Proceedings of the 3rd International Conference on Signal Processing and Machine Learning
DOI: 10.54254/2755-2721/6/20230823

A review of continuum robots for surgical applications

Kexin Li[1,4] ,Ziyang Qi[2] and Xueyan Feng[3]

[1]The School of Mechanical, Electrical and Information Engineering, Shandong University, Weihai,264200, China
[2]Zhenhai High School, Ningbo, 315299, China
[3]Tianjin No.55 Middle School, Tianjin, 300070, China

[4]202000800014@mail.sdu.edu.cn

Abstract. The design of continuum robots is inspired by biological trunks, tentacles, and snakes, allowing them to navigate through some confined spaces, manipulate objects in the unstructured environments, and follow curvilinear paths. In recent decades, a wide range of designs of continuum robots have been explored and have illustrated capabilities that go beyond rigid-link robots. We have witnessed increasing efforts to use these characteristics to improve minimally invasive surgical interventions in recent years. In this paper, we summarize the key technologies and several applications of continuum robots in the surgical field. We also define the key performance index to evaluate the performance of continuum robots in the surgical field. By discussing challenges to be overcome before the potential of continuum robots as surgical devices can be fulfilled, we propose some future directions for the continuum robobts.

Keywords: continuum robots, hyper-redundant robot, robot-assisted surgery, soft robot, surgical robot.

1. Introduction

Robots have influenced human life in many aspects and have been deployed in many fields, such as agriculture, education and the medical field [1]. Many people have been interested in the use of robotic devices in surgeries due to the fact that robots can save time and increase accuracy instead of traditional devices. Medical robots have contributed to the development of minimally invasive surgery (MIS) [2], which is a kind of surgery that can minimize patient discomfort, risk, cost, and time [3]. Minimally invasive surgery always requires more precision, faster healing, and smaller incisions. With the help of robots, surgeons can access surgical sites remotely and achieve high levels of precision. The most widely used surgical robot system is the da Vinci system. The da Vinci system is a teleoperated system where the surgeon manipulates a master input device in an immersive visualization environment. These inputs are translated into the motion of a 3-D vision system and wristed laparoscopic surgical instruments [2]. However, in the area of MIS, there are primarily rigid robots in use, which lack flexibility and are relatively large. Therefore, a continuum robot is needed, which is small, flexible, and can easily access difficult-to-reach areas with a high degree of freedom [4]. They can move smoothly on a curved trajectory.

This paper reviews a continuum robot which is the core of minimally invasive robots. Original medical robots are rigidly connected, but their limitations stem from their mutual connections. A continuum robot can solve this problem well. It has three segments that enable it to move flexibly in small spaces (see Fig. 1) [5]. After reviewing the technology robots used and their application areas, we also evaluate the index. It has been found that the continuum robots suggested in this article are more suitable for minimally invasive surgery as compared with continuum robots proposed in previous studies.

Our review begins by introducing the technologies used in continuum robots, as shown in section II. In section III, we will explain how motion's accuracy and stability are measured. A brief discussion of the application of continuum robots to the medical field will also be provided in section IV of this paper. Towards the end, in section V and section VI, some perspectives and challenges are presented.

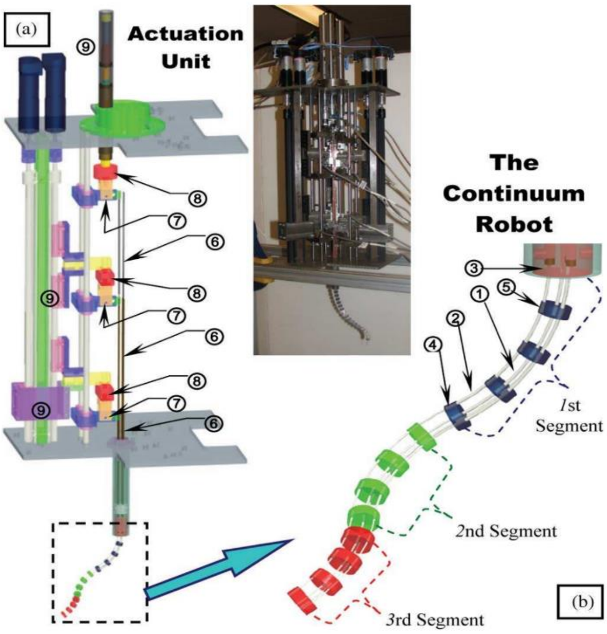

Figure 1. A 7.5-mm continuum robot with three segments [5].

2. Technology

The continuum robot is a newly invented high-end robot in modern times. Although it just has a small volume, it does have many complicated structures and different mechanical concepts, such as the structure, manufacturing materials, control method and programming of the continuum robots [2].

2.1. Structure

Most of the previous continuum robots are rigid link robots. They use screws to connect them, and they are bulky, so they don't have good flexibility. However, with the development of related research in recent years, continuum robots have made great progress. For example, take the skeleton of a snake as a framework. A continuum robot with hinge joints is proposed by Li et.al [6]. However, the excellent dexterity also narrows the central passage, which limits the use of the machine. Simaan et.al. also proposed a continuum robot composed of discrete joints and a central rod [4]. But the center rod also limits the end of the instrument. To solve this problem, Murphy et al. put forward the notch continuum machine (NCR), which can replace the original joint with a special metal original [4]. This technology has good accuracy and stiffness at the same time. And this robot has been used in laryngeal and vascular surgery etc.

DOI: 10.54254/2755-2721/6/20230823

2.2. Material

Among these robots, the most commonly used is the tendon-driven continuum robot. It is widely used in many mechanical operations tasks [7]. However, due to the limitation of traditional technology. It is difficult for the traditional continuum robot driven by tendons to perform more elaborate operations. In order to ensure a larger working space. The mechanism of fluid driving is put forward to replace the tendon [8-10]. This kind of software allows the robot to touch safely and increase the bending angle. But it also makes it more complicated to accurately locate and control it. To solve these problems, many new materials have been developed and applied to continuum robots. For example, robots embedded with micro-magnets or made of ferromagnetic composite materials as a continuum robot [11], which can rotate over 180 degrees. Therefore, the positioning accuracy of the nanometer level can be achieved. In recent years, new continuum robots have been developed by combining ionic liquid conductors and tendon-driving methods. This kind of robot is low in manufacturing cost and can expand the position feedback [12]. Besides, researchers have developed some hybrid-driven continuum robots in order to achieve accurate position positioning and variable stiffness in different environments. By integrating pneumatic and tendon drive, robots are able to show great advantages and rotate more than 90 degrees [13, 14]. This is a breakthrough for continuum robots.

2.3. Control

In addition, the control method of the continuum robot is also an important research direction. At present, the control methods of continuum robots mainly focus on how to determine the position and control the posture [15, 16]. These problems need to be solved by design and modeling. However, in order to make the control effect better, it is necessary to establish a complex mathematical model to analyze the behavior of the robot. Campisano et al. proposed a typical closed-loop control strategy for force-controlled continuum robots. It is based on the real-time Cosserat rod theory [17].

3. Performance index

The performance index of continuum robots is something we use to judge whether the performance is excellent. It can help us evaluate the robots and provide more guidelines for further optimizations. It is necessary and valuable.

3.1. Dexterity

Dexterity is one of the general evaluation indexes we use for robots. For continuum robots, standard dexterity evaluation methods include the condition number, end attitude angle, etc. The dexterity of the continuum robot was evaluated depending on the condition number by Wang et al. [18]. According to existing research, the evaluation method based on the condition number examines the uniformity of the robot Jacobian transformation matrix in all directions [19]. However, the robot's performance cannot be intuitively described using this method. Using the position dexterity evaluation method of forwarding kinematics to calculate the dexterity index, Wu et al. evaluated the dexterity of the continuum robot in 2016 [20]. As a result of this method, the continuum robot's dexterity can be intuitively expressed. In the pose dexterity assessment method, the dexterity of a point is defined as the number of poses the robot can achieve at that point. It is believed that the greater the number of poses a robot can achieve at a given point, the greater the number of actions the robot will be capable of performing.

3.2. Repeatability

For the purpose of evaluating the accuracy of robots, it is necessary to determine how repeatably one and the same point in the working field can be reached. To accomplish this, the same experimental setup is used for the dynamic experiments. A demonstration of the method for calculating the repeatability is presented before describing the experiments.

Our methodology followed the ISO 9283 standard to evaluate the pose repeatability of the continuum robots [21,22]. Pose repeatability measures the degree to which a pose can be achieved after repeated visits to the same command pose in the same direction. It is determined by its position and orientation

DOI: 10.54254/2755-2721/6/20230823

repeatability. The position repeatability (PR) is defined as three times the standard deviation of the distance to the mean position of the platform and the orientation repeatability (OR) is three times the angles' standard deviation [22].

4. Surgical applications

It has been possible to perform novel minimally invasive surgical procedures with the help of continuum robots in the past decades, with robots arranged in operating rooms all over the world. Through robotic technology, surgeons can perform surgery with exactness, intuitive ergonomic interfaces, and small-size continuum robots that can move flexibly. Using continuum robots can improve the effectiveness of minimally invasive surgery and reduce the damage to patients. Nowadays, continuum robots have been applied in many medical fields.

4.1. Lung interventions

In the past, bronchoscopes are typically restricted to moving only along the bronchial tree, which reduces their effectiveness [23]. A continuum robotic bronchoscopy system has long been considered an option for achieving more reliable bronchoscopy. There is already the MonarchTM platform and the IonTM platform, released in 2018 and 2019 [24]. Comparatively to conventional bronchoscopes, these devices can reach deeper into the lung by using robotic bronchoscopes.

There is a high mortality and morbidity rate among severely ill patients who suffer respiratory failure and require mechanical ventilation (MV). It is an important procedure to sample the distal lung from MV patients. Considering that there is no standard to justify the accuracy, no reproducibility, and skilled operators are required for the sampling process, Mitros et al. [25] proposed a specific robotic bronchoscope (see Fig. 2). The previous bronchoscope was large in size, lack of dexterity and it had insufficient registration of anatomical details. The proposed robotic bronchoscopy has 7 degrees of freedom, with an outer diameter of 4.5 mm and an inner working channel of 2 mm. It consists of a few parallel rods that can be bent by pushing or pulling. This device makes flexible movements inside the lung and the visualization of the distal airways with no more expert operators.

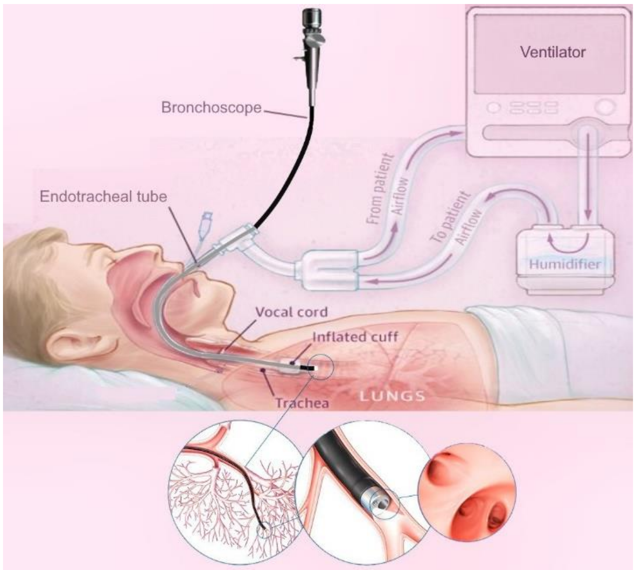

Figure 2. This schematic illustrates the insertion of the robotic bronchoscope into the lung through the mechanical ventilator during lung bronchoscopy in the ICU [25].

4.2. Endovascular interventions

In order to treat heart and endovascular diseases in a minimally invasive manner, medical structures have been put into blood vessels and fixed to specific locations by hand in the past [26,27]. So, surgeons

DOI: 10.54254/2755-2721/6/20230823

must get extensive training to ensure accurate placement. This problem may be overcome by combining existing devices and procedures with robotic navigation and steering.

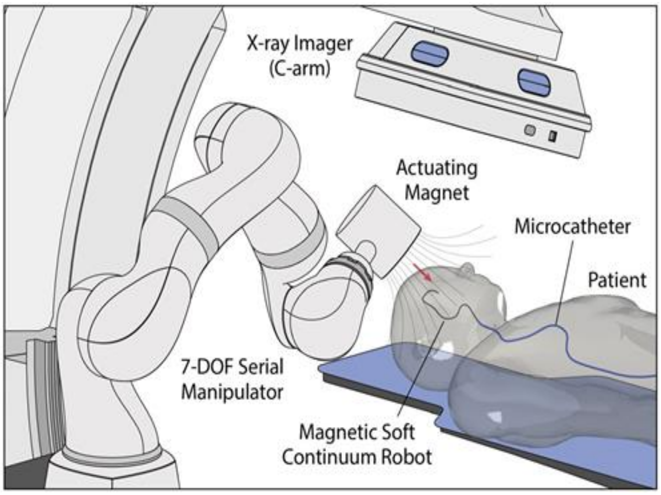

Figure 3. The telerobotically controlled magnetic soft continuum robot in the neurovasculature uses a 7-DOF serial manipulator and an actuating magnet [28].

Some robotic navigation and steering systems have been proposed, such as Magellan and Sensei, and Corpath GRX. Interventions ranging from peripheral vascular to neurovascular have been performed using these systems [27-30].

There is no mature application of continuum robots in endovascular neurosurgery for treating stroke or brain aneurysms. Current neurovascular robotic systems do not meet the requirements for using traditional guidewires with limited steering capability. Kim et al. [28] proposed a new platform (see Fig. 3). Based on a magnetically controlled soft continuum robot, this platform allows telerobotic neuro interventions. This continuum robot’s thin and flexible structure allows it to navigate narrow and winding paths in the brain. It also enables surgeons to operate at a long distance from radiation.

4.3. Otolaryngology

Most surgeons use straight endoscopes to enter through the ears, noses, and throats, but these instruments lack flexibility. It is therefore necessary to develop continuum robots.

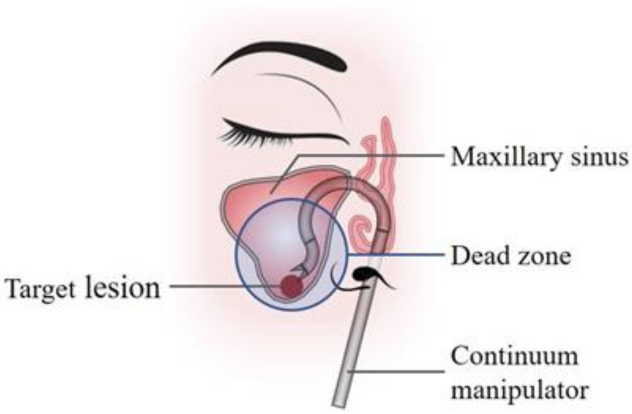

Figure 4. Dead zones of the maxillary sinus can be reached with continuum manipulators [31].

In clinical practice, flexible endoscopes are used for endoscopic sinus surgery. However, in deep sinus cavities, especially the maxillary sinus, flexible endoscopes can be challenging to steer due to their limited dexterity. By using continuum robots, lesions in the sinus can be checked and removed, as shown

DOI: 10.54254/2755-2721/6/20230823

in Fig. 4., Coemert et al. [29] introduced a flexible handheld manipulator for frontal sinus surgery, which enables the use of an endoscope and an instrument within a small cross-section (3×4.6 mm). A dual master-slave robotic system for maxillary sinus inspection and biopsy was developed by Yoon et al. [30].

5. Challenges

Here are the challenges that must be overcome for continuum robots. We summarize the below challenges from the perspective of fabrication, actuation, modeling, sensing, control and physics simulators.

5.1. Fabrication, actuation, and modeling

Several devices are currently making their way onto the market in the field of medical continuum robotics. Developing fabrication processes that enable greater function and smaller size scales will be essential to the field's growth as it matures. There is soft lithography, direct addictive manufacture, and other technologies to manufacture continuum robots, some of which contain magnetic composites. Soft lithography costs a lot of money and time. It is also challenging to produce multi-material structures because each shift in material increases the production time [32]. As for direct addictive manufacture, developing an ink that flows easily and keeps its shape after being deposited can be a challenge.

Now, in the actuation field, the methods that have the biggest possibility to miniaturize continuum robots are magnetic-driven, optical-driven, or thermal-driven methods, but their mechanical models are often highly nonlinear and complicated, making robust control challenging [33].

For modeling, due to the reduction of rigidity of continuum robots, actuators and end effectors have a more complex relationship. Considering the complexity of solving partial differential equations, some classical methods are difficult to apply to dynamics [34]. In addition, some methods are very complicated and have a high cost of computational expense [35].

5.2. Sensing and control

It is important to increase the continuum of robot perception. As a result of a relatively low strain transfer ratio, some sensors may provide less accurate results or even be destroyed [35]. In electromagnetic tracking, the magnetic field generator and magnetic field sensor are easily disturbed by the magnetic field of surrounding equipment [36]. For control systems, material properties related to robot flexure, transmission friction, hysteresis, and dead band modeling all pose high levels of uncertainty [37].

5.3. Physics simulator

In the robotic field, physics simulators are widely used, and they are the core of many recent advancements. Simulation frameworks for rigid robots are relatively mature but they are not suitable for continuum robots. The simulation of continuum robots is generally more challenging. It is important in continuum robotics to simulate transformable objects and handle novel actuation modes, such as tendon, pneumatic, and heat transference. Additionally, continuum robots must be able to interact with soft materials or fluids using physics simulators. In the surgical field, taking in user input for teleoperation requires real-time simulation, otherwise, user input would cause a delayed action. Evosoro is a continuum robot simulator [38]. Due to the fast and relatively inaccurate Sping-Mass modeling, this simulator has a big problem when solutions are transferred from the simulator to reality. A physics simulator for continuum robots in the medical field is necessary to be advanced [39].

6. Conclusion

We know that traditional open surgery will inevitably have errors in operation and accuracy. Minimally invasive surgery can minimize this problem. For instance, minimally invasive surgery can reduce the pain of patients and recover quickly. The core of minimally invasive robots is the continuum robot introduced in this paper. Many original medical robots are rigid-connected robots, but most of these robots have limitations owing to joint connection, and continuum robots can solve this problem well.

They can adjust their shape and position according to different paths. We also introduce the newly developed continuum robots in recent years, such as continuum body machines driven by ionic liquids and tendons. These robots have some difficulties in research, but they all have good development prospects.

After briefly introducing the control method of the robot and the technology it uses, we were also involved in the modeling of the continuum robot. There are still many challenges in the part of design, modeling, and control.

In this paper, we summarize the framework, design, and application technology of continuum robots, and put forward its future development prospects and challenges. In the future, continuum robots will be largely developed as people will constantly optimize its program. To achieve more accurate open operations, more materials will be developed to make the continuum robot so that it can have better flexibility. Continuum robots will have greater achievements in the surgical field in the future. It will be possible to create a continuum robot that can enter people's blood autonomously, change people's genes and solve some genetic diseases.

References

[1] Y. Zhong, L. Hu, and Y. Xu, “Recent advances in design and actuation of continuum robots for medical applications,” MDPI, 19-Dec-2020.

[2] J. Burgner-Kahrs, D. Rucker and H. Choset, "Continuum Robots for Medical Applications: A Survey", IEEE Transactions on Robotics, vol. 31, no. 6, pp. 1261-1280, 2015.

[3] M. Frecker and A. J. Snyder, “Surgical robotics: Multifunctional end effectors for robotic surgery,” PennState, Dec-2005.

[4] G. Zhang, F. Du, S. Xue, H. Cheng, X. Zhang, R. Song, and Y. Li, “Design and modeling of a bio-inspired compound continuum robot for minimally invasive surgery,” MDPI, 11-Jun-2022.

[5] K. Xu and N. Simaan, “Intrinsic wrench estimation and its performance index for Multisegment Continuum Robots,” IEEE Xplore, Jun-2010.

[6] H.; Renda, F.; Stefanini, C. Concentric Tube Robots for Minimally Invasive Surgery: Current Applications and Future Opportunities. IEEE Trans. Med Robot. Bionics 2020, 2, 410–424.

[7] F. Qi, F. Ju, D. Bai, Y. Wang, and B. Chen, “Kinematic analysis and navigation method of a cable-driven continuum robot used for minimally invasive surgery,” The International Journal of Medical Robotics and Computer Assisted Surgery, vol. 15, no. 4, article e2007, 2019.

[8] R. Kang, Y. Guo, L. Chen, D. T. Branson, and J. S. Dai, “Design of a pneumatic muscle based continuum robot with embedded tendons,” IEEE/ASME Transactions on Mechatronics, vol. 22, no. 2, pp. 751–761, 2017.

[9] J. D. Greer, T. K. Morimoto, A. M. Okamura, and E. W. Hawkes, “Series pneumatic artificial muscles (spams) and application to a soft continuum robot,” in 2017 IEEE International Conference on Robotics and Automation (ICRA), pp. 5503–5510, Singapore, 2017.

[10] C. Sun, L. Chen, J. Liu, J. S. Dai, and R. Kang, “A hybrid continuum robot based on pneumatic muscles with embedded elastic rods,” Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, vol. 234, no. 1, pp. 318–328, 2020.

[11] T. Greigarn, N. L. Poirot, X. Xu, and C. Cavusoglu, “Jacobianbased task-space motion planning for MRI-actuated continuum robots,” IEEE Robotics and Automation Letters, vol. 4, no. 1, pp. 145–152, 2019.

[12] D. Alatorre, D. Axinte, and A. Rabani, “Continuum robot proprioception: the ionic liquid approach,” IEEE Transac tions on Robotics, vol. 38, no. 1, pp. 526–5, 2022.

[13] J. Liu, J. Wei, G. Zhang, S. Wang, and S. Zuo, “Pneumatic soft arm based on spiral balloon weaving and shape memory polymer backbone,” Journal of Mechanical Design, vol. 141, no. 8, 2019.

[14] R. Kang, D. T. Branson, T. Zheng, E. Guglielmino, and D. G. Caldwell, “Design, modeling and control of a pneumatically actuated manipulator inspired by biological continuum structures,” Bioinspiration & biomimetics, vol. 8, no. 3, article 036008, 2013.

[15] M. C. Yip, J. A. Sganga, and D. B. Camarillo, “Autonomous control of continuum robot manipulators for complex car diac ablation tasks,” Journal of Medical Robotics Research, vol. 2, no. 1, article 1750002, 2017.
[16] M. Li, R. Kang, S. Geng, and E. Guglielmino, “Design and control of a tendon-driven continuum robot,” Transactions of the Institute of Measurement and Control, vol. 40, no. 11, pp. 3263–3272, 2018.
[17] F. Campisano, S. Caló, A. A. Remirez et al.,“Closed-loop control of soft continuum manipulators under tip follower actu ation,” The International Journal of Robotics Research, vol. 40, no. 6-7, pp. 923–938, 2021.
[18] Wang, J.; Lau, H.Y.K. Dexterity Analysis based on Jacobian and Performance Optimization for Multi-segment Continuum Robots. J. Mech. Robot. 2021, 13, 061012.
[19] Biyun, X.; Jing, Z. Advances in Robotic Kinematic Dexterity and Indices. Mech. Sci. Technol. 2011, 30, 1386–1393.
[20] Wu, L.; Crawford, R.; Roberts, J. Dexterity Analysis of Three 6-DOF Continuum Robots Combining Concentric Tube Mechanisms and Cable-Driven Mechanisms. IEEE Robot. Autom. Lett. 2016, 2, 514–521.
[21] ISO 9283:1998, “Manipulating industrial robots– performance criteria and related test methods.” International Organization for Standardization, Standard ISO 9283:1998, 1998.
[22] Gallardo, O. et al. (2022) Turning an articulated 3-PPSR manipulator into a parallel continuum robot, IEEE Xplore.
[23] P. Swaney et al., "Toward Transoral Peripheral Lung Access: Combining Continuum Robots and Steerable Needles", Journal of Medical Robotics Research, vol. 02, no. 01, p. 1750001, 2017.
[24] A. Agrawal, D. Hogarth and S. Murgu, "Robotic bronchoscopy for pulmonary lesions: a review of existing technologies and clinical data", Journal of Thoracic Disease, vol. 12, no. 6, pp. 3279-3286, 2020.
[25] Z. Mitros, B. Thamo, C. Bergeles, L. da Cruz, K. Dhaliwal and M. Khadem, "Design and Modelling of a Continuum Robot for Distal Lung Sampling in Mechanically Ventilated Patients in Critical Care", Frontiers in Robotics and AI, vol. 8, 2021.
[26] C. Heunis, J. Sikorski and S. Misra, "Flexible Instruments for Endovascular Interventions: Improved Magnetic Steering, Actuation, and Image-Guided Surgical Instruments", IEEE Robotics & Automation Magazine, vol. 25, no. 3, pp. 71-82, 2018.
[27] V. Mendes Pereira et al., "First-in-human, robotic-assisted neuroendovascular intervention", Journal of NeuroInterventional Surgery, vol. 12, no. 4, pp. 338-340, 2020.
[28] L. Wang, C. Guo and X. Zhao, "Magnetic soft continuum robots with contact forces", Extreme Mechanics Letters, vol. 51, p. 101604, 2022.
[29] S. Coemert, R. Roth, G. Strauss, P. Schmitz and T. Lueth, "A handheld flexible manipulator system for frontal sinus surgery", International Journal of Computer Assisted Radiology and Surgery, vol. 15, no. 9, pp. 1549-1559, 2020.
[30] H. Yoon, J. Jeong and B. Yi, "Image-Guided Dual Master–Slave Robotic System for Maxillary Sinus Surgery", IEEE Transactions on Robotics, vol. 34, no. 4, pp. 1098-1111, 2018.
[31] W. Hong, F. Feng, L. Xie and G. Yang, "A Two-Segment Continuum Robot With Piecewise Stiffness for Maxillary Sinus Surgery and Its Decoupling Method", IEEE/ASME Transactions on Mechatronics, pp. 1-11, 2022.
[32] D. Rus and M. Tolley, "Design, fabrication and control of soft robots", Nature, vol. 521, no. 7553, pp. 467-475, 2015.
[33] T. da Veiga et al., "Challenges of continuum robots in clinical context: a review", Progress in Biomedical Engineering, vol. 2, no. 3, p. 032003, 2020.
[34] J. Till, V. Aloi and C. Rucker, "Real-time dynamics of soft and continuum robots based on Cosserat rod models", The International Journal of Robotics Research, vol. 38, no. 6, pp. 723-746, 2019.

[35] T. da Veiga et al., "Challenges of continuum robots in clinical context: a review", Progress in Biomedical Engineering, vol. 2, no. 3, p. 032003, 2020.
[36] A. Franz, T. Haidegger, W. Birkfellner, K. Cleary, T. Peters and L. Maier-Hein, "Electromagnetic Tracking in Medicine—A Review of Technology, Validation, and Applications", IEEE Transactions on Medical Imaging, vol. 33, no. 8, pp. 1702-1725, 2014.
[37] P. Dupont, N. Simaan, H. Choset and C. Rucker, "Continuum Robots for Medical Interventions", Proceedings of the IEEE, vol. 110, no. 7, pp. 847-870, 2022.
[38] D. Shah, J. Powers, L. Tilton, S. Kriegman, J. Bongard and R. Kramer-Bottiglio, "A soft robot that adapts to environments through shape change", Nature Machine Intelligence, vol. 3, no. 1, pp. 51-59, 2020.
[39] J. Collins, S. Chand, A. Vanderkop and D. Howard, "A Review of Physics Simulators for Robotic Applications", IEEE Access, vol. 9, pp. 51416-51431, 2021.