Received: 22 August 2022 | Revised: 18 September 2022 | Accepted: 11 October 2022

DOI: 10.1002/rcs.2471

The International Journal of **Medical Robotics** and **Computer Assisted Surgery**

WILEY

REVIEW ARTICLE

Continuum robots for endoscopic sinus surgery: Recent advances, challenges, and prospects

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Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 62133009, 61973211, M-0221; The project of Institute of Medical Robotics of Shanghai Jiao Tong University; Science and Technology Commission of Shanghai Municipality, Grant/Award Number: 21550714200

Abstract

Purpose: Endoscopic sinus surgery (ESS) has been recognized as an effective treatment modality for paranasal sinus diseases. Over the past decade, continuum robots (CRs) for ESS have been studied, but there are still some challenges. This paper presents a review on the scientific studies of CRs for ESS.

Methods: Based on the analysis of the anatomical structure of the paranasal sinus, the requirements of CRs for ESS are discussed. Recent studies on rigid robots, handheld flexible robots, and CRs for ESS are presented. Surgical path planning, navigation, and control are also included.

Results: Concentric tube CRs and cable-driven CRs have great potential for applications in ESS. The CRs incorporated with multiple replaceable arms with different functions are preferable in ESS.

Conclusion: Further study on navigation and control is required to improve the performance of CRs for ESS.

KEYWORDS
continuum robots, endoscopic sinus surgery, paranasal sinus, surgical robots

1 | INTRODUCTION

The paranasal sinuses are paired and symmetrical, air-filled cavities situated within specific facial and skull bones. As shown in Figure 1, humans have four pairs of paranasal sinuses: maxillary, frontal, sphenoid, and ethmoid. They are named according to the bones in which they are located.[1,2] The paranasal sinuses can be regarded as the extensions of the nasal cavity, and all paranasal sinuses drain into the nasal cavity.[3] The prime functions of the paranasal sinuses are reducing the weight of the head, warming and humidifying the inspired air, supporting the immune defense of the nasal cavity, increasing resonance of the voice, and protecting the face and facial bones from trauma.[4,5]

As the paranasal sinuses directly communicate with the nasal cavity, they are easily affected by the infection of the upper respiratory tract. Chronic sinusitis is a common disease in this area. It can be caused by a viral or bacterial infection, allergies, air pollution, or structural problems in the nose.[7] Some patients have chronic sinusitis with nasal polyps or nasal sinus cysts. The average prevalence of chronic sinusitis ranges from 4.6% to 16.9% annually depending on the study methodology and sample size.[8] Nasopharyngeal carcinoma, papilloma, adenocarcinoma, and esthesioneuroblastoma are the common tumors involved in the sinonasal region.[9,10] Surgical interventions are performed to treat sinus diseases, especially for patients who fail appropriate medical therapy. Before 1985, sinus surgery was typically performed using an open surgical approach.

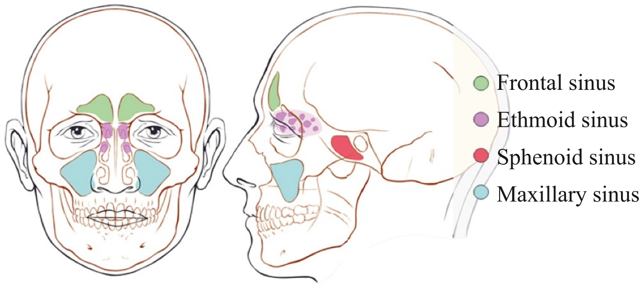

FIGURE 1 Locations of paranasal sinuses[6]

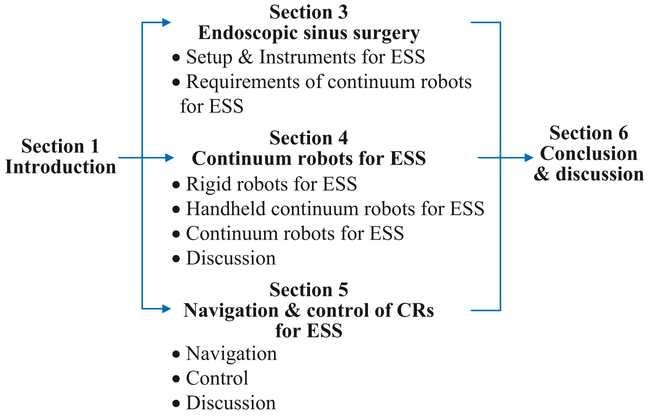

FIGURE 2 Outline of the structure

However, this approach can increase patient discomfort and hospital time.[11] With the development of specialized instruments, computer technology, and medical imaging techniques, endoscopic sinus surgery (ESS) has emerged as a minimally invasive procedure that is conducted by opening the natural ostium of the diseased sinus. At the same time, the evolution of minimally invasive techniques and the introduction of the endoscope have led to endoscopic surgery rapidly becoming the standard of care for a part of skull base tumors.[3,12,13] However, even experienced neurosurgeons or rhinologists face some challenges as the operation is performed through a tight space adjacent to internal carotid arteries and important anatomical structures.

In recent years, robotic surgery has received much attention, and it allows surgeons to perform many types of complex procedures with more precision, flexibility, and control.[14,15] As the most advanced platform for minimally invasive surgery, the da Vinci surgical system has been utilized in several surgical specialties.[16,17] However, such general-purpose surgical robots are not suitable for all clinical applications, especially for surgeries performed in constrained spaces. To improve the dexterity, workspace reach, and maneuverability in confined and unstructured space, continuum robots (CRs) have been studied for minimally invasive surgery.[18–20] Although these CRs are well-designed for their applications, the specifications such as diameter, curvature radius, or range of bending angle are not appropriate for ESS. Over the past decade, robot-assisted ESS has been studied. The research mainly includes rigid robot-assisted surgery, handheld flexible robots, and CRs. Previous review papers focus on rigid robot-assisted ESS[21,22] or briefly introduce the application of flexible robots in ESS.[23]

In this paper, according to the anatomy of paranasal sinuses, the requirements of surgical instruments are analyzed. Recent advances in CRs for ESS are reviewed. Compared with rigid robots, the advantages of CRs for ESS are introduced. In addition to the mechanical design, the navigation and control methods of CRs in relevant fields are discussed. Although some CRs are designed for ESS, there is still room for improvement, particularly in terms of navigation, control, and the development of smaller and more reliable robotic systems. This paper aims to provide current perspectives, as well as prospects of CRs for ESS. The remainder of this paper is organized as follows. Section 2 gives the review method. Section 3 briefly introduces the anatomy of the paranasal sinuses, and then the requirements of surgical instruments for ESS are analyzed. Section 4 reviews the CRs for ESS. The challenges of navigation and control of CRs are addressed in Section 5. Finally, Section 6 concludes this paper. The outline of this paper is shown in Figure 2.

2 | REVIEW METHOD

A comprehensive literature search was carried out by using the Web of Science. As for research about robots for ESS, the keywords are '(robot) AND (sinus surgery OR transnasal surgery OR skull base surgery)', and all the concerned English publications from 2005 to 2022 were collected; resulting in a total of 372 papers. The papers with commercial surgical robots (e.g., the da Vinci robotic system) for invasive surgery were excluded. The papers were further shortlisted based on research groups and demonstrations of the same robotic system. As for the traditional rigid instruments for ESS, 5 papers were identified through ResearchGate with keywords 'instruments sinus surgery'. Seventeen papers were identified through ResearchGate with keywords 'sinus surgery' to exact more information about the anatomy and diseases of the paranasal sinuses. As for control strategies for CRs, most of the papers were identified through the Web of Science with keywords '(CR) and (control)'. Moreover, some of the key cited articles in the references came from our accumulation and attention.

3 | ENDOSCOPIC SINUS SURGERY

3.1 | Setup and instruments for ESS

The paranasal sinuses are air-filled extensions of the nasal cavity. The anatomy of the paranasal sinuses is shown in Figure 3. Different from laparoscopic surgeries and other natural orifice transluminal endoscopic surgeries, the surgical path and operating space of ESS are constrained. For example, the pathways to the frontal sinus and maxillary sinus are anatomically curved and narrow.[24] The above situations put forward higher requirements for both surgeons and instruments. ESS is performed by opening the natural ostium of the diseased sinus. The typical operating setup of ESS is shown in

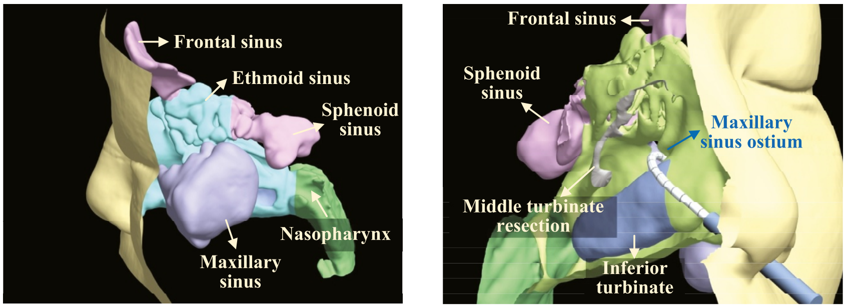

FIGURE 3 The anatomy of the paranasal sinuses

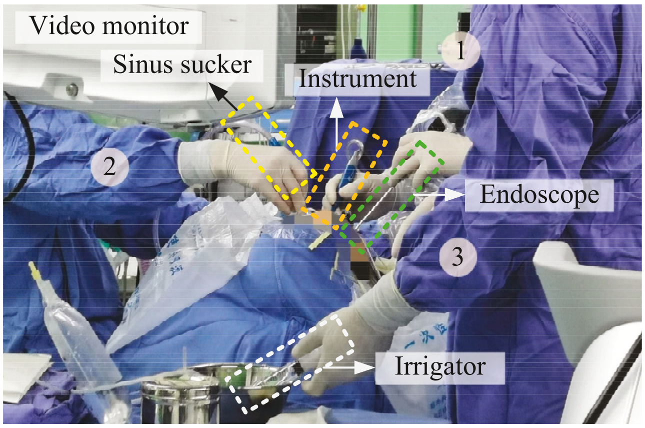

FIGURE 4 Setup of endoscopic sinus surgery (ESS)

Figure 4. The surgeon has a rigid endoscope in one hand and an instrument in the other. The endoscope is used to tent the nasal vestibule superiorly, allowing the instrument to pass through. The assistant uses the suction tube to remove the blood and peeled tissue in the operating field. The assistant uses the irrigator to wash the lens of the endoscope and keep the surgical view clear. The video monitor provides a large magnified image that can be advantageous for delicate work. In order to perform different surgeries, a broad range of specially designed endoscopic surgical instruments are required. The following instruments are important for basic ESS.[12,25–28]

1) Nasal Endoscopes: Using various endoscopes, the surgeon can directly visualize most sites within the operating field. The commonly used rigid nasal endoscopes, shown in Figure 5, have angles ranging from 0° to 70°. The 0° endoscope is preferred in most cases because of its minimal optical distortion and disorientation. Angled endoscopes, including 30°, 45°, and 70°, have been designed to extend the visualization of the surgical space of ESS. If angled endoscopes are used, relative instruments need to be curved so that the tip of the instrument can be controlled in the centre of the endoscope view. It should be noted that the manipulations become more difficult as the angles of the endoscope and instrument increase.

2) Forceps and Scissors: As shown in Figure 6A, biopsy forceps with different angles are indispensable tools for endoscopic examination of the sinuses. Blakesley forceps (Figure 6B) are most typically used to remove mobilized polyps or tissue. Back biters (Figure 6C) are used for removal of the uncinate process. Circular cutting punches (Figure 6D) can cut a full circle of 360°. They facilitate precise mucosa-sparing dissection. Bipolar forceps (Figure 6E) are used for ablation and coagulation of soft tissue in ESS.

3) Irrigation Cannulas: As shown in Figure 6F, irrigation cannulas are used to irrigate and aspirate the sinuses so that the surgical field can be kept clear.

4) Powered Instrumentation: A variety of blades (Figure 6G) for soft-tissue removal and burs (Figure 6H) for bone removal are available based on the same power platform. Microdebrider blades with rotating cutting openings and shaft angles are shown in Figure 6G. They allow operating in a non-bleeding environment while simultaneously suctioning and cutting soft tissue away. High-speed burs (Figure 6H) are used for bone removal in ESS.

3.2 | Requirements of continuum robots for ESS

As reviewed in Section 3.1, the rigid instruments for ESS should be designed with a broad range of specifications so that a variety of sinus surgeries can be performed. Compared with rigid instruments, CRs have great potential for enhancing dexterity, workspace reach, and maneuverability in confined and unstructured space. Based on the anatomical characteristics of sinuses and rhinologists' suggestions, the requirements of CRs for ESS are summarized as follows:

1. The anatomy of the sinuses is complex and varied. The surgical path is curved and narrow. Thus, surgical instruments should be designed with high dexterity and limited diameter to approach the blind regions.
2. The surgical field is critical in ESS. Proper hemostasis is needed, and the vision of the endoscope should be kept clear. Instrumentation must be visualized in the endoscopic field to reach the target tissue.
3. The operating space is adjacent to the orbital cavity, internal carotid artery, and other vital anatomical structures.[29] Surgical instruments should be controlled precisely to avoid damaging any of these structures.
4. ESS is performed mostly with a broad range of specially designed endoscopic surgical instruments.[12] The instruments should be changed easily during ESS.
5. Surgical path planning and navigation are important to ensure the safety of surgery in ESS.
6. Uncontrolled force application could cause serious complications. Thus, force feedback is also important in ESS.

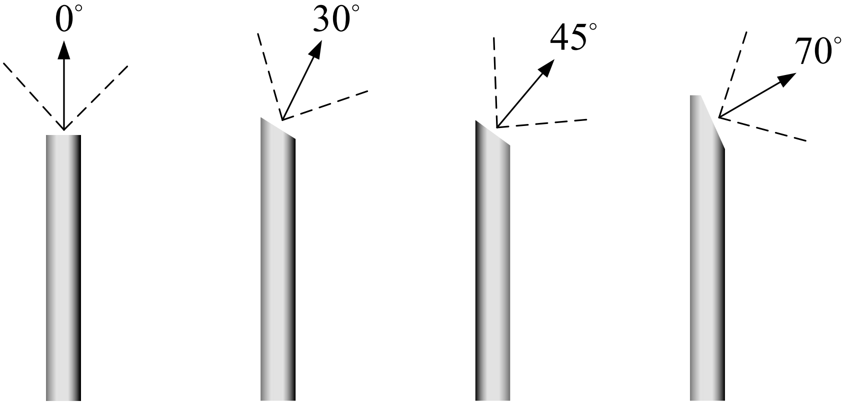

FIGURE 5 Rigid nasal endoscopes with angles ranging from 0° to 70°

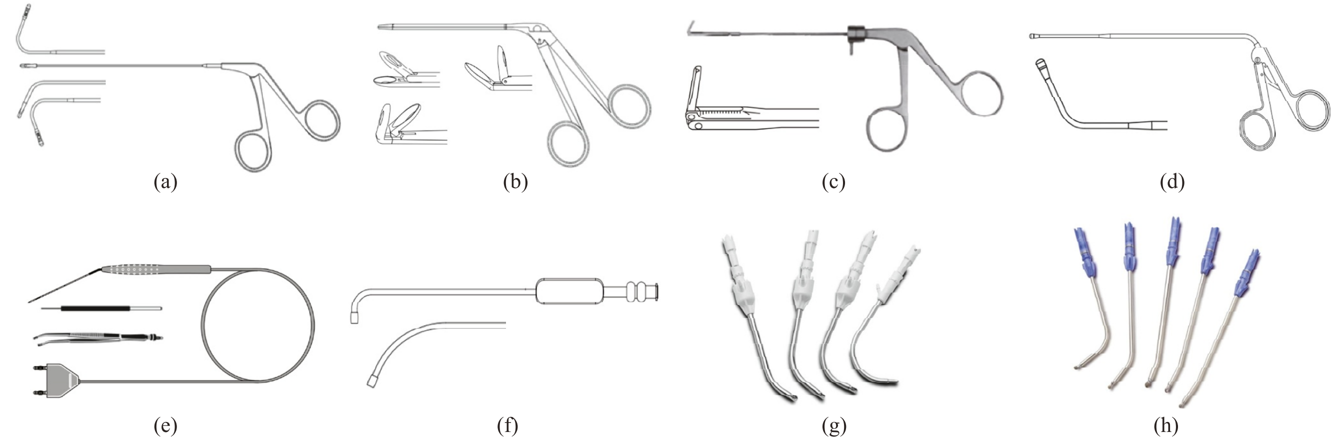

FIGURE 6 Rigid instruments for endoscopic sinus surgery (ESS)[28] (Copyright © 2017, Olympus Australia Pty. Ltd.). (A) Biopsy and grasping forceps. (B) Blakesley nasal forceps. (C) Back biters. (D) Circular cutting punches. (E) Bipolar forceps. (F) Irrigation cannulas. (G) Blades. (H) Burs.

4 | CONTINUUM ROBOTS FOR ESS

As discussed in the previous section, surgeons usually have to guide the endoscope themselves to view the surgical field during sinus surgery. This manner completely occupies one of their hands, limiting their ability to operate with more instruments. As for current rigid instruments, their dexterity and maneuverability in constrained space are restricted. In recent years, researchers have contributed to the studies of robot-assisted ESS.

4.1 | Rigid robots for ESS

The surgeon can only operate one tool at a time in ESS as the endoscope should always be held in the surgeon's left hand. To release the surgeon from the endoscope manipulation task, some researchers try to employ rigid-link robots to hold the endoscope for ESS. In,[30] a 7-degrees of freedom (degrees of freedom (DOF)) robotic endoscope holder was designed for sinus surgery. As shown in Figure 7A, the positioning arm adopted a negatively actuated air-locking system, and the operator could only manually manipulate it. He et al.[31] developed a 7-DOF active sinus robot (as shown in Figure 7B) for adjusting the pose of the endoscope, and an NDI optical tracking system was used to evaluate the accuracy. But the control method was not introduced in this robotic system. In,[32] an endoscope manipulator with passive and active structures (as shown in Figure 7C) was developed for ESS. The surgeon could manually place the endoscope near the patient's nostril through a 5-DOF passive structure. With an IMU-based interface attached to the surgeon's foot, a 4-DOF motorized structure could actively control the endoscope's position. On the basis of,[32] a more detailed implementation[33] was achieved, and cadaver studies were conducted to evaluate the design. In,[34,35] an endoscopic positioning system (Figure 7D) was studied. In this system, a 7-DOF mechatronic holding arm was used for rough positioning of the endoscope. A robotic hand with 5-DOF was attached to the tip of the arm, realizing the movement of the endoscope. The pose of the endoscope was controlled by the surgeon through a custom foot pedal.

The above representative rigid robots for ESS in recent years are summarized in Table 1. Although these rigid robots for ESS are designed to hold an endoscope, most of them still require manual operation. In,[32–35] control interfaces connected with foot are used, but it is not convenient for the surgeons to always concentrate on the foot control. In addition, the endoscope used in the above prototypes is still rigid, and its dexterity is limited in ESS.

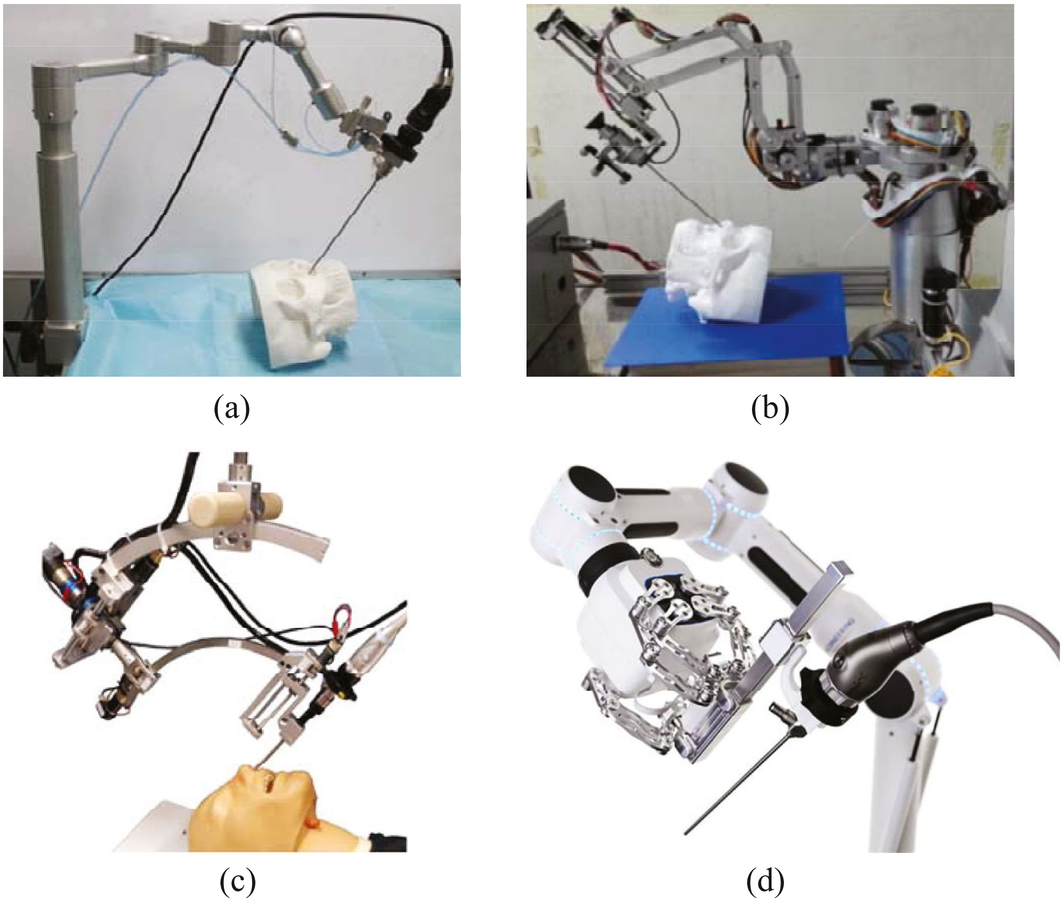
(a)
(b)
(c)
(d)

FIGURE 7 Rigid robots for endoscopic sinus surgery (ESS). (A) Robotic endoscope holder for sinus surgery[30] (Copyright © 2015, IEEE). (B) Assistant robot system for sinus surgery[31] (Copyright © 2016, ASME). (C) Endoscope manipulator with passive and active structures for ESS[32] (Copyright © 2015, IEEE). (D) Robotic endoscope positioning system for transnasal sinus and skull base surgery[34,35] (Copyright © 2020, Friedrich et al.).

TABLE 1 Representative rigid robots for ESS

Research Group	DOF	Driving mode	Control interface
Sun et al.[30]	7	Passive	None
He et al.[31]	7	Active	None
Lin et al.[32]	5 for passive structure; 4 for active manipulator	Passive and active	IMU-based control interface attached to surgeon's foot.
Friedrich et al.[34,35]	7 for manual operation of rigid-link robot; 5 for endoscope movement	Passive and active	Custom foot pedal with joystick.

4.2 | Handheld continuum robots for ESS

Due to the complex anatomical structure of the paranasal sinuses, it is still a challenge to reach some blind regions and avoid obstacles with the existing rigid surgical instruments. To improve the maneuverability and dexterity of the surgical tools, some handheld bendable CRs have been studied. As shown in Figure 8A, amanual grasper with controllable curvature was developed for sinus surgery in.[36] The bendable part was implemented by a multi-backbone continuum mechanism, and a grasper was attached to the tool's tip. A thumb-activated joystick at the rear of the handle enabled the surgeon to regulate the CR bending. However, restricted by the workspace of the thumb and the CR's structure, the bending angle was limited. In,[37] a drivable endoscope (Figure 8B) with bending angle from 0° to 125° was designed to improve the visualization of the sinus anatomy. The miniature endoscope had a camera at its distal end and a built-in channel for irrigation. The efficacy and usability of the drivable endoscope were evaluated by clinical studies. Coemert et al.[38] designed a handled flexible manipulator (Figure 8C) with an instrument channel and an endoscope channel. It contained two segments, and each segment could achieve a planar bending. However, the manipulator could only bend no more than

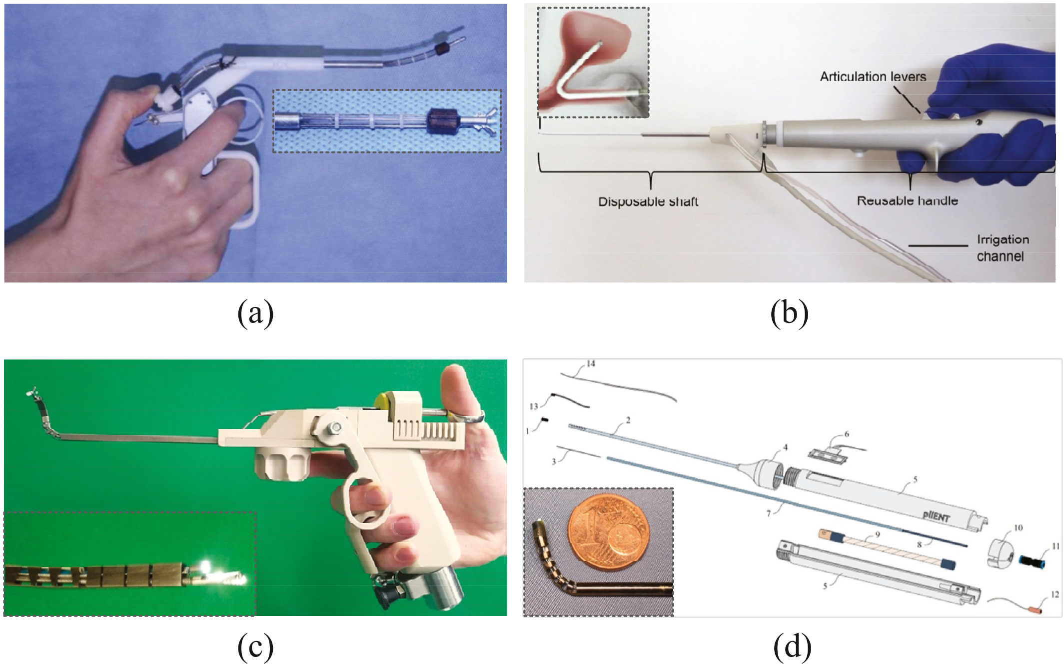

FIGURE 8 Handheld continuum robots (CRs) for endoscopic sinus surgery (ESS). (A) A stiff steerable grasper for sinus surgery[36] (Copyright © 2014, ASME). (B) A drivable endoscope[37] (Copyright © 2019, Springer). (C) A handheld flexible manipulator for frontal sinus surgery[38] (Copyright © 2020, Coemert et al.). (D) A robotic steerable endoscope for maxillary sinus surgery[39] (Copyright © 2022, Legrand et al.).

76° in one direction. It was only designed for frontal sinus surgery. As shown in Figure 8D, Legrand et al.[39] developed a miniature robotic steerable endoscope for maxillary sinus surgery. The diameter of the bendable part was 2.3 mm, and its maximum bending angle was 125°, allowing to visualize all maxillary sinus walls. The performance of the steerable endoscope was validated in the cadaver experiments.

The above handheld CRs for ESS can achieve continuous shape change, and they are more adaptable to different conditions in ESS. But in practical applications, there are still some problems. For instance, the surgeons have to maintain their hand posture in order for the CRs to reach a specified state in Figure 8A and C, therefore long-term operation may induce tiredness. The design of actuation units in Figure 8B and D alleviates this problem. But each of the above handheld CRs occupies the surgeon's hand, making it difficult to operate more instruments. Furthermore, it should be noted that, compared with the existing rigid endoscope shown in Figure 5, the endoscope's pixel quality will be compromised due to the robot's increased flexibility. Because it is challenging to fabricate a flexible endoscope with high resolution and small outer diameter.

4.3 | Continuum robotic system for ESS

According to the analyses of the rigid robots (Figure 7) and handheld CRs (Figure 8) for ESS, some requirements of continuum robotic system can be outlined:

1. The positioning robot is needed for supporting the CRs such that the surgeon's hand can be released.
2. The human-robot control interface should be designed ergonomically, so that it can be manipulated easily.
3. More instruments should be included in the continuum robotic system to achieve more operations in ESS.

According to the actuation and mechanical structure, CRs can be categorized into three types, that is, multi-backbone CRs, concentric tube CRs, and cable-driven CRs. Each type of CR has its characteristics. Multi-backbone CRs can provide high stiffness, but the outer diameters tend to be large. Concentric tube CRs can perhaps be scaled to the smallest overall diameters among CRs. Cable-driven CRs without obvious backbone can achieve larger deformation with smaller diameter.[40] Due to the constraints of the surgical space, the CRs for ESS are mostly designed with concentric tube mechanisms or cable-driven mechanisms.

4.3.1 | Concentric tube CRs for ESS

Some concentric tube CRs have been studied for ESS. Burgner et al.[41] developed a robotic system for transnasal skull base surgery. As shown in Figure 9A, the robotic system incorporated two concentric tube manipulators with gripper and curette end effectors, which could be teleoperated via haptic devices. An endoscope was held in place by a passive arm for viewing of the surgery site. Although the sheath diameter of the system was small, the passive visual feedback channel limited the performance of the system. Moreover, the distance between the two channels was fixed at 35 mm, limiting its application to sinus surgery through one nostril. In,[42] a multi-arm concentric tube robotic system, shown in Figure 9B, was proposed with application to transnasal surgery for orbital tumors. The main contribution of this system was that the centric tube instruments could be exchanged as single units. A commercial adjustable rigid endoscope was incorporated with the robot on a lockable positioning arm. The view angle of the endoscope was adjustable between 15° and 90°. In,[44] to improve the dexterity of the endoscope and the ability to carry out different instruments, a three-arm concentric tube CR was developed for transnasal surgery. It contained one active vision channel and two manipulation channels constrained by a 10 mm sheath. Compared with the CR in,[44] the proposed design (Figure 9C) in[43] made the manipulators more flexible. The vision arm and the operation arm were designed with two tubes and three tubes, respectively. The significant advantage of these concentric tube CRs is that the manipulator diameter can be reduced to around 2 mm or even less. Because the actuation unit can be arranged behind these concentric tubes. However, this mechanism also brings some drawbacks. For instance, the translational and rotational motions of each tube should be driven by two motors. As a result, the actuation unit's dimensions are always so large [see Figure 9] that it is difficult to support and position in the surgical platform.

4.3.2 | Cable-driven CRs for ESS

Another type of continuum robotic system for ESS is using a cable-driven mechanism. The shape of the CR is controlled by actuation cables, and the actuation unit can be designed in a compact structure. As shown in Figure 10A, Rosen et al.[45] developed a flexible and bendable robot for skull base and sinus surgeries. It was integrated with scanning fibre endoscopes and two instruments. However, the outer diameter of the CR was 12 mm. Furthermore, the bending motion of the instrument module was not continuous, which was not suitable for the ESS. In,[46] a cable-driven continuum robotic system was developed to perform maxillary sinus surgery. Two NiTiNol tubes were used to achieve the implementation of elasticity and stiffness. Despite its achievement of a large bending with a small diameter, it only had one segment with a planar bending. Furthermore, the necessary sensors, such as endoscope, were not included, making the application of ESS impractical. On the basis of,[46] a two-segment continuum robot with piecewise stiffness, shown in Figure 10B, was proposed for maxillary sinus surgery.[47,48] The proximal segment could achieve a planar bending, and the distal segment could achieve a spatial bending. By combining the rotational motion of the cannula, the entire continuum module could achieve a three-dimensional (3D) motion. The diameter of the continuum manipulator is 4 mm. Various surgical instruments could be changed by a modular design. A custom-designed endoscope with a 2.1 mm diameter was attached to the distal end of the CR. Although the above designs have great potential in application to ESS, there are still some problems. The endoscope is always located at the tip of the CR and follows the CR motion. As a result, while the CR is moving and operating, the surgical view is continually swaying, which is not in accordance with the doctor's working practices and causes exhaustion. This problem has been considered in.[49,50] As shown in Figure 10C, Yoon et al. proposed a dual master-slave robotic system for maxillary sinus surgery. It contained dual continuum manipulators. One had an integrated endoscope, while the other had a biopsy end effector. The endoscope end effector had 2 DOFs, and the biopsy end effector had a 1-DOF gripper and a 4-DOF bending mechanism with two segments. The total diameter of the dual arms is 9 mm. The dual arms were controlled independently by two master devices.

4.4 | Discussion

In this section, we review several types of robotic systems for ESS, including rigid robots, handheld CRs, concentric tube CRs, and cable-driven CRs. The specifications and characteristics of these representative CRs for ESS are summarized in Table 2. It should be noted that the DOF of each CR is only relative to the continuum module. The rigid robots are mostly designed to hold the endoscope, and release one of the surgeon's hands. The instruments in the rigid robots are not flexible. For handheld CRs, the dexterity and maneuverability are limited due to the constraint of manipulation by hand. Furthermore, the functions of handheld CRs are relatively simple. For concentric tube CRs, they consist of several flexible precurved tubes. An actuation unit grasps each tube at its proximal end and rotates and rotates them relative to each other. Thus, the concentric tube CR can be scaled to a small diameter. For this advantage, these concentric tube CRs for ESS are developed with multiple arms. But how to reduce the dimension of the actuation unit is a worthy research topic in the future. As for cable-driven CRs for ESS, the driving mode of the actuation cables is relatively uniform, so the actuation unit can be designed in a compact structure. The above CRs for ESS are mostly arranged with an endoscope and other surgical instruments. A practical design is that one bendable arm is integrated with an endoscope, and the other bendable arms are for surgical instruments, such as the design approaches in.[43,49]

Currently, the instruments embedded in these CRs for ESS are mostly grippers and forceps. Some customized monopolar forceps[44] or bipolar forceps[47] are designed for ablation or coagulation of soft tissue in ESS. Despite the fact that these studies are intended to be applied to ESS, there is still a gap between actual surgical operations and the results. Some enhancements to the robotic system design are worthy of additional thought and investigation. (1) The powered instruments like microdebriders are not included in the above robotic system, but they form an essential part of the instrumentation required to perform ESS. The powered instruments are critical for

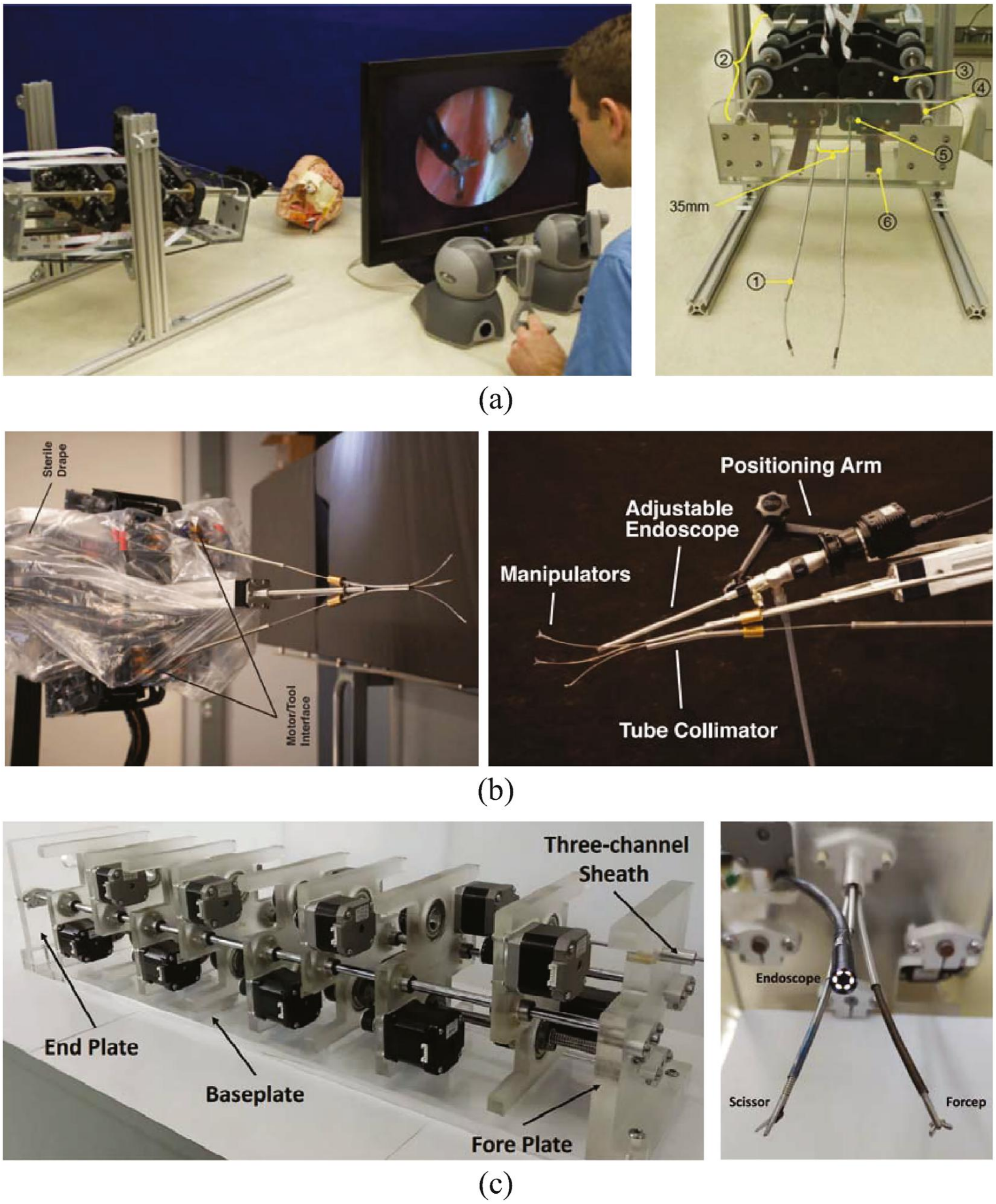

FIGURE 9 Concentric tube continuum robots (CRs) for endoscopic sinus surgery (ESS). (A) A telerobotic system for transnasal surgery[41] (Copyright © 2013, IEEE). (B) A multi-arm concentric tube CR for orbital tumors[42] (Copyright © 2021, SAGE). (C) A multi-arm concentric tube robot system for transnasal surgery[43] (Copyright © 2020, International Federation for Medical and Biological Engineering).

soft-tissue shaving and bone cutting. However, as shown in Figure 6G and H, these instruments are used by rotating their inner blades at a high speed. It is challenging to manufacture them in a flexible structure and incorporate them into the CRs.[51] (2) The ideal CRs for ESS would provide easy visualization and control of two or more instruments in the surgical field. (3) The resolutions of the bandable endoscopes used in the above CRs [39,47,49] for ESS range from 200 × 200–400 × 400 pixels. At a further development stage, the endoscope should be replaced with a higher resolution one. (4) Although the instrument exchanges of some CRs [42,49] can be achieved, a fast and efficient method still needs to be studied.

5 | NAVIGATION AND CONTROL OF CRS FOR ESS

In order to accurately approach the target in ESS, navigation and control of CRs are also important parts. The surgical path from the nostril to the target is always narrow and constrained, and the visibility of CRs in ESS is limited. Moreover, owing to the inherent deformable characteristics, strong nonlinearities, and uncertainties of the CRs, it is still a challenge to design high-performance control algorithms. A few researchers[47,52] have concentrated on this topic. In addition, the studies of other robot-assisted surgeries can also be extended to the CRs for ESS. In this section, the current

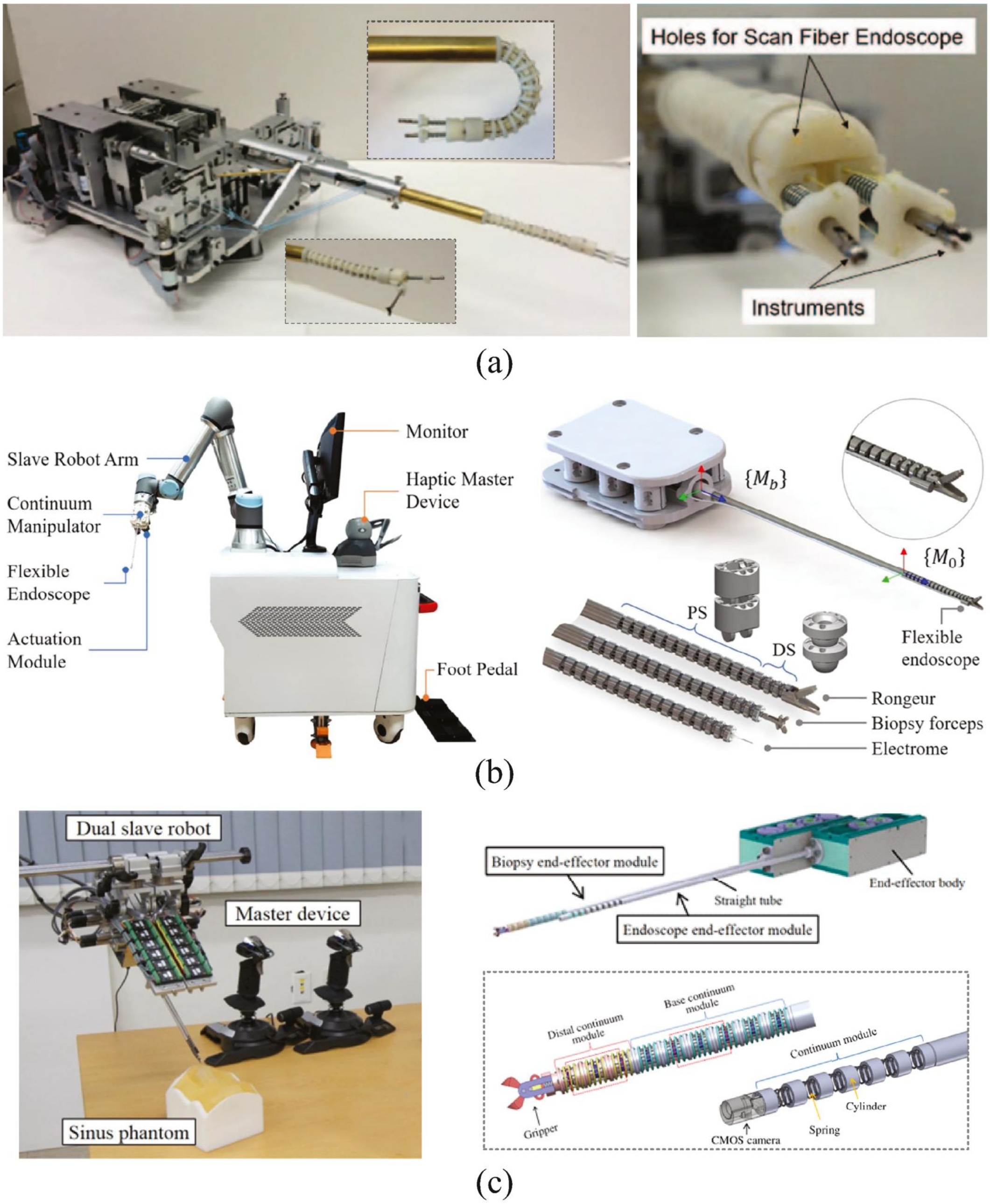

FIGURE 10 Cable-driven continuum robots (CRs) for endoscopic sinus surgery (ESS). (A) A flexible and bendable robot for skull base and sinus surgeries[45] (Copyright © 2017, IEEE). (B) A two-segment CR with piecewise stiffness for maxillary sinus surgery[47] (Copyright © 2021, John Wiley & Sons Ltd.). (C) A dual master-slave robotic system for maxillary sinus surgery[49] (Copyright © 2018, IEEE).

progress and prospects of some navigation and control methods of CRs for ESS will be discussed.

5.1 | Navigation

To reach the target lesions and tumors, different endoscopic approaches to the paranasal sinuses and skull base have been studied in.[53] Before surgery, enhanced magnetic resonance imaging (MRI) and computed tomography (CT) should be performed in all patients to assess the extent of the tumors and the surrounding internal carotid artery.[54] A major concern is that the tumors need to be separated carefully without damaging the surrounding important structures. But even though the surgeon knows the approximate location of the tumor, the management of the tumor is still a challenge when working only with the image guidance in ESS. For this reason, a wide intraoperative exposure is needed to allow complete dissection and improve the safety of surgery,[55] but more normal tissues will be damaged. Therefore, to ensure the safety of surgical operations, surgical path planning and navigation are important. In,[56] a binarized

TABLE 2 Specifications and characteristics of the representative continuum robots (CRs) for ESS

Type	Research group	DOF	Dimensions of bendable part (mm)	Length (mm)	Bending angle (deg.)	Application	Characteristics
Handheld CRs	Remirez et al.[36]	2	5	80	–	Paranasal sinus surgery	Multi-backbone bending mechanism; a thumb-activated joystick.
	Van Zele et al.[37]	1	2.3	–	0 ~ 125	Paranasal sinus surgery	A camera at its distal end, and a built-in channel for irrigation.
	Coemert et al.[38]	2	3 × 4.6	40	0 ~ 76	Frontal sinus surgery	Two segments, and each with a planar bending; an instrument channel and an endoscope channel.
	Legrand et al.[39]	1	2.3	–	0 ~ 125	Maxillary sinus surgery	A miniature robotic steerable endoscope; visualize all maxillary sinus walls.
Concentric tube CRs	Burgner et al.[41]	Gripper: 6; curette: 6	Outer: 2.32; middle: 1.68; inner: 1.16	Gripper: 176.6; curette: 147.4	–	Transnasal skull base surgery	Passive visual feedback channel; the distance between the two channels was fixed at 35 mm.
	Bruns et al.[42]	Each arm: 6	Outer: 1.90; middle: 1.52; inner: 1.01	110	–	Transnasal surgery	The centric tube instruments could be exchanged; a adjustable rigid endoscope.
	Wang et al.[43]	Vision arm: 4; operation arm: 6	Outer: 3.0; inner: 2.45	100	–	Transnasal surgery for orbital tumors	One vision arm and two operation arms.
Cable-driven CRs	Rosen et al.[45]	6	12	81	−180 ~ 180	Skull base and sinus surgeries	Main directional joint, and two tool directional joints; two fibre endoscopes; tools could only bend at a fixed point.
	Hong et al.[47,48]	3	Continuum module: 4; endoscope: 2.1	44	−270 ~ 270	Maxillary sinus surgery	Two segments; proximal segment with planar bending, and distal segment with spatial bending. Endoscope was passive.
	Yoon et al.[49,50]	Endoscope: 2; biopsy: 4	Endoscope: 4; biopsy: 5	Endoscope: 39; biopsy: 58.5	Endoscope: −180 ~ 180; biopsy: −270 ~ 270	Maxillary sinus surgery	Dual arms; bendable endoscope end effector; biopsy end effector was two segments, and each with a spatial bending.

Note: The symbol—represents the specification is not introduced. The DOF of each CR only includes the continuum module, not the sliders.

three-dimensional grid map was created based on the patient's CT images, and endoscopic surgical approaches were searched and optimized using the A-star algorithm. A KARL STORZ NAV1 Sinus-Tracker navigation software incorporating augmented reality elements was investigated in.[57] In the CT scan series, the software allowed the surgeon to draw surgical pathways in ESS. As shown in Figure 11A, these pathways could be fused with the endoscopic image, indicating the surgeon's operation intraoperatively. In,[58] the movement of a CR's end effector was transmitted to an auditory display synthesizer, which subsequently generated audio feedback to notify the operator of the CR's location within the environment. As shown in Figure 11B, the auditory display could assist the user in steering the CR's end effector to each waypoint in the transnasal surgery. There are few practical uses for navigation in current sinus surgery. Two main types of navigation systems, optical systems and electromagnetic systems, are widely studied in robot-assisted surgeries. Optical systems require a direct line of sight to the instruments, whereas electromagnetic systems require care to reduce interference from other magnetic and conductive objects.[59] Compared with optical trackers, the dimensions of electromagnetic sensors are much less. As such, the electromagnetic sensors are more suitable to be integrated within the CR's tip for navigation. In future work, surgical path planning with minimal trauma and enhancement of the navigation accuracy of the CRs for ESS need more investigation.

5.2 | Control

In order to achieve accurate path tracking in ESS, surgeons often expect that the CR can perform the intended procedure as precisely as possible. A specifically designed motion control strategy can ensure the desired performance of the CRs in the confined operating space. In this section, we review existing control strategies of CRs for ESS and analyze their characteristics. At the current stage, master-slave control algorithms are mainly adopted for CRs in ESS. In order to improve the autonomy and operation accuracy of CRs for ESS, autonomous control and shared control are future research directions, which will be discussed in this part.

5.2.1 | Master-slave control

In CR-assisted ESS, the CRs are always controlled by teleoperation under the typical master-slave paradigm and vision-based navigation.[60] As shown in Figure 12, this method allows the surgeon to manipulate the CRs intuitively under the endoscopic guidance and navigation system. Generally, the teleoperation robotic system consists of master devices, a host computer, and the designed CR with its actuation unit. Through the master-slave control algorithm, the control input of the master device is transformed to the motion input of the actuation unit.[61] The commonly used master devices are Geomagic Touch (3D Systems Inc.),[42,47] Falcon (Novint Technologies Inc.),[46,62] omega.x haptic devices (Force Dimension Inc.).[63] Sidesticks or joysticks can also be used as master devices in ESS.[49,61] The mapping algorithm has a significant impact on master-slave control. There are two main options in the master-slave mapping, that is, the mapping based on the task space or actuator space. The task space mapping directly aligns the master device's input to the position motion of the CR. As for the actuator space mapping, the input of the master device is directly related to the actuator space variables. In

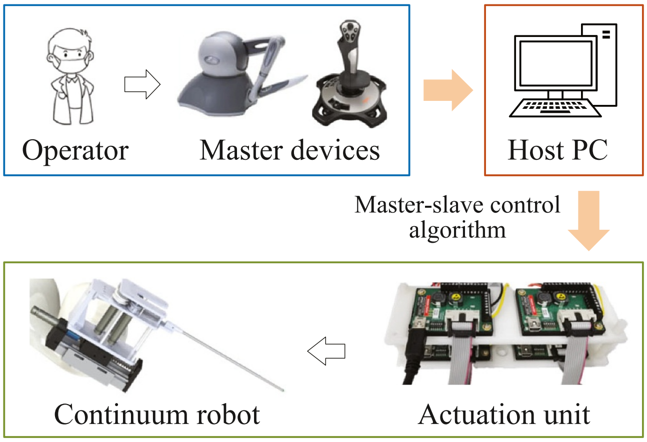

FIGURE 12 Block diagram of the telerobotic master-slave control structure of continuum robots (CRs) for ESS[61] (Copyright © 2022, IEEE).

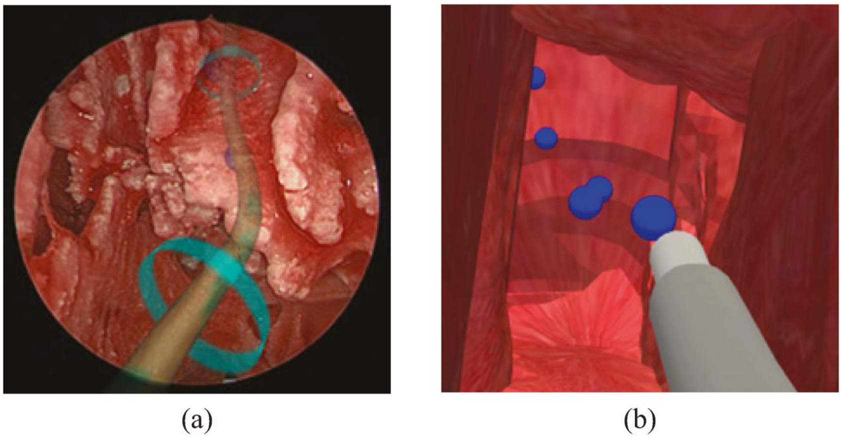

FIGURE 11 (A) The surgical pathway created by KARL STORZ NAV1 SinusTracker navigation software[57] (Copyright © 2020, Linxweiler et al.). (B) Visualization of the implemented simulation environment with waypoints for navigation guidance[58] (Copyright © 2019, World Scientific Publishing Company).

each mapping scheme, the absolute mode or incremental mode can be chosen. Although master-slave control strategies with haptic devices have been applied in,[41,42,46–48] haptic feedback of CRs have not been considered in ESS. Perhaps, one of the most challenging aspects is how to sense the interaction force.[59]

5.2.2 | Autonomous control

Although the intuitive and real-time manipulations of the CRs can be achieved by master-slave control, some repetitive and simple motions of the CRs can be autonomously controlled by themselves. Furthermore, high-performance control methods can facilitate and secure master-slave interaction in ESS. Un-like traditional rigid-link robots, CRs are primarily actuated by tendons, cables, and so forth. The uncertainties of CRs always exist due to manufacturing errors and their inherent deformability. For this reason, it is hard to obtain accurate models of CRs and design high-performance control algorithms. In general, surgical robots do not need to move very quickly. Therefore, a controller based on a differential kinematic model is sufficient. The commonly used kinematic modeling method is based on the constant curvature assumption.[64,65] Recently, researchers[66,67] have contributed to the studies of advanced control algorithms and path tracking accuracy enhancements. The control methods of CRs can be roughly classified into two categories: model-based methods and model-free methods. The problems of differential inverse kinematics algorithms are closely related to the properties of the basic Jacobian matrix.[68] As for the model-based methods, the commonly used Jacobian-based schemes include the Jacobian pseudo-inverse, transpose, and damped least squares methods.[69] These approaches have also been extended to CR control.[70–72] Compared with open-loop control, the closed-loop control strategy is preferable in path tracking requiring high precision, but the state information of CRs is needed to serve as feedback to the control system. Fibre Bragg grating sensor[52,73,74] and electromagnetic sensor[75,76] can be used to provide the shape or position information of the CRs.

Although model-based closed-loop algorithms can be adopted to improve the CR tracking performance, their effectiveness is heavily dependent on modelling accuracy. For model-free methods, accurate modeling of the robotic system is always skipped, and empirical estimation and optimal design[77–79] are investigated to construct the controller. The Jacobian of the CR is estimated in each iteration step according to the real-time input and output data of the controlled part of the CR. Although the model-free method reduces the independence on modeling accuracy, the iteration in each step may lower the control frequency. Some machine learning algorithms[80–82] have been investigated to compensate for the uncertain nonlinear dynamics of the CRs. The learning-based method can overcome the difficulty of nonlinear modeling, but it requires large training data to learn complex tasks. The performance of the above methods is limited if the CRs are influenced by disturbance and uncertainty. Recently, disturbance/uncertainty estimation and attenuation (DUEA) techniques have been widely studied[83] in industrial applications. The DUEA method can be regarded as a control strategy that falls somewhere in between model-based and model-free methods. DUEA techniques include disturbance observer-based control, uncertainty and disturbance estimator-based control, active disturbance rejection control, and so forth. Some researchers[84,85] have delved into the studies of DUEA control of CRs. The core idea of the DUEA method is to estimate and compensate for the total disturbance of the CRs in real time. The DUEA method has great potential in dealing with the disturbance and uncertainty of the CRs.

5.2.3 | Shared control

The motivation for shared control is that the surgeon's manipulations of the CRs can be assisted by autonomous control. In other words, the surgeon's intentions and the assistive system can be fused into a shared control structure.[86] As shown in Figure 13, the control input of the CR is generated from both remote manual control and autonomous control, and the surgeon has the ultimate control of the CR. Some dangerous and crucial decisions and actions should be controlled by the surgeon's commands, whereas some complex and nonintuitive manipulations are performed by autonomous control algorithms.[87] The adjustment of the control weights of human and autonomous control systems is the key to shared control. Due to the difficulty to merge surgeon and automatic inputs, only few shared control systems have been investigated for robot-assisted surgeries.[88–90] In,[47] a continuum robotic system with a follow-the-leader strategy based on anatomical constraint was proposed for maxillary sinus surgery. Once the CR reached the maxillary sinus along the reference path by the proposed path-following algorithm, the robot performed manually in the maxillary sinus. As for the CRs with applications to ESS, shared control can coordinate the interaction between the surgeon and the CR. In some repetitive and easy tasks, the CR can proceed by autonomous path tracking algorithm under the surgeon's monitoring. For some crucial actions, the CR is controlled by the surgeon. Moreover, the vision, position, and force information

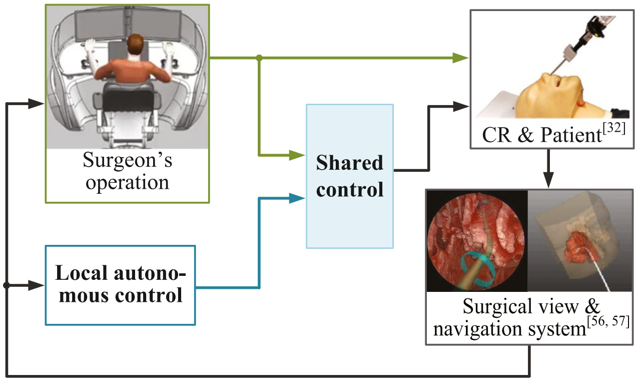

FIGURE 13 Block diagram of shared control method of continuum robots (CRs) for ESS.

provided by the surgical view and navigation system can be used as feedback to both the surgeon and autonomous control.

5.3 | Discussion

In this section, the navigation and control of the CRs for ESS are discussed. It is still challenging and significant to fuse preoperative MRI/CT data, endoscopic view, and the electromagnetic or optical system to provide real-time navigation for ESS. Master-slave control is mostly adopted in the current CRs for ESS. However, high-performance control strategies are needed to improve the path tracking accuracy to ensure the safety of surgeries. Shared control can assist the surgeon to take more advantages of the advanced sensing and control of the continuum robotic system. Shared control of the CRs for ESS is an area that is worth studying in the future.

6 | CONCLUSION AND DISCUSSION

ESS is appropriate to treat paranasal sinus diseases that do not respond to medicinal treatment, as well as tumors of the sinuses and skull base. ESS is performed in a confined space adjacent to important anatomical structures, and the operational difficulty and complications of this surgery still present a challenge to rhinologists. To allow surgeons to perform many types of complex procedures with more precision and fewer complications, robot-assisted ESS has been studied in recent years. To improve the dexterity and workspace reach of robots, CRs have been investigated for ESS. In this paper, we systematically review the CRs with applications to ESS. Following a review of the setup and current regularly used instruments for ESS, the requirements of CRs for ESS are discussed. Then, relevant advances in rigid robots, handheld flexible robots, and CRs for ESS are reviewed. The specifications and characteristics of these robots for ESS are analyzed. The rigid robots are mostly designed for holding the endoscope, but their functions are limited. The dexterity of handheld CRs can be improved, but the operational space is restricted by the hand's holding. The advantage of concentric tube CRs for ESS is that the CRs can be manufactured in a small diameter, but the actuation units of concentric tube CRs are always too large. The cable-driven CRs can be designed with a small diameter and their actuation units can be easily positioned. The CRs incorporated with multiple replaceable arms with different functions are preferable in ESS.

Despite the progress in the design and fabrication of CRs for ESS, there are few studies on navigation and control. The current studies of CR control for ESS are mostly master-salve control. Despite the intuitive operation provided by this method, the control accuracy and ability to deal with complex tasks are limited. For this, some control strategies with potential applications to ESS are discussed, including model-based control, model-free control, and DUEA control method. Shared control can be chosen to deal with the relationship between master-slave control and autonomous control of the CRs. The safety and feasibility of the CR-assisted ESS could be further improved with shared control.

This paper presents an overview of the CRs for ESS, with the goal of making it easier for new researchers to enter this field. Nevertheless, there is still a long way to go for potential clinical applications. This may be accomplished by putting in more in-depth research and collaborations between academics and surgeons.

ACKNOWLEDGEMENTS

This work was supported in part by the National Natural Science Foundation of China (Grant 62133009, Grant 61973211, and Grant M-0221), in part by the Science and Technology Commission of Shanghai Municipality (Grant 21550714200), and in part by the project of Institute of Medical Robotics of Shanghai Jiao Tong University.

CONFLICT OF INTEREST

All authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are vailable from the corresponding author upon reasonable request.

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How to cite this article: Cao Y, Shi Y, Hong W, et al. Continuum robots for endoscopic sinus surgery: recent advances, challenges, and prospects. *Int J Med Robot*. 2022;e2471. https://doi.org/10.1002/rcs.2471