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Tactile Sensing Technologies in Minimally Invasive Surgical Robots: A Review

Shujun Ding[1*], Zhenjia Liu[2], Yizhi Lv[3]

[1]*Jinan Licheng No.2 High School, Jinan, China*
[2]*Guanghua Cambridge International School, Shanghai, China*
[3]*New Channel-Jinan A-Level Training School, Jinan, China*
**Corresponding Author. Email: 1707384407@qq.com*

Abstract. Minimally invasive surgical (MIS) robots have transformed modern surgical practices by enabling procedures with reduced trauma and faster patient recovery. However, one major drawback of current robotic systems is the lack of tactile perception, which impairs a surgeon's ability to accurately assess tissue properties during manipulation. Tactile sensing technologies have thus become critical in restoring haptic feedback to improve surgical safety and precision. This review presents a comprehensive analysis of tactile sensors used in MIS robots, focusing on four main categories: resistive, capacitive, optical, and spring-based sensors. Their working principles, integration strategies, and performance in surgical environments are systematically compared. Additionally, emerging approaches such as sensorless force estimation and multi-modal sensing are discussed, highlighting their potential to overcome current limitations in size, sterilizability, and signal fidelity. Despite notable advancements, challenges remain in balancing sensor miniaturization, mechanical robustness, and multi-degree-of-freedom force detection. This review concludes by outlining future research directions, including the development of hybrid sensor systems, real-time AI-based force interpretation, and enhanced haptic interfaces, which are essential to advancing tactile feedback capabilities in next-generation robotic surgery.

Keywords: minimally invasive surgical robots, haptic feedback, tactile sensing technologies.

1. Introduction

Surgical robots are robotic systems designed to assist in surgical procedures, with the aim of enhancing surgical precision, reducing trauma, and improving patient recovery. Their invention has enabled a shift from open surgeries to minimally invasive procedures, opening up new possibilities in clinical practice. Studies, such as those by [1], have found that the proportion of minimally invasive surgeries has increased significantly over the past two decades.

With the advancement of robotic-assisted surgeries, minimally invasive surgical (MIS) robots have seen considerable development. However, robotic operations often result in the surgeon losing tactile perception of the tissue, leading to decreased accuracy and potential surgical errors. As pointed out by [2], haptic feedback significantly reduces the gripping force exerted by both experts and novices, and

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a strong correlation has been observed between grip force and tissue damage. This suggests that haptic feedback can reduce the likelihood of tissue injury and improve surgical precision.

The integration of haptic feedback into MIS systems began approximately two decades ago. This technology enables the surgeon to perceive tissue texture, pressure, and the interaction forces between instruments and tissues remotely by sensing characteristics such as hardness, shape, texture, and temperature. Continuous progress has been made in both haptic data acquisition and feedback mechanisms. Early explorations, such as in the Versius robotic system and the Hugo™ robotic system for laparoscopic procedures, incorporated force-based haptic feedback. With advancements in force sensing, sensor integration, and feedback methodologies, systems like the Da Vinci Surgical System and the CorPath GRX for cardiac procedures have also explored haptic feedback integration.

During the early development of surgical robots such as the Da Vinci system, surgeons relied primarily on visual information. With the introduction of piezoresistive sensors in the 2000s, force sensing entered the experimental stage. The development of MEMS technology allowed the integration of miniature sensors into MIS tools, and optical sensors also began to be adopted. By the 2010s, sensors were being widely applied in robotic surgery. Today, various flexible and stretchable sensors have been extended into numerous biomedical fields.

In this review, we provide a comprehensive overview and analysis of different types of sensors used in MIS, evaluating their advantages and limitations. We also examine their integration into robotic end effectors—such as grippers and cutting tools—as well as their role in robotic palpation. Based on sensing mechanisms, sensors are categorized as resistive, capacitive, and optical.

2. Different sensors and application

The tactile information required during surgery primarily includes contact forces, environmental parameters (such as temperature), and the texture of target tissues. As human touch is an inherently multimodal perception, accurate tactile sensing necessitates the acquisition of multidimensional information. Therefore, sensors capable of detecting multiple physical parameters are preferred due to their ease of integration. Most force detection relies on material deformation to infer the magnitude of applied forces. For tissue texture detection, contact methods employ friction or deformation to sense surface roughness, while non-contact optical methods utilize changes in light reflected or refracted from the surface.

2.1. Resistive-based sensors

Resistive sensors measure physical quantities such as pressure and temperature through changes in electrical resistance. A unique characteristic of these sensors is their ability to generate voltage upon deformation, eliminating the need for an external power supply. Strain gauges, the most commonly used resistive sensors in MIS for force measurement, detect resistance changes due to deformation. These changes can be measured using a Wheatstone bridge circuit. A key parameter for strain gauges is the gauge factor (GF), calculated as follows:

$$GF = \frac{\Delta R/R}{\varepsilon}$$

where R is initial resistance, ΔR is resistance difference, εis strain.

Because force measurement involves multiple directions, accurate sensing requires compensation for off-axis strain. In the design of the Sensingplus1 bipolar forceps, strain gauges were placed in positions that maximized fork deformation under applied force, enhancing sensitivity and signal-to-noise ratio.

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Ana Luisa Trejos et al. found that strain gauges must withstand sterilization cycles at temperatures around 120°C. They tested various adhesives and coatings and concluded that the combination of Loctite M-3981 adhesive and Loctite M-11FL coating best preserved sensor performance after repeated sterilizations [3].

Another type of resistive sensor is the Force Sensitive Resistor (FSR), which, compared to piezoelectric sensors, is less sensitive to small vibrations and low-amplitude forces, and exhibits drift under constant loading. However, FSRs offer excellent temperature tolerance (up to 170°C) and are relatively insensitive to humidity. Lu Li et al. introduced a design with four electrodes and a polymer film embedded with conductive and non-conductive particles. By adopting a "through-mode" configuration and depositing a semiconducting polymer on the surface, the response time and linearity were improved, enabling the detection of smaller forces under preloading conditions [4].

Resistive sensors are typically compact—strain gauges and FSRs often measure only a few millimeters—making them suitable for integration into small MIS instruments. Biocompatible silicone encapsulation allows them to withstand sterilization. These sensors are well-established, with mature fabrication techniques and easily measurable resistance changes, contributing to their widespread applicability.

2.2. Spring-based sensors

Spring-based sensors also rely on the conversion of mechanical deformation into electrical signals, using mechanisms such as resistance or capacitance.

Chunyang Jiang et al. [5] developed a triaxial force sensor using a three-spring structure integrated with strain gauges. They employed modeling and calibration to decouple the axes and reduce signal interference. Man Bok Hong and Yung-Ho Jo [6] used a torsional spring integrated into surgical forceps to improve compliance and adjust sensitivity during the synthesis of two force vectors. However, the design's limited two degrees of freedom restrict its suitability for MIS applications.

Spring elements are usually metallic, offering good high-temperature resistance. Nonetheless, the influence of the elastic modulus must be considered. Achieving multi-degree-of-freedom force sensing within constrained volumes remains challenging. High stiffness ensures fast response, while signal drift is primarily influenced by other electronic components. Key limitations include low force resolution, necessary for detecting subtle tactile cues, and mechanical fatigue, which affects longevity. For flexible springs, material-induced drift is also a concern.

2.3. Capacitive sensors

Capacitive sensors detect physical quantities by measuring changes in capacitance. These sensors offer high sensitivity to small forces and, due to their non-contact electrode structure, are less prone to mechanical wear. When pressure is applied, the distance between electrodes changes, altering capacitance (C), as described by:

$$C = \frac{\varepsilon A}{d}$$

where εis the permittivity of the dielectric material between the electrodes, A is the overlapping area of the electrodes, d is the distance between the electrodes.

In MIS applications, capacitive sensors must be compatible with surgical robot platforms and meet requirements such as at least four degrees of freedom. Typical sensor sizes are in the centimeter range, but MIS demands that components be miniaturized to just a few millimeters.

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Uikyum Kim et al. [7] developed a sensor capable of measuring three degrees of traction force and one degree of gripping force. Using a triangular prism structure with dual capacitive elements at the tip, their design provides accurate force feedback while maintaining compactness. Its compatibility with surgical platforms also enables realistic testing environments.

S. Akhmatdinov et al. developed multilayer pressure sensors that mimic human skin [8], enabling depth-specific pressure detection. Their flexible material reduces rigidity and offers a wide sensitivity range, making it suitable for surgical applications. However, their use of PDMS limits their resistance to high temperatures, requiring alternative materials for sterilizable applications.

Capacitive sensors are small, low-cost, easily integrable, fast-responding, and highly sensitive, making them popular choices for MIS. However, sterilization requirements necessitate careful selection of encapsulating materials.

2.4. Optical sensors

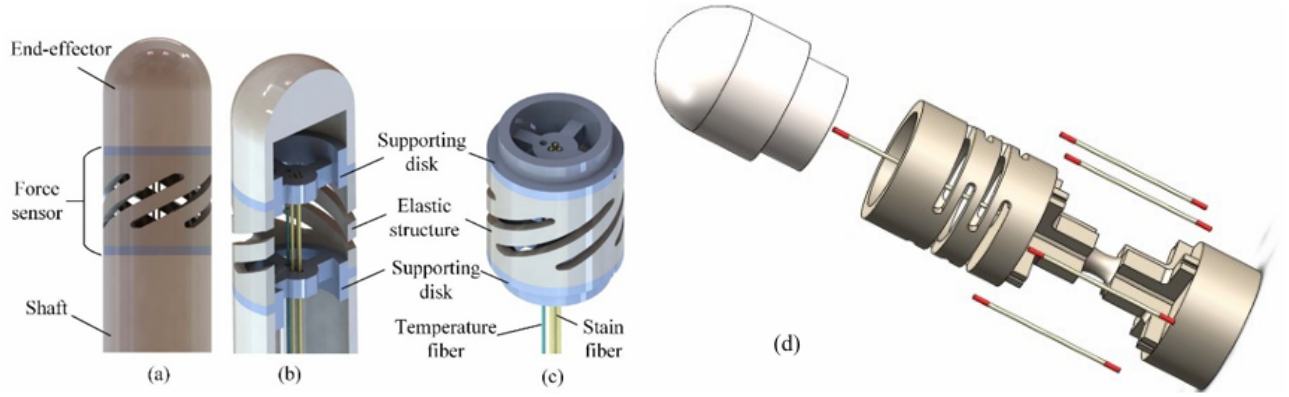


Figure 1: Structure of the force sensor. (a) Sensor is fixed on the shaft of the surgical instrument. (b) Sectional view of the sensor and the distribution of the FBGs. (c) Three-dimensional representation of the force sensor and the FBGs. (c)Three-dimensional representation of the force sensor [9]. (d) Sensor explosion diagram and FBG distribution diagram [10]

Optical sensors measure physical quantities through the interaction of light with the object or environment, such as reflection or refraction. Unlike electrical sensors, they are immune to electromagnetic interference. Among optical sensors, Fiber Bragg Gratings (FBGs) have attracted attention due to their compact size and integration potential. These sensors measure force based on changes in fiber length under external force, which shifts the Bragg wavelength:

$$\Delta\lambda_B = \lambda_B \bullet ((1 - p_e)\varepsilon + \alpha\,\Delta\,T)$$

where $\Delta\lambda_B$ is the change in the Bragg wavelength, λ_B is the original Bragg wavelength, p_e is the photoelastic coefficient of the fiber, $\varepsilon\ is\ the\ applied\ strain$, α is the thermal expansion coefficient, ΔT is the temperature change.

Elastic deformations such as stretching or bending alter the optical signal, enabling force detection. However, balancing axial and radial stiffness is challenging in triaxial force sensing and affects resolution in multiple directions.

Jianhua Li et al. [9] addressed this by designing a helical beam structure using parallel spiral grooves. The groove angle determines stiffness, which is optimized via finite element analysis to enhance directional resolution while maintaining compactness and modularity.

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Jie Jiang et al. [10] incorporated I-beam structures and U-shaped grooves to balance stiffness, placing multiple FBGs at different positions. By comparing wavelength shifts, they isolated specific FBGs and compensated for temperature effects, enabling more accurate force measurements. These designs are well-suited for robotic palpation, leveraging their miniaturized form factors.

Aizhan Issatayeva et al. [11] embedded four symmetrically distributed optical fibers into a needle, using Scattering-Level Multiplexing (SLMux) to detect distributed strain. Shape reconstruction algorithms were applied to estimate needle trajectory and curvature. Because symmetric FBGs experience similar temperature shifts, comparing their strain differences enabled temperature compensation and accurate deformation detection.

Optical sensors can be miniaturized and effectively integrated at the distal end of surgical instruments. Owing to the short wavelength of light, optical sensors offer high spatial resolution, enabling fine and precise measurements. Their fast response time satisfies the real-time monitoring requirements in surgical procedures. Additionally, the diversity of optical sensing principles allows for the development of multifunctional sensors capable of simultaneously detecting and transmitting multiple parameters.

However, optical signal processing is typically more complex than electrical signal processing. The conversion of optical signals into usable data requires sophisticated optoelectronic converters and advanced filtering techniques, often involving computationally intensive algorithms. Furthermore, optical fibers are highly sensitive to bending, particularly at joint regions, which presents a significant challenge for integration into articulated surgical tools and may lead to operational inconvenience.

2.5. Sensorless force estimation

A novel approach to force sensing has emerged—sensorless force estimation—which eliminates the need for physical sensors by relying on models or algorithms. Current methods include model-based, vision-based, and deep learning-based approaches.

Angelica I. Aviles et al. [12] proposed a visuo-neural approach, consisting of two modules. The visual module estimates surface deformation via energy functions, while the neural network module (a recurrent neural network) maps geometric and visual features to force estimations. Yangming Li et al. [13] developed a model-based approach for estimating gripping force in cable-driven MIS tools using unscented Kalman filters. Their method incorporates motor encoder readings and output torque, using dynamic modeling to reduce uncertainties from the mechanical system. These techniques are biocompatible and adaptable to various tissue geometries.

Sensorless force estimation methods eliminate the limitations associated with physical sensing materials, providing greater long-term stability. Nevertheless, they face challenges related to the accuracy of the system model, the integration constraints due to the size of the estimation components, and the method's sensitivity to temperature variations. In unstructured and dynamic environments, it is particularly difficult to establish a reliable and stable model. Moreover, achieving accurate real-time force estimation often requires high sampling rates and complex algorithmic processing, which may limit their practical feasibility and necessitate further investigation.

3. Discussion

Surgical robotics tactile sensors have improved a lot lately. But many problems still remain and limit their performance. This section talks about these issues, looks at current methods, and suggests possible fixes to make robotic surgery tools sense touch better.

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3.1. Current approaches and limitations

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3.1.1. Sensor-based force feedback

Most current robotic surgical systems rely on sensors, such as strain gauges and piezoelectric sensors, to measure and provide force feedback during surgeries.

The limitation of this approach lies in the fact that sensor-based robotic surgery primarily focuses on the forces applied to the patient and the surgical site, with minimal attention given to other aspects. The feedback system, in particular, suffers from low fidelity and is limited to force feedback only. Even when providing some assistance during the procedure, the feedback cannot guarantee precision or comprehensibility. Furthermore, there is a lack of sufficient clinical trials to demonstrate the practicality and reliability of tactile feedback systems in robotic minimally invasive surgery (RMIS), according to Okamura, A. M. [14]

3.1.2. Tactile feedback for tissue differentiation

Alternative technologies, such as tactile feedback for tissue differentiation, provide real-time tactile information to help surgeons distinguish between different types of tissues or structures, thereby facilitating more precise operations. Tactile feedback offers sensory information beyond the limited visual field of the surgical site, allowing the surgeon to differentiate between tissues and avoid inadvertent damage to critical anatomical structures. Tactile perception is often applied in more complex and delicate procedures, where additional sensory information is essential to assist surgical decision-making. However, such technologies still face limitations in terms of sensitivity and accuracy, resulting in a dilemma: they may be redundant in conventional surgeries performed by experienced surgeons, yet insufficiently reliable for more complex surgical environments.

3.1.3. Sensorless haptic feedback systems

For sensorless haptic systems, dynamic compensation algorithms are employed to generate haptic feedback instead of relying on physical sensors. As noted by Yilmaz et al. [15], dynamic compensation approaches still need additional optimization to reliably achieve parity with sensor-driven performance levels, unconventional innovations have brought new possibilities to these methods. With advances in computational power and accumulated experience in robotic surgery, model-based estimation approaches show promising potential. Nevertheless, achieving a level of accuracy comparable to traditional sensor-dependent systems remains a significant challenge.

3.1.4. Real-time tactile feedback for remote surgery

Approaches:

In the context of telesurgery, haptic feedback may become a critical component. Surgeons can perform preliminary palpation and receive force-related information during remote procedures, effectively eliminating the barrier of distance. The high transmission rate of 5G networks and edge computing technologies reduce feedback latency, supporting real-time information transfer and

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intraoperative force control. Augmented reality (AR) systems that integrate both tactile and visual data can enhance situational awareness for remote surgeons. However, network and processing delays inevitably hinder the delivery of real-time haptic feedback. Moreover, AR-based tactile systems require complex configurations to achieve realistic touch sensations.

From these studies, we can see that although haptic feedback technology has come a long way, there are still some challenges we need to overcome. The biggest issues are making the systems accurate enough to be used in real surgeries, developing practical solutions that can be easily implemented, and exploring new methods like sensorless feedback. Overall, the future of robotic surgery depends on further improving these technologies, making surgeries safer and more effective.

3.2. Future potential directions

3.2.1. Hybrid sensor systems

Mixing rigid and soft sensors might offer both durability and flexibility. Hybrid materials could let robots adjust stiffness, improving adaptability in different surgeries.

3.2.2. Ai-augmented real-time processing

Machine learning models should be improved to handle touch data faster and adjust forces in real time. Making AI more efficient is key to reducing delays.

3.2.3. Multi-modal sensor integration

Combining touch, vision, and temperature sensors could help robots tell tissue types apart and adjust force. Future systems need better links between these sensors.

3.2.4. Advanced haptic interfaces

Creating new haptic controllers could give surgeons direct force feedback during operations. These tools would mimic real touch, helping surgeons make better force decisions

4. Conclusion

Tactile sensing has emerged as a pivotal component in the advancement of minimally invasive surgical (MIS) robotics, addressing one of the fundamental limitations of robotic surgery: the absence of haptic feedback. This review has provided a comprehensive examination of the principal tactile sensing technologies employed in MIS systems, including resistive, capacitive, spring-based, optical, and sensorless approaches. Each modality presents distinct advantages and inherent constraints, particularly in terms of sensitivity, miniaturization, integration complexity, and sterilization compatibility.

Resistive and capacitive sensors offer a mature technological foundation, with relatively straightforward fabrication and signal processing techniques. However, their long-term stability and sensitivity under surgical sterilization protocols remain areas of concern. Optical sensors, particularly those based on Fiber Bragg Gratings, demonstrate high spatial resolution and immunity to electromagnetic interference, making them attractive for miniaturized and precise applications such as robotic palpation. Nonetheless, their structural complexity and sensitivity to mechanical alignment pose integration challenges. Sensorless force estimation, although still in a nascent stage, introduces

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promising pathways for simplifying system architecture and enhancing biocompatibility, but currently lacks the robustness and reliability required for clinical deployment.

Across all technologies, a recurring challenge lies in achieving multidimensional, real-time feedback within the stringent spatial, thermal, and mechanical constraints of surgical instruments. Moreover, the integration of multimodal feedback—combining force, temperature, and texture sensing—remains technically demanding but critical for replicating the richness of human touch.

Looking forward, the trajectory of research points toward the development of hybrid sensing systems, advanced signal processing algorithms, and AI-augmented feedback mechanisms. While progress has been significant, practical implementation in clinical settings requires further refinement in sensor design, system integration, and real-time feedback fidelity. Continued interdisciplinary collaboration among engineers, clinicians, and material scientists will be essential to translate laboratory advancements into viable surgical tools. Ultimately, the integration of reliable tactile feedback is not merely a technological enhancement, but a prerequisite for realizing the full potential of robotic-assisted minimally invasive surgery.

References

[1] St John, Ace, et al. "The rise of minimally invasive surgery: 16 year analysis of the progressive replacement of open surgery with laparoscopy." JSLS: Journal of the Society of Laparoscopic & Robotic Surgeons 24.4 (2020): e2020-00076

[2] Wottawa, Christopher R., et al. "Evaluating tactile feedback in robotic surgery for potential clinical application using an animal model." Surgical endoscopy 30 (2016): 3198-3209..

[3] Trejos, Ana Luisa, et al. "A sterilizable force-sensing instrument for laparoscopic surgery." 5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics. IEEE, 2014.

[4] Li, Lu, et al. "Development of an inexpensive tri-axial force sensor for minimally invasive surgery." 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2017.

[5] Jiang, Chunyang, et al. "Analysis of a 3-Axis Force Sensor for Minimally Invasive Surgery." 2022 IEEE International Conference on Robotics and Biomimetics (ROBIO). IEEE, 2022.

[6] Hong, Man Bok, and Yung-Ho Jo. "Design and evaluation of 2-DOF compliant forceps with force-sensing capability for minimally invasive robot surgery." IEEE Transactions on Robotics 28.4 (2012): 932-941.

[7] Kim, Uikyum, et al. "Force sensor integrated surgical forceps for minimally invasive robotic surgery." IEEE Transactions on Robotics 31.5 (2015): 1214-1224.

[8] Akhmatdinov, S., et al. "A novel haptic system with advanced force sensing capabilities for soft-robotic applications." 2023 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS). IEEE, 2023.

[9] Li, Jianhua, et al. "A compact FBG-based triaxial force sensor with parallel helical beams for robotic-assisted surgery." IEEE Transactions on Instrumentation and Measurement 71 (2022): 1-9.

[10] Jiang, Jie, et al. "A High-sensitivity Three-Dimensional Force Sensing Sensor for Minimally Invasive Cardiac Ablation Surgery." 2024 IEEE International Conference on Mechatronics and Automation (ICMA). IEEE, 2024.

[11] Issatayeva, Aizhan, et al. "Design and analysis of a fiber-optic sensing system for shape reconstruction of a minimally invasive surgical needle." Scientific reports 11.1 (2021): 8609.

[12] Aviles, Angelica I., et al. "Sensorless force estimation using a neuro-vision-based approach for robotic-assisted surgery." 2015 7th International IEEE/EMBS Conference on Neural Engineering (NER). IEEE, 2015.

[13] Li, Yangming, et al. "Dynamic modeling of cable driven elongated surgical instruments for sensorless grip force estimation." 2016 IEEE international conference on robotics and automation (ICRA). IEEE, 2016.

[14] Okamura, Allison M. "Haptic feedback in robot-assisted minimally invasive surgery." Current opinion in urology 19.1 (2009): 102-107.

[15] Yilmaz, Nural, et al. "Enhancing robotic telesurgery with sensorless haptic feedback." International Journal of Computer Assisted Radiology and Surgery 19.6 (2024): 1147-1155.