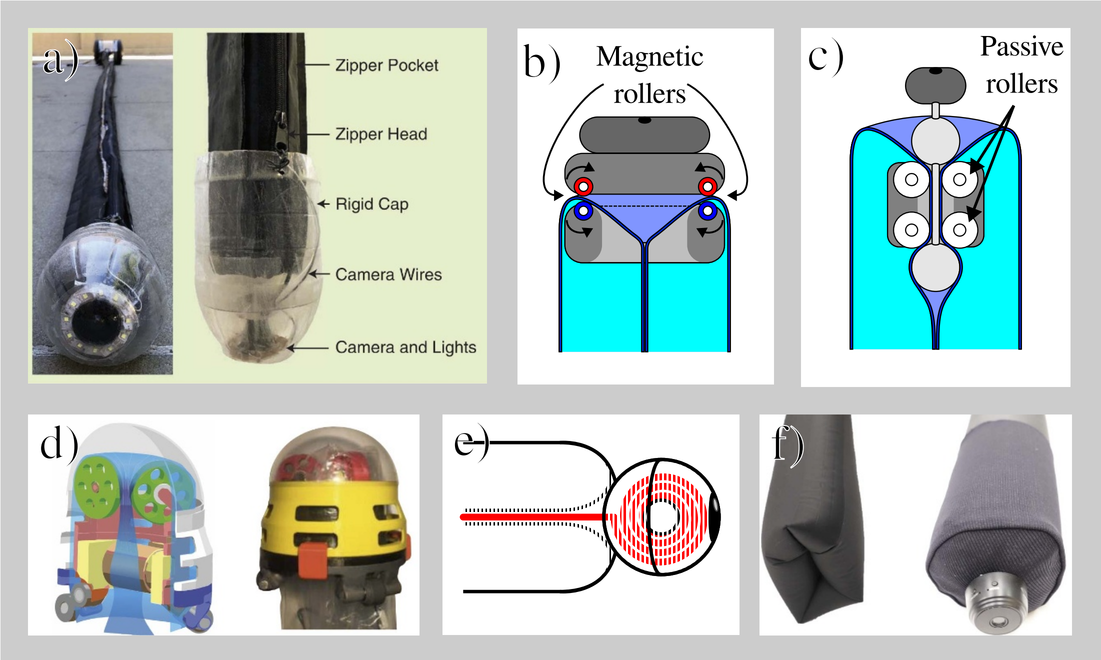


Figure 5. Tip mount mechanisms in the literature. (a) Rigid friction cap [59]. © 2020 IEEE. Reprinted, with permission, from [59]. (b) Magnetic cap with roller magnets [135]. (c) Internal payload-carrying mechanism [55]. (d) Cap with roller locking mechanisms [56]. © 2020 IEEE. Reprinted, with permission, from [56]. (e) Motorized lead attachment cap [50]. (f) Soft cap [52]. © 2023 IEEE. Reprinted, with permission, from [52].

one of the core strengths of eversion robots—their softness and adaptability—making them less suitable for applications such as colonoscopy.

- **Tendon-based payload-carrying approach:** In some cases, a tendon system is used to hold the payload, but this method poses challenges due to friction from the everting material. This friction can cause velocity differences between the robot's tip and the payload, leading to instability. While solutions like shape-locking mechanisms and stiffness control have been proposed, the inherent issues with tendons make this method less ideal for heavy payloads [75, 142].

A significant limitation across these assorted cap mechanisms is that they are typically made from rigid materials, which reduce the overall compliance of the eversion robot. Rigid caps limit the robot's ability to maneuver through narrow spaces, hindering its effectiveness in confined or complex environments. As eversion robots are inherently soft and compliant, using a hard cap effectively contradicts their design philosophy and limits their adaptability.

- **The soft cap (figure 5(f)):** To address this, a soft cap has been proposed as an alternative. The soft cap is constructed from textile materials, providing full compliance with the robot's flexible structure. This cap can maintain its position at the tip through friction, but because it is soft, it can deform and squeeze through narrow openings. Additionally, it can accommodate multi-layered or protruding objects on the robot body without restricting navigation. However, due to its inherent softness, this cap is limited to carrying lighter payloads, as it lacks the rigidity needed for heavier loads [52, 53].
- **Internal payload-carrying approaches (figure 5(c)):** The ideal payload delivery strategy would be without any need for an external cap. Even soft caps, while more compliant than rigid alternatives, still introduce unwanted friction against the colon wall and may compromise the eversion robot's performance. Internal mechanisms, as demonstrated by works such as [55, 65], enable cap-free payload attachment directly at the tip of the eversion robot. These designs eliminate external friction, preserving the robot's flexibility and squeezability. While they still face limitations—such as slower operational speeds and restricted payload capacities—this approach represents the most promising direction for colonoscopy applications.

In summary, a variety of cap mechanisms exist for eversion robots, each with unique advantages and drawbacks. Selecting the appropriate cap mechanism depends on the specific requirements of the application, such as payload weight, environmental constraints, and the speed and degree of maneuverability

Table 4. Tip payload carrying options for eversion robots summarized.

Tip Mount Type	Advantages	Limitations	References
Rigid friction cap	Easy to prototype	Cannot squeeze through narrow openings, limits tip navigation, hinders eversion	[54, 59, 72, 77]
Motorized lead cap	—	Cannot squeeze through narrow openings, encumbers the tip, complex control	[50]
Magnetic cap	Can work for underwater applications	Cannot squeeze through narrow openings, unreliable, can easily fall with environmental contact	[135]
Roller locking caps	Can support retraction	Cannot squeeze through narrow openings, do not tolerate protrusion of objects from robot body	[33, 51, 56, 61, 104, 116, 129, 138]
Tendon based approaches	Can avoid friction between the outer cap and the environment, the robot can squeeze through narrow openings	Need additional mechanisms to avoid unfolding material friction acting on the tendon, cannot carry heavy payloads	[55, 75, 83, 142]
Soft cap	The robot can squeeze through narrow openings	Cannot carry heavy payloads	[52, 53]
Cap-free solutions	The robot can squeeze through narrow openings, no additional friction to the environment introduced	Cannot carry heavy payloads	[55, 60, 65, 143]

required. For colonoscopy applications, cap-free approaches seem the most promising, as they neither create additional friction, nor impact squeezability. Table 4 provides a summary of existing payload carriage options for eversion robots.

2.5. Applications

Having analyzed material options, navigation strategies, and payload delivery methods from the perspective of robotic colonoscopy, we also aim to reflect on other potential applications of eversion robots and the technologies best suited to those contexts. Eversion robots have been developed for various applications, ranging from search and rescue to medical procedures:

- **Search and rescue:** One of the earliest explored applications of eversion robots was in search and rescue scenarios [50]. Their ability to squeeze through narrow openings and maintain continuous contact with the environment makes them particularly well-suited for navigating semi-obstructed pathways to reach trapped individuals. Eversion robots can also be equipped to deliver payloads such as cameras used to locate victims [59] or even water to sustain them until rescue teams arrive [51]. To maintain the inherent compliance of the robot, payload tips can be constructed from flexible materials. For example, the soft cap solution proposed in [52] presents a promising approach for carrying payloads without compromising the robot's ability to navigate confined and fragile environments. Maintaining a rotary motor-free structure is critical in such scenarios to avoid causing vibrations, and potentially further destabilizing the surrounding area. In terms of navigation, while no single technique has emerged as ideal for this application, designs incorporating rigid components—such as those in [36]—are less favorable due to their compromising the robot's flexibility and adaptability.
- **Medical applications:** A significant portion of eversion robot research does of course focus on medical applications [144], largely due to the fact that frictionless eversion motion offers the ideal method of moving devices around within the human body without causing irritation to surrounding tissue [44]. An eversion robot's sleeve can be made from bio-compatible materials, and, unlike its traditional counterparts, it can operate without any metallic or rigid parts, reducing the risk of tissue damage [46]. In case of malfunction, an eversion robot will simply leak air and deflate without harming the surrounding environment, and can easily be retrieved from the body without complication—a further benefit.
- **Pipe inspection:** Eversion robots are well suited to pipe inspection applications [97, 132, 145]. They can traverse confined pipe systems to detect structural damage or obstructions, often carrying a sensor

Table 5. Selected recent studies focused on medical applications. The table entries reference the performance criteria listed in table 1. Qualities shown in **bold** meet the requirement for most people, those in *italic* partially satisfy the requirement, and those underlined do not satisfy the requirement for most people. The plain text is used when the data is given in a different format than it is in table 1. A full, color-coded version of this table is provided as supplementary material.

Paper	Material	Robot Diameter (mm)	Robot Length (m)	Maximum Bending Angle	Payload Carrying Method
Kim *et al* [143]	Ripstop nylon	*25*	0.9	6.08 m^{-1}	**Cap-free approach**
Shi *et al* [137]	Silicone/ Polyurethane-coated ripstop fabric	**18**	**1.6**	**201.8°**	Rigid roller locking cap
Wu *et al* [141]	PTFE	**2**	0.15	40 mm bending radius	**Cap-free approach**
Giri *et al* [139]	Stretchlon film	*27*	*1.45*	**130°**	Does not carry payload
Davy *et al* [40]	LDPE	**8**	0.25	Not available	Does not carry payload

or tool mounted at the tip. Thanks to their soft, compliant structure, eversion robots minimize the risk of damaging the internal surfaces of pipes. Unlike traditional inspection tools, they do not leave any debris behind, as they can be fully retracted following the task [65]. Given that pipe diameters typically remain consistent and that surfaces are generally smoother than other environments, a wide range of payload-carrying strategies can be employed effectively. Similarly, navigation requirements are usually modest, with small directional adjustments at the robot tip often sufficient to follow the pipe's path-making most navigation mechanisms applicable in this use case.

- **Exploration and mapping of unknown environments:** Eversion robots are ideal for exploration in delicate, inaccessible or hazardous environments [108]. For example, they can be deployed on archaeological sites without risk of damaging artifacts due to their soft, no-friction and low vibration movement [59]. They are also suitable for radioactive or contaminated areas, as the sleeve material is typically a low-cost polymer or fabric, making single-use robots economically viable. In such environments, where terrain and obstacles are largely unknown, predetermined bending strategies are impractical. Instead, integrated PAMs offer a promising navigation solution, as they are capable of achieving high bending angles in open or lightly obstructed settings, which are common in these exploration scenarios.
- **Object manipulation in hard-to-reach places:** Eversion robots can manipulate objects in otherwise inaccessible areas. Upon reaching its intended location, a robot's gripper or similar tool at the tip can be used to pick up or manipulate objects [128, 146]. This is crucial for colonoscopies because surgical instruments must navigate to and access far-off sections of the colon to remove abnormal tissues such as cancerous growths or polyps.

Other applications for eversion robots explored in the literature include haptic feedback [103], underwater exploration [135] and burrowing [130]. In general, eversion robots are adept at accessing challenging locations and performing specific tasks once there—a combination of capabilities that makes them highly adaptable across a variety of fields.

2.6. Quantitative benchmarking

In table 1, the key requirements for an eversion robot to successfully perform colonoscopy are summarized. The main considerations include maintaining a diameter smaller than (or compressible to) 24 mm, achieving a minimum length of 1.55 m, bending more than 70° in constrained environments, and delivering a camera and associated tools without compromising the robot's softness and compliance. These specifications incorporate the SD values reported in table 1, ensuring that the technology can accommodate the anatomical variability of the majority of patients.

Drawing on these requirements, design guidelines can be established from the state of the art in eversion robotics, providing a basis for tailoring current technologies to colonoscopy. Table 5 highlights selected recent studies that are made for medical applications. The qualities are given in different text styles referring to values in table 1. A full version of this table is included in the supplementary material, where all reviewed papers are analyzed and color coded according to how well they satisfy the identified colonoscopy requirements. In this supplementary table, green indicates designs that meet the diameter and length criteria for most patients, orange denotes partial suitability where only a subset of patients are accommodated, and red signifies that the requirements are not met in the majority of cases. For payload delivery, green is assigned to cap-free designs, identified as the most appropriate solution for colonoscopy. Orange is used for other soft payload carrying approaches, which, while feasible, introduce additional friction with the colon wall, as well as for tethered or base-tensioned strategies, which avoid friction but are limited in payload capacity or stability due to tendon friction. Red marks either the paper has no payload carrying method, or rigid approaches, as these compromise the robot's softness and increase friction against the colon wall.

3. Discussions

3.1. Which current materials and technologies are promising for colonoscopy

Our review of the literature highlights significant promise in the use of fabric materials for eversion robots. Fabrics are highly adaptable, in that they can be coated or uncoated, thick or thin, and fully-flexible or semi-rigid. Moreover, the method of yarn or thread combination (e.g. woven, knitted, or non-woven structures) influences their mechanical and structural properties, making them particularly attractive when creating adaptable and responsive robotic bodies.

However, this versatility also introduces added complexity when selecting the most suitable fabric for a given application. A more detailed material analysis is therefore necessary to identify optimal candidates for colonoscopy-specific eversion robots. While fabrics are promising, polymeric materials—particularly TPU—should not be overlooked, as they offer complementary advantages depending on design requirements and manufacturing constraints.

An important parameter governing the eversion behavior of the robot is bending stiffness, also known as flexural rigidity [147]. This property significantly affects the robot's ability to bend smoothly and navigate the colon's natural curvatures. The bending stiffness D is defined by:

$$D = \frac{E \cdot h^3}{12\left(1 - \sigma^2\right)} \tag{1}$$

where E is the Young's modulus, h is the material thickness, and σ is the Poisson's ratio. Notably, the thickness has a cubic influence on bending stiffness, indicating that minimizing material thickness is critical in achieving the low resistance required for smooth eversion and maneuverability. A lower Young's modulus further assists in reducing stiffness.

Considering equation (1), along with the values in table 2 and assuming a Poisson's ratio of 0.4 for all materials, the calculated bending stiffnesses are: polyethylene $0.175\,\mu\mathrm{N}\cdot\mathrm{m}$, TPU $0.026\,\mu\mathrm{N}\cdot\mathrm{m}$, TPU-coated fabric $0.006\,\mu\mathrm{N}\cdot\mathrm{m}$, and silicone-coated fabric $0.918\,\mu\mathrm{N}\cdot\mathrm{m}$. Among these, TPU-coated fabric emerges as a particularly promising candidate. Previous studies have demonstrated that TPU-coated fabric with a thickness as low as 0.031 mm can be successfully employed in soft robotic applications, with reported Young's moduli below 2 MPa [63], offering excellent flexibility. In principle, a TPU material with even lower thickness and modulus of elasticity could be developed without a fabric substrate; however, this would likely result in rapid fracture. TPU further offers versatility in bonding and sealing, with methods such as heat welding and ultrasonic welding [148]. The latter is particularly attractive, as it provides high precision and, similar to sewing, can be tailored to specific fabrication requirements, such as implementing navigation PAMs.

Among available navigation approaches, pre-bending—in which the robot is pre-shaped to match the colon's anatomy—appears simple but is impractical in clinical settings. While colon geometry can be estimated using medical imaging, the colon is dynamic and deforms with patient movement, making hard-wired pre-bent shapes unreliable.

Rigid navigation methods such as [36, 51] also present significant drawbacks. They compromise the key benefit of eversion robots—their ability to squeeze through narrow pathways of variable geometries. For colonoscopy applications, in which the colon diameter can change significantly along its length, preserving this squeezability characteristic is essential.

A more suitable approach is tip-based navigation, in which steering is localized at the robot's tip. This method retains the robot's overall compliance and allows for controlled navigation through sharp bends of high curvature and tight radii, which are commonplace within the colon. While an ideal soft robotic tip-steering solution has yet to be realized, the development of such mechanisms is a promising avenue for research.

Another critical requirement is the ability to deliver diagnostic and therapeutic payloads, such as cameras and surgical tools, deep into the colon. Existing approaches that use large rigid caps to carry payloads are clearly suboptimal, as they increase friction against the colon wall, reduce flexibility, and pose a risk of tissue damage, thus defeating the core advantages of eversion robots.

Soft cap-based solutions [52, 53] offer some improvement by preserving the robot's compliance, but they still generate unwanted friction during motion. The ideal payload-carrying method should therefore not involve the use of external caps. Promising research suggests that we explore the internal channel as a route to keeping payloads at the tip of the eversion robot. These methods better preserve the robot's frictionless behavior and offer a better solution for clinical applications.

3.2. Future research directions

There is a need for additional research on the materials proposed thus far in the literature for the construction of eversion robots. With fabric and polymer options both in the running, this research will need to identify the optimal material for smooth eversion. With colonoscopy specifically in mind, this material assessment should address the following:

- **Eversion performance:** How smoothly each material can evert as a function of the inflation pressure applied.
- **Natural maneuvering capabilities:** How each material behaves in terms of bending when inflated or manipulated.
- **Internal friction:** Which materials are most suitable for keeping the internal friction at a minimum.
- **Retraction:** Which materials allows smooth retraction without kinking.
- **Environment dependent eversion performance:** Assessing the material's suitability for navigating the colon environment, particularly with respect to the shape of the colon and its numerous turns.
- **Bio-compatibility:** Whether the material is suitable for use in medical applications, given unavoidable contact with human tissue.

The results of this study should provide valuable insights into which materials are most suitable for a colonoscopy application. The findings would guide further hardware designs, ensuring we use materials that best meet the demands of this specialized environment.

Another gap identified in the literature relates to textile material elasticity. Soft robotic research often categorizes textile materials into two types: knitted elastic fabrics (stretchable along two axes) and woven non-elastic fabrics (generally non-stretch) [149]. However, by integrating elastic yarns into woven structures, it is possible to create fabrics with two-way stretchability (stretchable along single axis) [150]. This material was already trialed in our previous research [151–153], but as yet has not been thoroughly investigated nor compared to alternatives. Proper characterization of these material types could open up new doors in the development of highly maneuverable soft robots.

Another important area for future research concerns the force thresholds that are acceptable for achieving painless colonoscopy, as well as the levels of force that may risk damaging the colon, even perforating the colon wall. Such data are particularly critical for robotic colonoscopy, where these thresholds may become essential design specifications for safe navigation within the colon.

Finally, there is currently a lack of standardized reporting in eversion robot studies. Key specifications that should be consistently reported include operating pressure range, material thickness, material modulus of elasticity, and robot diameter. For navigation-focused studies, maximum achievable bending radius and bending angle should also be documented.

4. Conclusions

This application driven review paper outlines the robotic requirements for colonoscopy and examines how eversion robots could effectively address these challenges. It analyses the essential colonoscopy customization options for eversion robots, incorporating constituent materials, sealing techniques, navigation strategies, and payload-carrying mechanisms.

The analysis reveals that there are a number of promising materials. Although fabric-based materials are highly flexible and adaptable, polymer materials may offer distinct advantages. Among these, TPU emerges as a particularly suitable candidate. This is attributed to its availability in ultra-thin film form, its relatively low Young's modulus—allowing for improved bending compliance—and its compatibility with established sealing techniques such as heat welding and ultrasonic welding.

Future research should aim to address open questions such as which materials enable the smoothest eversion, which offer the least resistance during motion, which are more resistant to kinking, which possess the lowest internal friction, and which are both bio-compatible and suitable for scalable manufacturing. A systematic exploration of these criteria, applied to both fabric and polymer options, is essential to identifying the most effective materials for eversion robot design with colonoscopy applications specifically in mind.

In terms of navigation, tip-steering mechanisms appear to offer the greatest potential, given the complexity of the colonic environment. If a robot's tip could successfully navigate the twists and turns, the eversion robot body would naturally follow. For this reason, the development of soft, internally actuated tip-steering techniques would appear to offer the best option for further research. In contrast, navigation systems that have rigid components compromise the inherent compressibility of soft robots and impose unwanted size constraints, effectively undermining one of the principal advantages of using soft materials.

Payload delivery is another crucial challenge. Systems that rely on rigid caps to carry tools or cameras are less desirable, as they increase friction against the colon walls and may lead to discomfort or injury. Again, such designs counteract an essential benefit of eversion robots, given their potential to minimize invasiveness and maximize patient comfort. The optimal approach would be a payload delivery method that does not require any kind of external cap. Some promising solutions have been proposed in the literature. One such method leverages an inchworm-like motion mechanism to transport payloads without a cap [55]; however, its practical viability is limited due to slow operation. Another recent approach attaches the payload to the tip of the robot without using a cap while also addressing the challenge of retraction [65]. These methods, though still in early stages, show strong potential and warrant further investigation. One final key aspect that needs further exploration is how to maintain an internal channel running from the robot's base to its distal tip, enabling tools and imaging systems to be delivered effectively—a concept that has been investigated by Seo *et al* [60]. Taken together, these developments suggest a clear design guideline: eversion robots for colonoscopy application should favor internalized tip steering [55, 139] and cap-free payload integration, ideally with a continuous working channel [60, 143].

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

Colonoscopy Suitability Table available at https://doi.org/10.1088/2516-1091/ae37b2/data1.

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