Robotica (2024), 1–11
doi:10.1017/S0263574724000055

REVIEW ARTICLE

A review of bioinspired locomotion in lower GI endoscopy

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Received: 4 January 2023; **Revised:** 8 November 2023; **Accepted:** 28 December 2023

Keywords: biomimetic robots; motion planning; legged robots; surgical robots; automation

Abstract

Flexible endoscopy is the gold standard modality for diagnosis and therapeutic intervention of various colorectal conditions. A high bar is currently set for any new technology to replace the current modern colonoscope, but limitations do exist. For a robotic system to gain acceptance, ideally a clear advantage over the established standard needs to be demonstrated. The application of robotic technology inspired by locomotion observed in animals has been demonstrated in many fields including colonoscopy. A myriad of novel concepts has been proposed, which can overcome the anatomical and technical challenges.

This review discusses novel and innovative examples of bioinspired robotic locomotion in the colon with a detailed comparison of studies alongside separating the discussion by animal sections of insect, marine and reptile locomotion. We also discuss the current advantages and challenges a bioinspired robot will bring to the colon.

Bioinspired robotics in the colon is an exciting field of research with the potential to improve upon current existing high standards of practice in colonoscopy. By addressing areas that the conventional colonoscope is weaker in, studies are demonstrating improvement upon current limitations of standard practice and providing an insight into new methods of engineering and fabrication. Focus on the technological, mechanical and regulatory barriers is key to achieve acceptance into standard practice and will allow the aspiration of a safe, low discomfort, low cost and potentially fully autonomous robotic colonoscope to be not too distant in the future of colonoscopy.

1. Introduction

Flexible endoscopy is the gold standard modality for diagnosis and therapeutic intervention of various lower gastrointestinal (GI) conditions such as polyps and colorectal cancer. Conventional colonoscopes consist of a control head and a flexible shaft with a manoeuvrable distal tip. The head is connected to a light source and the endoscope has channels to allow air and water delivery and suction. The working channel is used to pass endoscopic tools (e.g., biopsy forceps) and therapeutic devices. The endoscope is manoeuvred by an endoscopist manually in order to advance inside the colon [1].

A high bar is currently set for any new technology to replace the current modern colonoscope. Routine procedures can be completed in 20 min with low rates of complications such as perforation, which range from 0.01% to 0.6% [2, 3]. Various sedation options allow patient discomfort to be addressed in most cases. For a robotic system to gain acceptance, ideally a clear advantage over the established standard needs to be demonstrated, be it in adenoma detection rate, decreased patient discomfort or another objective metric.

Limitations do exist in the current practice; patient discomfort experienced during colonoscopy is multifactorial. These factors may include gender, abdominal pain indication for colonoscopy, inadequate bowel preparation and high levels of pre-procedure anxiety [4, 5]. For those patients who find standard colonoscopy too painful or the existing colon anatomy too challenging for a standard colonoscope, novel robotic technologies could be the technological solution required. Faster procedures and a reduced learning curve to achieve proficiency are potential advantageous benefits.

Translating this robotic technology to colonoscopy is stemmed from its success in the surgical paradigm and has been well documented in minimally invasive surgery. With the aid of surgical microrobots, micro procedures can be performed reducing healing time and complications [6]. Unrealistic initial expectations and a lack of a holistic platform are some obstacles that need to be overcome to promote a wider use of robotics in the medical field [7].

The application of robotic technology in aerospace, search and rescue, navigation, surgery and endoscopy has been inspired by locomotion observed in animals. A myriad of novel concepts has been proposed to improve safety, tolerability and therapeutic potential. These include increasing the dexterity of the flexible tubing, increasing the range of motion and the dexterity of the instrument and strengthening the structure of the instrument. Bioinspired principles such as contract-and-expand crawling, suction and unsuction along a path and propulsion forward with fins have been applied to robotics to access difficult cavities and navigate internal organs, overcoming the anatomical and technical challenges. Autonomous or semi-autonomous locomotion is also in development, which could involve active pulling of the endoscope or semi-automatic control driving the instrument replacing the passive pushing from outside the body [8, 9].

It must also be acknowledged given the vast changing landscape of the GI tract from the mouth to the anus, and the exact desirable characteristics for a robot will differ when targeting locomotion in the upper GI tract compared to the lower GI tract, taking into account the size of the lumen, gravity factors and also nearby organs.

This review discusses novel and innovative examples of bioinspired robotic locomotion in the colon with a detailed comparison of studies alongside separating the discussion by animal inspired sections of insect, marine and reptile locomotion. We also discuss the current advantages and challenges a bioinspired robot will bring to the colon [8, 10].

2. Insect-inspired robot designs

The leading area explored in the design for an autonomously moving device has been inchworm locomotion.

A worm-like design is naturally desirable due to the shape and ability to move in hollow tortuous environments representing the colon. Their movement is relatively simplistic, which reduces the technological challenge in recreating this locomotion.

Several studies (Fig. 1) have used the principle of 'inchworm technology' to develop miniature robots, which produce traction by clamping the colon wall with gentle vacuum suction followed by sequences of elongation and contraction phases [9, 11]. Variations of worm movement have also been adapted for device design. 'Inchworms' move with a clamper and extensor actuation and 'earthworms' with an expanding and contracting motion. Shape memory alloy (SMA), hydraulic, pneumatic, DC motors and piezoelectric actuators have all been used as actuation modalities to power worm-inspired robots [8, 9, 12]. Implementation of worm locomotion was first performed by Ikuta et al. in 1988. MEDI-WORM, driven by a SMA actuator was a robot capable of moving with inchworm technology.

Lin et al. (2011) and Formosa et al. (2019) publishing experiments showed that their worm prototypes are effective for locomotion in the colon. Chen et al. (2019) reported a novel assembly of balloons, which provided a highly controllable worm robot with high anchoring force: this enabled better manoeuvrability and stability in the colon and an improved level of comfort for the patient. Excessive expansion of the balloons, however, could induce considerable discomfort in the large bowel [18, 19].

Endotics established in Cascina, Italy is currently the only worm-inspired flexible robotic colonoscope that obtained FDA approval. It is a pneumatically driven robotic disposable colonoscope able to crawl through the colon by using two mucosal clamping devices, located at the proximal and distal ends of the probe, and a central soft extension/retraction mechanism, mimicking an inchworm-like locomotion. The robotic device is remotely controlled by a hand-held interface. A study with 40

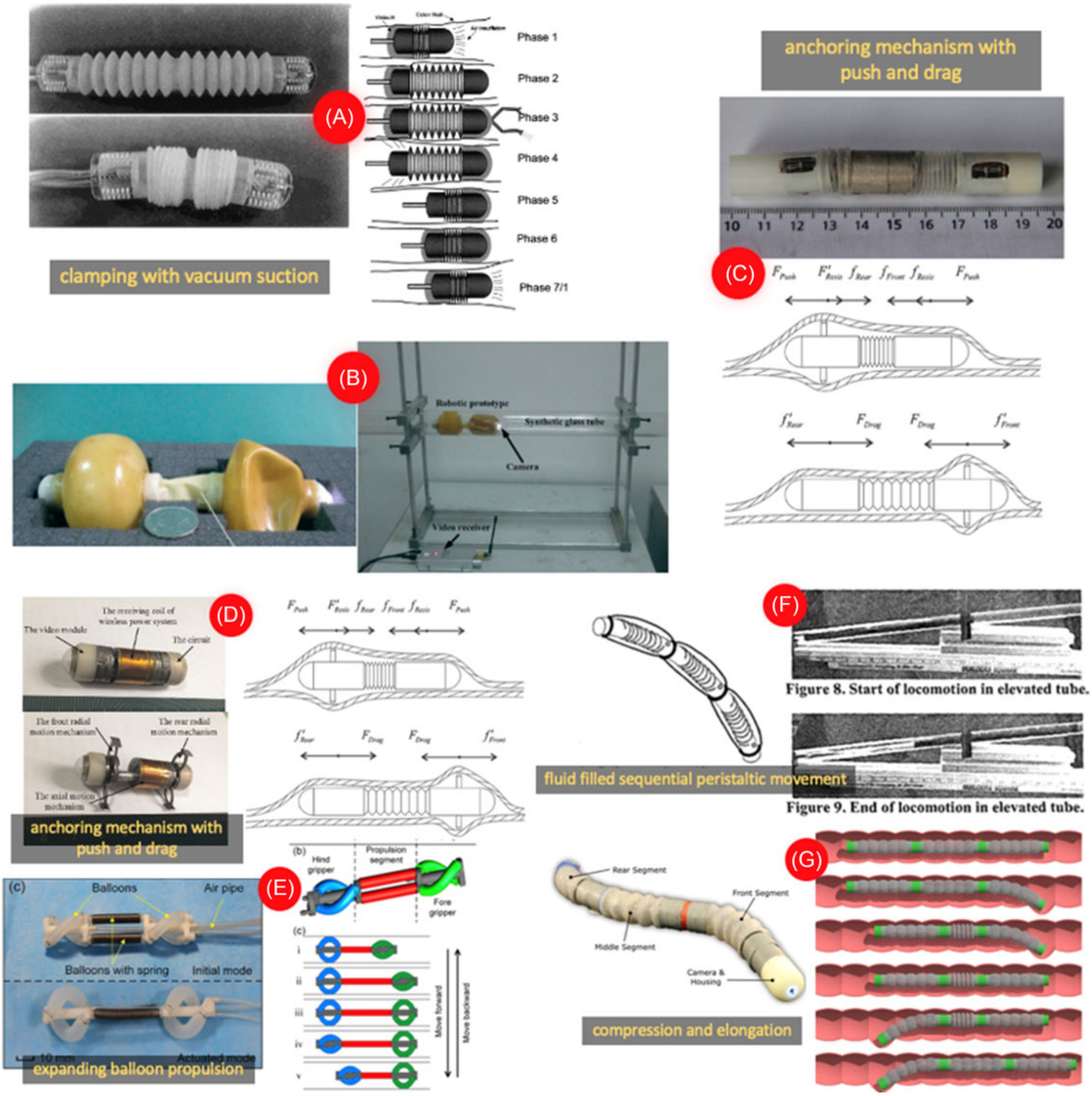

Figure 1. *Examples of inchworm robots grouped by movement pattern: Clamping with vacuum suction; Dario 1999 (A) and Gao 2011 (B). Anchoring mechanism with push and drag; Lin 2011 (C) and He 2015 (D). Expanding balloon propulsion; Chen 2019 (E). Fluid-filled sequential peristaltic movement; Mangan 2002 (F). Compression and elongation; Bernth 2017 (G) [10, 13–17].*

patients compared the Endotics System to a traditional colonoscope. Stress exerted, pain and discomfort were improved using the Endotics device compared to traditional colonoscopy. Polyp detection (93.3% and 100%) and caecal intubation rate (93.1% and 100%) were lower compared to traditional endoscopy [20].

Caterpillar locomotion (Fig. 2) has also been demonstrated with a flexible robotic colonoscope, which is actuated by an external electric motor through a flexible shaft. Kim et al. developed three 'caterpillar' like rotating belts, which were placed on a device that allowed gripping on the lumen and forward movement similar to the worm [21]. Preliminary porcine studies demonstrate feasible locomotion with the capability to navigate to the transverse colon, travelling an approximate distance of 60 cm in under 2 min [21].

Figure 2. *Caterpillar- and spider-inspired insect locomotion: Kim 2014 (A), Lee 2019 (B).*

Besides inchworm devices, locomotion modalities of different insects have also been a source of inspiration (Fig. 2). Lee et al. have developed a six-legged, spider inspired, robotic colonoscope [22] based on a reel-based mechanism (forward movement along a tension wire) actuated by an external electric motor. Provisional studies have shown that locomotion is feasible in a pig colon with minimal tissue damage [22].

EndoSamurai [23], R-scope [24], Anubiscope [25] and Isis-scope [26] are a few examples of other bimanual, insect-inspired designs in the early development phase, which have been proposed to deliver therapy in colonoscopy [27].

Other upcoming research devices used in porcine colons were also able to reach further distances in similar procedure times when compared to standard colonoscopy. Prototypes have been shown to be able to traverse the rectum, sigmoid and descending colon albeit with efficiency declining in curved portions of the bowel, such as flexures [4, 11, 15, 16].

Joystick control and navigation, dual power units and wireless control have been used to drive these innovative platforms [13, 16].

3. Marine-inspired robotic designs

Marine animals such as octopi have evolved to efficiently locomote in water (Fig. 3). In addition, their ability to grip and stabilise objects using suction is exquisitely unique. Their movement mechanism relies on reducing friction and drag. This is particularly interesting given the advent of water-assisted colonoscopy and may suggest a novel robotic solution to endoscope navigation within the lumen of the colon [28].

The octopus arm lacks a rigid structure; thus, it can squeeze through narrow apertures. Its unique muscular arrangement allows elongation, bending and stiffening, which could potentially enable navigating within a colonic lumen. These capabilities are all desirable in a surgical manipulator, and in a future endoscopic soft robot they may help improve navigation in challenging areas such as the small bowel [29].

The octopus' arm has been the inspiration for Stiffness Controllable Flexible & Learnable Manipulator for Surgical Operations (STIFF-FLOP). STIFF-FLOP is a silicon-based soft robot actuated by a combination of pneumatics and material, which can take liquid, solid or in between states, resulting in variable stiffness; this mechanism is known as granular jamming. The STIFF-FLOP system has been successfully demonstrated in two cadaveric procedures where rectal resection was performed endoscopically. Its established use is still however mainly in minimally invasive surgery [30].

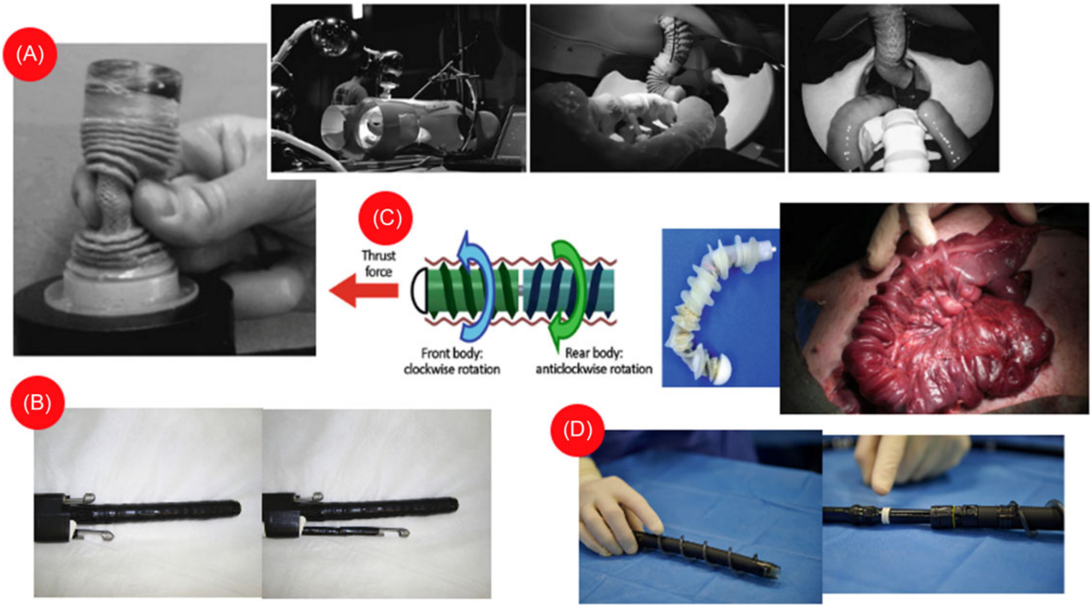

Figure 3. *Design inspired by marine animals: STIFF-FLOP (A), Wagh 2012 (B), Trovato 2010 (C) and PowerSpiral (D).*

The feasibility of using octopus-inspired suction as a means of endoscopic locomotion in the bowel remains in the preliminary stage of research. Wagh et al. [31] conducted a novel pilot study with customised suction tips retrofitted to a colonoscope, which are fixed and changeable in position to traverse the bowel. The increased grip produced by the suction tips resulted in a sequential suction-and-release manoeuvre that enabled the colonoscope to traverse inside the entire small bowel. Studies consisted of ex vivo tests on resected porcine intestinal segments and in vivo procedures on live anaesthetised animals. The design of the suction cup was a major focus in the study with the optimal aim being to produce a reliable, non-traumatic and easily reproducible tip. The current suction cups are in the form of an external attachment, which is affixed along the desired colonoscope. A future model will aim to integrate the endoscope with movable suction tips making a novel suction enteroscope. Future work will also involve developing a slimmer and more flexible suction devices, which can allow oral entry [31].

A flexible endoscopic robot with flexible helical fins representing a fish that can be controlled manually and automatically has been developed by Trovato et al. (Fig. 3) [32]. This novel robot consists of a front body with clockwise helical fin and a rear body with anti-clockwise fin, both connected by a motor. As the front body and rear body of the robot are connected, when one half cannot rotate, the other half can continue to provide thrust force and overcome the temporary resistance thus continuing locomotion. Ex vivo and in vivo preliminary studies show the robot being able to move forward and backwards in the colon [32]. A possible disadvantage of the robot is when the radius of the colon is too small or too large compared to the helical fins resulting in inability to continue movement.

Using a similar principle, Olympus has developed the PowerSpiral (Fig. 3). This is an enteroscope that uses soft spiral-shaped fins placed on an overtube, which can pull the intestine on the enteroscope and provides a novel option of reaching the small bowel via the oral cavity. A user-controlled motor powers the fins and allows control of the direction and speed of the spiral segment. A prospective feasibility study was performed by Beyna et al. in 2021, which demonstrated technical success in 97% of procedures [33]. In 14 patients, complete antegrade pan-enteroscopy was demonstrated with the PowerSpiral reaching the caecum [33].

Figure 4. *Designs inspired by Reptiles: NeoGuide (A) and i2 Snake (B).*

4. Reptile-inspired robot design

Snake-inspired robots were introduced in the early 1970s by Shigeo Hirose. Similar to worm designs, snake designs are prevalent given their form of locomotion and perceived suitability for the target colon. Snake locomotion is based on the fact that the friction in the lateral direction is larger than that in the longitudinal direction, which is why snakes push sideways with their body in order to move forward. Snake-inspired locomotion provides a large amount of contact between the ground and the posterior aspect of the robot. This large surface area results in the device having advantageous traction, a characteristic that is highly desirable in variable environments such as the bowel [34].

The NeoGuide Endoscopy System is a commercially approved computer-assisted colonoscope consisting of a 16-segment insertion tube that achieves a snake-like movement of the endoscope (Fig. 4) [20]. Each segment is independent and electromechanically controlled. Position sensors at the distal tip of the endoscope allow real-time 3D mapping of the colon to be obtained. Computerised mapping enables the scope to change the segments shape at different insertion depths in a ‘follow-the-leader’ manner to negotiate colonic flexures. This provides reduced looping and reduces unintentional lateral forces to the colon wall, which subsequently reduces patient discomfort during the procedure. In a study of 10 patients, successful caecal intubation with an overall average procedure time of 34 min (range: 24–60 min) was achieved. There was also a reduction in the looping rate compared to standard colonoscopy [20].

The i^2 Snake Robotic Platform for Endoscopic Surgery includes a snake-like robotic endoscope equipped with a camera, a light source and two robotic instruments (Fig. 4). Global positioning and insertion of the i^{2}Snake are achieved using a robotic arm controlled by a master–slave teleoperation system. [23]

5. Discussion

Table I summarises the key factors of the prototypes from the studies in this review in relation to locomotion.

5.1. Future versus now

The current average expected time of a flexible colonoscopy is approximately 20 min. This is considered an efficient time frame to obtain critical diagnostic information. A challenge to robotic colonoscopy will be the inefficiency in the forward or backward movement seen in some studies resulted in on average a longer duration of procedure. This is seen in clamper extensor mechanisms robots; however, they also

Table I. *Summary of locomotion factors in the various studies (‘-’ represents no information available on this category).*

	Study	Distances assessed	Invasiveness	Speed	Tethered/ Untethered	Environment	Cost	Autonomy	Position and orientation
Insect	**Dario 1999**	Able to traverse 130 cm in 25 min	–	10 cm/min	Untethered. Has a service pipe as a fail safe	Porcine animal tissue model	Low cost	Autonomous	Electromagnetic sensor
	Gao 2011	10 cm length assessed	No obvious perforation or trauma	315 s to travel 1 cm effectively	Untethered	Porcine colon	–	Non-autonomous	–
	Lin 2011	No movement in diameters larger than 2.2 cm	–	0.008 to 0.05 cm/s	Untethered	Porcine colon	–	Non-autonomous	–
	He 2015	3 intestinal diameters with each less than 60 s	–	0.062 to 0.129 cm/s	Untethered	Porcine colon	–	Non-autonomous	–
	Chen 2019	Device will function in diameter between 2.2 and 3.2 cm	–	0.5 cm/s	Untethered	Acrylic tube	Low cost	Non-autonomous	–
	Mangan 2002	–	–	0.508 cm/s	Tethered	Acrylic tube	–	Non-autonomous	–
	Bernth 2017	–	–	0.121 cm/s	Untethered	Plastic tube	Low cost	Non-autonomous	–

Table I. *Continued.*

	Study	Distances assessed	Invasiveness	Speed	Tethered/ Untethered	Environment	Cost	Autonomy	Position and orientation
	Kim 2014	Faster movement when inclined and moving backwards	–	2.38–2.55 cm/s	Tethered	Porcine colon	–	Non-autonomous	–
	Lee 2019	–	No perforation or damage observed	0.955 ± 0.194 cm/s	Tethered	Porcine colon	–	Non-autonomous	Position controller (motor based)
Marine	**Cianchetti 2014**	–	–	–	Tethered	Human colon	Low Cost	Non-autonomous	–
	Wagh 2012	–	Minimal focal erosions and disruption of lamina propria	Increments of 25 cm (No time)	Tethered	Porcine colon	–	Non-autonomous	–
	Trovato 2010	Maximum travel distance 70 cm	No damage	4 cm/min	Tethered	Porcine colon	–	Non-autonomous	–
	Beyna 2021	450 cm maximum length assessed	Atrauma noted on photographs	Median total procedure time was 54 min (range 10–163)	Tethered	Human colon	–	Non-autonomous	Compatible with MEI
Reptile	**NeoGuide**	–	–	34 min average	Tethered	Human colon	–	Non-autonomous	Compatible with MEI
	I2 Smake	–	–	–	Tethered	–	–	Non-autonomous	–

report the safest methods of movement observed in the in vitro and ex vivo trials in the various studies [9, 13].

Future bioinspired robotic designs have the potential to be superior to the current standard colonoscopy. A lower range of force on the colon will provide a more comfortable procedure and therefore allow better completion rates of procedures. There is also ongoing work on autonomous and semi-autonomous designs, which will allow better navigation of difficult routes. Autonomous sensing ability can allow recalculation of tendon length for movement, and automatic and continuous anchoring, contracting and un-anchoring of segments can allow smoother continuous movement [35]. Hence, a shallower learning curve could result from a more comfortable procedure and assisted navigation and operation allowing less procedures to be deemed incomplete.

5.2. Technological and manufacturing barriers

A common obstacle to the development of robots and progression of locomotion technology in the bowel is in manufacturing the smaller scale components required. This can prove critical in decreasing discomfort and also tissue trauma on the colon wall. Commonly hydraulic and pneumatic systems allow actuators to be outside the main body, which can aid miniaturisation, but some designs require the system to be in the main body such as fluid powered robots and this may require larger diameters, which can increase the likelihood of discomfort [28, 32]. The weight of the system versus the load bearing the robot can undertake is also challenging as you aim to miniaturise manufacturing to work in the diameter of the colon as reported by Gao et al. The lighter the robot, the less friction that it will also exhibit on the bowel walls. Also decreasing the size of actuators will provide a key role in moving the technology into the small bowel [13].

The temperature in the bowel wall created during robot locomotion is also a factor to consider. Certain materials may deform if used with high temperatures and this may result in slower speeds of movement. Heat that is emitted can also result in combustible gas being released in the colon and also the direct damage to the lumen wall secondary to heat needs to be considered. Hence, testing in as close to a biosimilar environment is key. Being able to assess the movement of peristaltic force and assess for any mucosal damage on as real-like material will help progression before in vivo human trials [35]. This precludes the use of some actuation techniques that are common in soft continuum robots, such as SMAs.

Some studies have researched a wireless energy supply that could potentially increase the degree of movement and possibly reduce pain and discomfort with the removal of wires to an outside control or power unit. It can also be argued, not having a tethered system removes the fail safe of a device failure where the operator still can manually withdraw and retrieve the robot from the colon. Further challenge to a wireless system includes ensuring an adequate power supply for a prolonged procedure. The reliability of DC torque and piezoelectric motor designs reporting lower power reliability due to the complex mechanisms required should also be further investigated [8, 9, 12].

Studies have also begun implementing real-time position and orientation tools to the robot in the colon. A novel concept is the use proprioceptive sensing that could be used in conjunction with machine learning to reconstruct the shape of the robotic endoscope for visualisation and navigation purposes [35].

5.3. Regulatory and economic hurdles

A significant challenge to implementation of robotics in colonoscopy will be the regulatory and approval hurdles that these new technologies face before they can reach the clinical sector. These aspects are crucial for these innovations and will require any group to thoroughly demonstrate and clearly outline safety and regulatory guidelines.

With the recent evolvement towards green endoscopy, biocompatible materials and easily disposable recyclable materials are an imperative action point for all future innovative projects. Prudent consideration is required during the design phase of such robots, for example in the coating of the robot. Latex adjacent to nylon mesh tends to suffer from fatigue and corrosion with rubbing during each cycle of movement contraction. The allergic reaction potential of latex for some patients would also be a potential absolute contraindication. Silicone-based material to aid robotic movement has the advantage of being flexible, highly biocompatible, easily produced and economical [8, 9].

The cost of production plays a factor in the transition of these novel concepts into clinical and commercial practice also. With the current misconception being that these robotic technologies are higher cost compared to the current standard. A clear long-term outline of the cost saving, or head-to-head comparison would be ideal to demonstrate to decision makers the advantages of robotic colonoscopy.

6. Conclusion

Bioinspired robotics in the colon is an exciting field of research with the potential to improve upon current existing high standards of practice in colonoscopy. By addressing areas that the conventional colonoscope is not doing so well in, will be a great starting point and studies are demonstrating improving upon current limitations of standard order of practice and providing an insight into new methods of engineering and fabrication. Focus on the technological, mechanical and regulatory barriers is key to achieve acceptance into standard practice and will allow the aspiration of a safe, low discomfort, low cost and potentially fully autonomous robotic colonoscope to be not too distant in the future of colonoscopy.

Author contributions. JA conceived, designed and wrote all of this article. EF provided clinical advice. FRB, AD and NP provided oversight and overall supervision of this manuscript.

Financial support. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Competing interests. The authors declare none.

Ethical approval. Not applicable.

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Cite this article: J. F. Ahmed, E. Franco, F. Rodriguez Y. Baena, A. Darzi and N. Patel, "A review of bioinspired locomotion in lower GI endoscopy", Robotica. https://doi.org/10.1017/S0263574724000055