Current Status and Challenges in Soft Surgical Robot Technology for Minimally Invasive Surgery

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Abstract. The demand for minimally invasive surgery is growing at a speedier pace. In this context, soft robotics, characterized by high flexibility, multiple degrees of freedom, and intrinsic safety. Also, has been identified as an important development direction for next generation surgical robots. This paper presents a systematic review of the recent advances in soft surgical robots in terms of structural design and manufacturing processes, driving methods, and sensing technologies. The paper will study technical benefits and the wide application prospects of this field by examining typical medical situations, for instance, endoscopic surgeries, cardiac surgeries and breakthroughs in related technologies. To this end, the paper highlights the development bottlenecks of soft robots and further evaluates the challenges faced at technical levels on force feedback, system integration, and material development. Simultaneously, the essay describes clinical translation difficulties such as safety, stability of material, doctor operation, legal, etc. Ultimately, this paper was an analysis of state-of-the-art developments across the globe. It also provides the future trends of soft robots for intelligent integration and group collaboration. Finally, it aims to provide reference and aid for clinical researchers working in associated fields.

Keywords: Soft robotics, minimally invasive surgery, Core technologies, Application challenges, Future outlook.

1. Introduction

With the global aging of the population and the increasing demand of patients for postoperative quality of life, there is a growing need for the development of surgical techniques with smaller incisions and greater safety. For major global fatal diseases such as cardiovascular diseases and gastrointestinal cancers, minimally invasive surgery has shifted from an exploratory approach to the preferred treatment method. Progressing from early laparoscopic techniques to widely adopted rigid systems like the da Vinci Robot, minimally invasive surgery continues to advance. However, in complex anatomical environments, rigid robotic systems represented by the da Vinci system face inherent limitations: insufficient flexibility, difficulty in obstacle avoidance, and potential safety risks [1].

Soft robotics addresses these gaps. Constructed primarily from flexible materials, soft robots deform continuously and smoothly (similar to biological organisms) and offer infinite degrees of freedom, high compliance, and inherent safety. In recent years, they have shown great potential in intravascular navigation, neurosurgery, pulmonary surgery, and endoscopy. Their lightweight and adaptable nature makes them a key direction for next-generation surgical robots, promising to enhance surgical safety and patient comfort while maintaining efficacy [2].

This paper analyzes the innovative achievements of soft robots in structural design, drive technology and sensor technology, demonstrates their advantages over traditional robots through application scenarios, and objectively assesses the challenges in terms of technological maturity, clinical transformation and regulatory compliance. At the same time, the future development directions (such as technology integration and group collaboration) were discussed, aiming to provide support for researchers and clinical workers to promote the clinical application of soft surgical robots.

2. Structural Design and Manufacturing Processes for Soft Surgical Robots

2.1. Bionic Structural Design

Soft surgical robots have a structural design that tries to replicate the morphology, structure and movement pattern of biological organisms to create more efficient and safer surgery. In the case of a Harvard University team of researchers, they resulted in an implantable soft robot made of a silicone cylinder less than 1 millimeter in thickness. It has a ring-shaped air bladder that creates auxiliary pumping assistance to the failing hearts by imitating the working of the heart with inflation and deflation. The design allows the non-invasion of the cardiac muscles and eliminates the risk of clotting characteristic of the traditional ventricular assist devices (VADs) because of contact with blood [3]. Another reported patented design is a bionic cardiac fixator for the off-pump coronary artery bypass grafting. The device uses a negative force suctioned to the surface of the heart by employing a U-shaped suction structure, which takes the shape of the suction cup mechanism used by octopus tentacles. The adaptable material and the rigid-to-flexible transition mechanism with pneumatic operation maintain the surgical field in a stable condition with minimized cardiac trauma, as well as build a strong foundation for the use of the robotic system in difficult clinical conditions [4]. The biomimetic designs not only improve the functionality and safety of the robots but also form a solid base for the use of the robotic system in complicated clinical environments.

2.2. State-of-the-Art Technologies in Manufacturing

The next-generation manufacturing technology should enable complex biomimetic structures and, miniaturization of soft robots. Multi-material 3D printing technologies, especially inkjet and photopolymerization-based methods, allow for firm regulation of the allocation of various flexible materials. It can be used to produce soft robots with gradient stiffness, microchannels and complex internal architectures. As an example, scientists used 3D printing, which utilizes multi-materials to produce magnetic soft robotic chains made of elastic materials and loaded with neodymium iron boron, which are magnetic particles. These chains spontaneously form complex structures in response to magnetic field direction with an impressive potential to broaden the maximally invasive tools. Also, laser cutting technology has been extensively applied in the creation of thin-walled and expandable soft structures. An example is a soft robotic expandable basket catheter used in left atrial mapping with a thermoplastic polyurethane thin-walled structure in the shape of balloons, which is made by laser cutting. It gets up to 85% conformability to complex atrial anatomy, which greatly outperforms the traditional basket catheters [5]. These new manufacturing methods not only improve the design flexibility and manufacturing precision of soft robots but also provide the basis to develop them at smaller sizes and higher performance.

3. Methods and Technologies of Actuation of Soft Surgical Robots

3.1. Fluid Actuation

Fluid actuation is one of the most established and embraced drive interventions in the existing soft surgical robots, mostly including pneumatic and hydraulic ones. Its underlying principle is where fluid is injected or sucked out of closed chambers in the robot, which causes a change of shape that can be expansion, contraction, or bending to produce motion. Pneumatic actuation is widely researched because it is easy and fast responding. As an example, the Harvard University cardiac assist robot uses pressurized air to expand and contract annular air sacs, which simulate the cardiac contraction, but hysteresis may result in nonlinearity, and noise degrades the precision of control [3]. Contrarily, remaining fluid is a fluid, such as water or oil, so hydraulic actuation provides greater force output and control. An example is a soft robotic catheter to perform vascular catheter surgery that uses hydraulically driven filamentary artificial muscles that provide omnidirectional bending capability and an expandable workspace and attain forces up to 0.375 N, which are enough to sustain

a cardiac ablation procedure [6]. Moreover, hydraulic actuation can also effectively reduce the risk of air embolism as a result of gas leakage, thus providing much safer operation in clinical applications.

3.2. Smart Material Actuation

Smart material actuation is a very promising branch of soft robotics that wants to take advantage of inherent physical or chemical property variations in materials to create deformation and force. Two mainstream smart actuation media are shape memory alloys (SMA), as well as electroactive polymers (EAP). SMA, on heating, can go back to a pre-configured shape, allowing repetitive mechanical behaviors by controlled cycles in heating and cooling. SMA, however, has sluggish response time and its actuation efficiency is poor. EAPs (dielectroelastomers) are able to reduce in thickness and increase in area under electric fields and hence propel robotic movement. The advantages of this technique are that it is fast responding, generates high energy density, and eliminates noise. Also, soft materials whose movement is mediated by magnets have received a lot of interest. Flexible robots that are able to execute sophisticated movements can be built in the presence of magnetic fields by encasing the magnetic particles in the flexible material. An example is the recent work of magnetic soft robotic chains navigating blood vessels or carrying out therapeutic duties under external magnetic field control by the researchers [5]. Smart material actuation provides new avenues of historic miniaturization, wireless operation and intelligent actuation to soft robotics.

3.3. Cable Actuation

Cable actuation is a time-honored but efficient drive system, which works on the bicycle principle of using a brake cable. It regulates the deformation of the robot by straining cables encircling the inner region of a flexible one. The strengths behind the use of this type of drive are that they have mature technology, their force is highly transmissible and it is also comparatively easy to control. Nevertheless, actuation of the cable has disadvantages, as well. The cables and conduit walls are frayed and this loss of force affects the accuracy of the control. A variety of cables makes the systems cumbersome. Also, control errors are caused by cable stretch and hysteresis. Researchers are trying to fix these issues by trying new materials and structures, like a low-friction coating/lining, and cable routing optimization. Cable-actuated soft robots. In some hybrid-actuated soft robots, cable actuation can be used with the other drive mechanisms of fluid-actuated or smart material-actuated systems to combine their strengths to allow different and more complicated motion patterns and increase performance [5].

4. Sensing and State Awareness of Soft Surgical Robots

4.1. Pose Sensing

To enable the implementation of closed-loop control and high-accuracy manipulation in soft surgical robots, accurate pose sensing is vital. It is also challenging to apply rigid sensors directly to the critical nonlinear and large deformations of the soft robot structures. Therefore, several pose sensing technologies have been created by researchers to fit soft robots. Of these, Fiber Bragg Grating (FBG) sensors have been widely researched because they are small, have high sensitivity, and are not sensitive to electromagnetic interference [7]. The soft robot can be fitted with FBG sensors. Electromagnetic (EM) tracking systems are also a commonly used method of pose sensing: A single study has significantly improved the quality of the shape perception to the behavioral decision-making processes through the use of multi-core FBG fibers and an enhanced filtering algorithm [8]. Additionally, a variety of EM tracking systems are a well-known pose sensing solution. Through the combination of a miniature electromagnetic sensor in the end-effector of the soft robot, real time position and orientation details in three-dimensional space should be known under the influence of an external magnetic field emitter. As an example, a study of a soft robotic catheter in its working environment used an EM tracking sensor to accurately measure the movement path of the catheter tip. Outside these two mainstream technologies have been new miniaturization low-cost shape

perception products that are premised upon optoelectronic sensors and spherical mirrors [9]. These pose-sensing technologies are vital in the provision of vital data in the correct operation and transportation of soft robots.

4.2. Tactile/Force Sensing

Precise force sensing in minimally invasive surgery is essential to prevent tissue damage, measure tissue properties, and be able to handle them in a delicate manner. The soft robots have a flexible structure allowing the distribution of stress better in the tissue contact, but it complicates the accurate measurement of the force measured accurately. In lieu of this, scientists have come up with diverse integrated soft force sensors. An example is a low-cost soft robotic catheter in vascular interventions that has a soft force sensor of the tip that comprises hydraulic filamentary artificial muscles. This sensor measures the contact forces between the catheter tip and tissue based on the variations of the driving hydraulic fluid with a sensitivity of 10.7 kPa/N. An alternative project suggested employing a hydrogel layer as a shield between soft robots and cardiac tissue to regulate the effects of inflammatory reaction and to now use its mechanical characteristics to sense the indirect forces [3]. Moreover, force sensing can be done through the use of optical fiber sensors. An example is that, in one study, a sensing surgical instrument was designed using fiber Bragg gratings (FBGs). One of the strategies utilized to perform high-precision exercise of force in two directions was attaching FBG sensors to the instrument shaft [10]. The promise behind these advancements in tactile/force sensing technologies is that these technologies can greatly improve surgery safety and precision.

5. Current Challenges and Future Outlook

5.1. Technical Challenges

Precise force sensing and real-time feedback represent core technical bottlenecks in soft robotics, particularly in minimally invasive surgery, where surgeons rely on tactile feedback to assess tissue properties and contact states. Existing systems generally lack effective force feedback mechanisms. Sensor sensitivity, hysteresis effects, and long-term stability require urgent improvement; raw sensor data is difficult to convey accurately and intuitively to the operator. The absence of precise force feedback not only limits surgeons' perception and control over the surgical process but also increases surgical risks.

Table 1. Bottleneck Analysis of Soft Robotics Actuation Systems

Actuation Type	Existing Achievements / Key Components	Advantages	Pending Problems
Smart Material	Electro-pneumatic ventricular assist device based on Dielectric Elastomer Actuator (DEA) [11]	Lightweight (<200 g), low power consumption (1.6 W), fast response	Low actuation efficiency, short stroke, high actuation voltage (or magnetic field strength), material fatigue and aging [12]
Fluid	Miniaturized pumps, valves, and pipelines	Enables miniaturization and improved mobility	Miniature components fail to meet pressure/flow/response requirements for complex surgeries.
Cable	Mature Technology	High force efficiency, simple control	Multiple cables increase volume/complexity; friction/hysteresis are hard to eliminate

The drive system serves as the “muscle” of soft robots, with its performance determining mobility, load capacity, and response speed. As shown in Table 1, all drive methods face challenges when integrating compact, reliable systems into flexible structures. Integration and miniaturization remain major obstacles to clinical application.

Table 2. Characteristics and Limitations of Existing Materials for Soft Surgical Robots

Material Type	Specific Materials / Technologies	Advantages	Main Limitations
Commonly Used	Silicones (EcoFlex, Dragon Skin)	High elasticity, easy processing	Low mechanical strength, poor wear resistance, long-term biocompatibility risks
Currently Focused	Hydrogel	Tissue-like softness/water content, high biocompatibility	Weak mechanical strength, dehydration shrinkage

Table 3. Material Breakthrough Directions and Value for Soft Surgical Robots

Breakthrough Type	Specific Materials / Technologies	Advantages	Core Value
Composite Material	3D-printed biocompatible composites [13]	Elastic modulus tunable (15 kPa–1.4 GPa)	Enables tissue integration; solves hard-soft interface matching
Multi-Material Integration	3D-printed TPU + conductive PLA [14]	Integrates actuation, sensing, variable stiffness	Resolves rigidity-flexibility conflicts; enables multifunctionality
Smart Material	Temperature/pH/electrically responsive stiffness-tunable materials [14]	Soft for movement, rigid for precision/support	Adapts to complex surgical scenarios

The performance of soft robots is largely determined by material properties. Table 2 summarizes the limitations of existing materials, while Table 3 highlights breakthrough directions. Currently used and emerging materials still exhibit significant shortcomings in key dimensions such as mechanical properties and biocompatibility. Composite materials and smart materials offer solutions, emerging as core research directions for achieving functional breakthroughs.

5.2. Clinical Challenges

The trend of the further evolution of soft tissue surgical robots will be based on the profound combination of various most advanced technologies, such as artificial intelligence, novel approaches to imaging, and fast communication technologies. The concept of embodied intelligence frameworks is becoming a foundation and direction of development of robots, providing them with self-understanding and proactive working characteristics. An example is the Robonurse-vla AI surgical robot that utilizes a vision-language-action model to identify and place surgical tools as so automatically in response to voice cues given by a physician, thus lessening the need to place more sensors [15, 16]. At the same time, the surgical field of view overlaid with 3D anatomical models in the case of augmented reality (AR) and 5G communication technology will offer surgeons remote precision operations with low latency and promote the decentralized distribution of high-quality medical resources [17]. This technological convergence by integrating fulgurantly the capabilities of perception, decision-making, and execution at the system level will essentially amplify the autonomy, accuracy and availability of surgical procedures.

Micro-nano robot swarm collaboration, inspired by the animal kingdom, has become a highly innovative solution to address intricate surgical operations such as targeted drug delivery and distributed monitoring. The success of swarm coordination depends on the ability to overcome agent-to-agent communication issues, task distribution and collaborative control. As an example, one

research team has developed a signal transmission protocol between micro-nano robots, which allows swarmed coordination of large systems with strong capabilities [18]. Also, a heterogeneous multi-robot TAP of a distributed Team Allocation Protocol is proposed. The protocol allows effective autonomous teaming under communication-limited conditions and introduces new paradigms of collaborative work of the functionally different micro-robots in surgical practice in the future [19]. At the same time, the developments in magnetic-controlled micro-swarm robots navigation control have allowed adaptive manipulation of precision in fluidic environments [20]. Clustered cooperative operations extend the application space of individual robots (soft robots) to reconfigurable intelligent medical systems, which is certainly a research direction of enormous potential and development space in the future.

5.3. Future Outlook

The future development of soft tissue surgical robots will rely on the deep integration of multiple cutting-edge technologies, including artificial intelligence, advanced imaging techniques, and high-speed communication technologies. Embodied intelligence frameworks are emerging as a core development direction, endowing robots with autonomous comprehension and proactive operational capabilities. For instance, the Robonurse-vla AI surgical robot system employs a vision-language-action model to automatically identify and deliver surgical instruments based on physician voice commands, eliminating the need for additional sensors. Simultaneously, the integration of augmented reality (AR) with 5G communication technology will provide surgeons with a surgical field of view overlaid with 3D anatomical models, supporting low-latency remote precision operations and driving the decentralized allocation of high-quality medical resources [17]. By deeply integrating perception, decision-making, and execution capabilities at the system level, this technological convergence will fundamentally enhance the autonomy, precision, and accessibility of surgical procedures.

Inspired by natural insect colonies, micro-nano robot swarm collaboration has emerged as a cutting-edge solution for tackling complex surgical tasks like targeted drug delivery and distributed monitoring. Achieving swarm coordination hinges on resolving challenges in agent-to-agent communication, task allocation, and collaborative control. For instance, a research team pioneered a signal transmission mechanism among micro-nano robots, enabling large-scale swarm coordination with robust performance [18]. Furthermore, a distributed Team Allocation Protocol (TAP) for heterogeneous multi-robot systems has been proposed. This protocol enables efficient autonomous team formation in communication-constrained environments, pioneering new paradigms for collaborative operations among functionally diverse micro-robots in future surgeries [19]. Concurrently, breakthroughs in magnetic-controlled micro-swarm robot navigation control have enabled adaptive precision manipulation in fluidic environments [20]. Clustered collaborative operations expand the application boundaries of soft robots from individual tools to reconfigurable intelligent medical systems, undoubtedly representing a research direction with immense potential and development space for the future.

6. Conclusion

This paper presents a systematic biography, the fundamental technologies, common usages, and obstacles of soft robotics in surgical procedures today, as well as the future projections of the technology of the least invasive surgery. The possibility of soft robots is immense as they are inherently compliant, highly adaptive, and safe. There has been a major advancement in central technologies in terms of structural design and manufacturing methods, from fluid-driven to smart materials-driven systems, and to multimodal sensing and perception. Nevertheless, the process of turning laboratory-based prototypes into extensive clinical usage is twofold: on the technology side (the absence of force feedback, integration of the system, the development of new materials), and on the clinical side (validation of safety, training of surgeons, legal and cost aspects).

The future of surgical robotics is soft surgical robots. They promise to reduce trauma during the minimally invasive procedures and shape surgical precision to new standards. Nevertheless, with the most challenging tasks in the future, gradual advancements in the fields of materials science, artificial intelligence, and micro/nano manufacturing will certainly broaden the development horizon of the soft surgical robots. They will eventually be brilliant in clinics and positively change thousands of patients.

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