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Review

A Review on Tactile Displays for Conventional Laparoscopic Surgery

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Abstract: Laparoscopic surgery (LS) is a minimally invasive technique that offers many advantages over traditional open surgery: it reduces trauma, scarring, and shortens recovery time. However, an important limitation is the loss of tactile sensations. Although some progress has been made in robotic-assisted minimally invasive surgery (RMIS) setups, RMIS is still not widely accessible. This review aims to identify which tactile display technologies have been proposed and experimentally validated for the restoration of tactile sensations during conventional laparoscopic surgical tasks. We conducted a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. We identified relevant articles published over the past 10 years through a search on Web of science, Scopus, IEEE Xplore Digital, and PubMed repositories. A total of 143 articles met the inclusion criteria and 24 were included in the final review. From the reviewed articles, we classified the proposed tactile displays into two categories based on the use of skin contact: (i) skin tactile displays, which include vibrotactile, skin-indentation, and grip-feedback devices, and (ii) non-contact tactile displays based on visualization tools. This survey aims to contribute to further research in the area of tactile displays for laparoscopic surgery by providing a better understanding of the current state of the art and identifying the remaining challenges.

Keywords: tactile display; haptic feedback; laparoscopic surgery; minimally invasive surgery

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1. Introduction

Laparoscopic surgery (LS) is a minimally invasive technique that offers many advantages over traditional open surgery: reduces trauma, scarring, and shortens recovery time. In LS, surgeons use an endoscope camera and long surgical instruments to access the anatomy of the patient through natural openings or keyhole incisions (5–12 cm in diameter) [1]. However, laparoscopic techniques have several drawbacks [2]. The images obtained from the endoscope camera are in most cases 2D, with loss of depth perception. Instruments pivot around the incision point, creating a mirror effect that requires the surgeon to move the instruments in the opposite direction, restricting range of motion, and contributing to poorer hand-eye coordination. Recent advances in the development of robotic-assisted surgery technologies have been shown to be effective in addressing these problems. Robotic systems can improve surgeon capabilities by providing magnified 3D vision with depth perception, highly dexterous surgical tools, and intuitive human–robot interfaces with improved ergonomics and high-precision tool motion control [3]. Robot-assisted surgery platforms have been developed for a wide range of surgical applications, including laparoscopic [4], endonasal [5,6], and ophthalmic [7] surgeries. The benefits of robot-assisted minimally invasive surgery (RMIS) come at the cost of being expensive, bulky, and time-consuming to set up [8]. Moreover, RMIS systems show a longer and steeper learning curve, as they are not widely available as compared to conventional laparoscopic instruments.

Despite the benefits obtained from RMIS techniques, an important limitation in LS remains: the loss of haptic sensation (force and tactile). Haptic information is important for the surgeon to discriminate between healthy and abnormal tissues, manipulate delicate tissues, and identify organs. Several studies have found a strong correlation between lack of haptic feedback and operational injuries. This limitation is acknowledged by the increasing number of studies on the development of tactile and force sensors. However, less interest has been found in the development of tactile feedback displays. Most of the proposed devices have been developed for RMIS, in which critical constraints, such as size, weight, or sterilibility, can be omitted because the surgeon is physically decoupled from the patient. Since RMIS is still far from being generally accessible, this survey focuses on recent progress in the development of tactile feedback technologies that can be implemented with conventional laparoscopic instruments.

1.1. Haptic Feedback in Minimally Invasive Surgery

Haptic feedback systems are commonly divided into two main types: kinesthetic or force feedback, and tactile or cutaneous feedback [9]. The difference lies in the feedback signal they provide [10]. Kinesthetic feedback provides the surgeon with information about the position, velocity, and force of objects. It relies on mechanoreceptors found within the joints and muscles. Traditional LS provides kinesthetic feedback to some extent through the transmission of forces along the shaft of the surgical tool. Tactile feedback provides information on a range of properties of surface tissues, such as temperature, pressure distribution, and texture, and is commonly termed the sense of touch. Humans obtained tactile information through stimulation (e.g., deep pressure, stretching, and vibrations) of mechanoreceptors located on the skin. Unlike kinesthetic feedback, in LS, the tactile feedback is completely lost. Compared to kinesthetic feedback, the display of tactile information is a significantly more difficult task due to the large number of tactile sensations available in human hands. Figure 1 shows the workflow of a tactile feedback system for laparoscopic surgery.

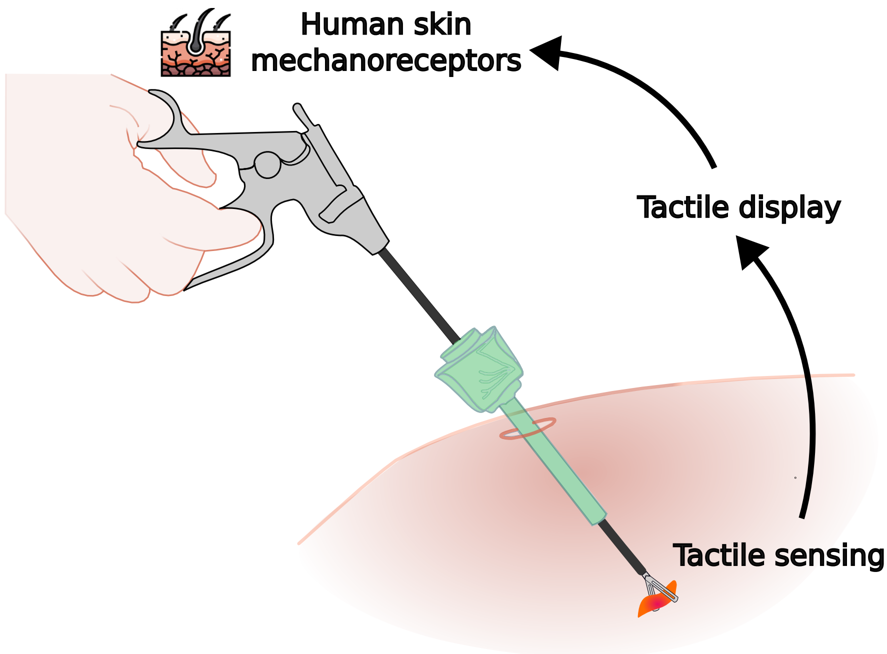

Figure 1. Tactile feedback in minimally invasive surgery. Tactile sensors convert the tactile stimuli into data sent to the tactile display, which recreate the same feedback sensation into the human skin mechanoreceptors.

In LS, it is important for the surgeon to recognize the consistencies, shapes, and structures of the tissue, and the lack of tactile feedback information represents an important challenge. Despite efforts to provide reliable tactile feedback in the surgical room, there is still no system ready for clinical applications [8].

1.2. Related Surveys

Several surveys on haptic feedback in minimally invasive surgery have been conducted [8,11,12]. However, emphasis has been placed on kinesthetic feedback for RMIS, and recent progress in tactile feedback has been only partially included. In addition, a fundamental requirement for tactile display corresponds to tactile sensing. Efforts in tactile sensing designed to overcome surgical challenges in LS applications have also been reviewed [13,14]. However, recent progress in tactile feedback display technologies for LS has not yet been reviewed. The closest survey corresponds to [10], where Schostek et al. review state-of-the-art tactile feedback in laparoscopic surgery. However, more than 10 years have passed since its publication, and new technologies have not been included. This survey aims to fill the gap in recent advances in the development of tactile devices for LS in the last decade.

2. Materials and Methods

2.1. Research Question

We define the research question following the Population, Interventions, Comparators, and Outcomes (PICO) framework [15], as shown in Table 1, commonly used in systematic reviews. We identified the following research question: In conventional laparoscopic surgery, which tactile display technologies are proposed and experimentally validated for the restoration of tactile sensations during LS tasks?

Table 1. PICO framework for the definition of research question and inclusion/exclusion criteria.

	Inclusion Criteria	Exclusion Criteria
Population	Conventional laparoscopic surgery	Other types of LS (e.g., robot-assisted surgery)
Intervention	All forms of tactile displays	-
Comparators	Not applicable	-
Outcomes	Tactile information rendering from LS tasks in ex vivo or phantom setups	Study does not include LS tasks in ex vivo or phantom setups

2.2. Search Methodology and Systematic Review

We conducted a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [16] (see Figure 2). We identified relevant articles through a search on Web of science, Scopus, IEEE Xplore Digital, and PubMed repositories. The search period for the review was set over the past decade, from January 2012 to January 2023. The search strategy was performed using the search terms shown in Table 2.

Table 2. Search strategy.

Search Strategy
TITLE-ABS ((“minimally invasive” OR “laparoscop*” OR “endoscop*” OR “MIS”) AND “surg*” AND (“somatosensory” OR “tactile” OR “cutaneous”) AND (“display” OR “feedback” OR “augmentation” OR “interface” OR “device”)) AND PUBYEAR > 2012

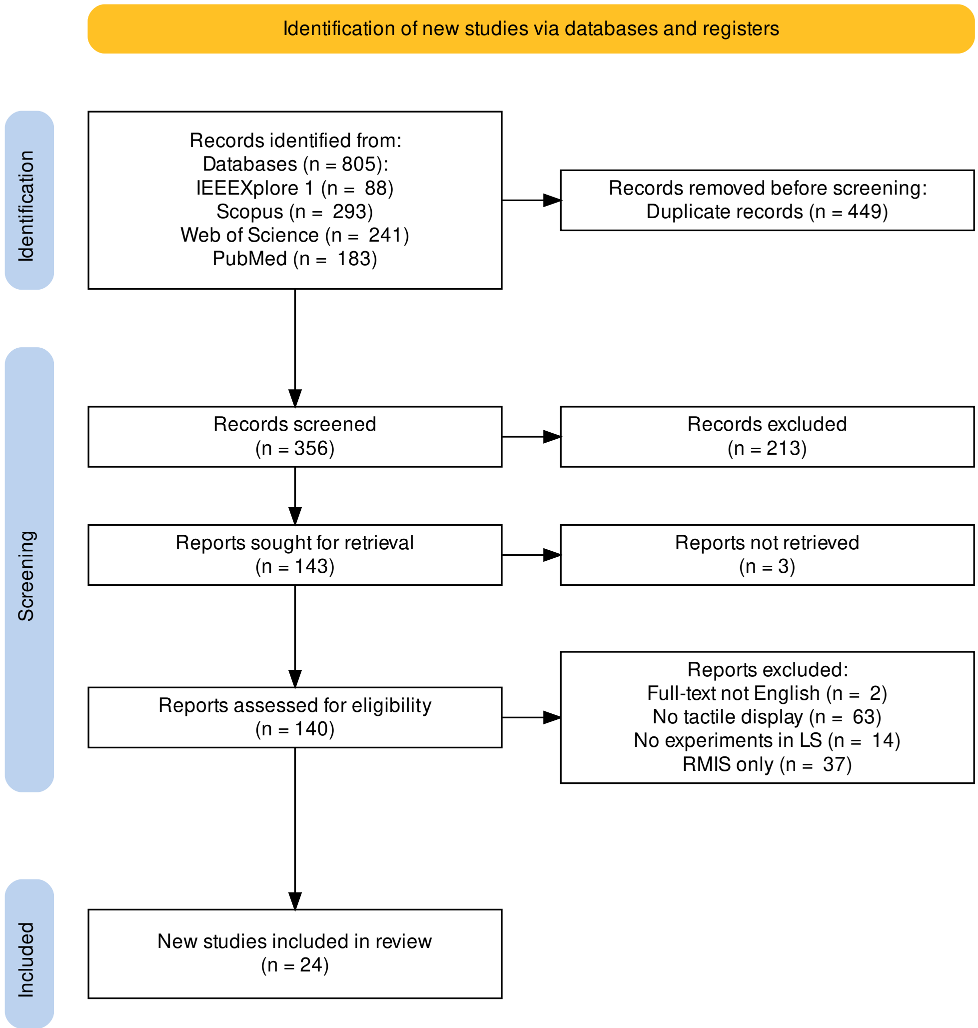

Figure 2. The study selection process.

2.3. Study Selection and Inclusion Criteria

Only articles published in English were considered in the search. Articles with duplicate titles were initially automatically excluded. For the screening, the titles and abstracts were reviewed. Not peer-reviewed articles (e.g., short essays, general discussions, posters, and project/workshop proposals) were excluded. Articles not related to tactile display technologies in LS were removed. Surveys and reviews were removed. Articles that did not have the full text available were also excluded. Articles that met the criteria were reviewed in full. We are interested in studies on tactile displays for conventional laparoscopic surgery. We only included articles that contained experimental validation in this application, either in virtual environments, phantom models, or experiments ex vivo. We also excluded those related to RMIS or those that do not include tactile display technologies. We obtained a total of 805 articles from the database search (IEEEXplore: 88, Scopus: 293, Web-of-Science: 241, Pubmed: 183). In addition, 449 duplicates were initially removed. There were 356 articles remaining that were considered for screening. After reviewing the title and abstract, 213 articles were excluded. The reasons were: they were not peer reviewed (10 articles), irrelevant to the reviewed topic (164 articles), and surveys or reviews (39 articles). Three articles were not retrievable. A total of 140 articles were eligible for a full-text review. After review, 2 articles in a language other than English were excluded. Sixty-tree articles that did not include tactile feedback technology were removed. Fourteen articles did not include experimental validation in laparoscopic surgery. Thirty-seven articles related only to RMIS were also excluded. Finally, 24 articles were selected for this review.

3. Results

3.1. Descriptive Analysis of the Reviewed Studies

Figure 3 shows the number of publications per year in the last decade.

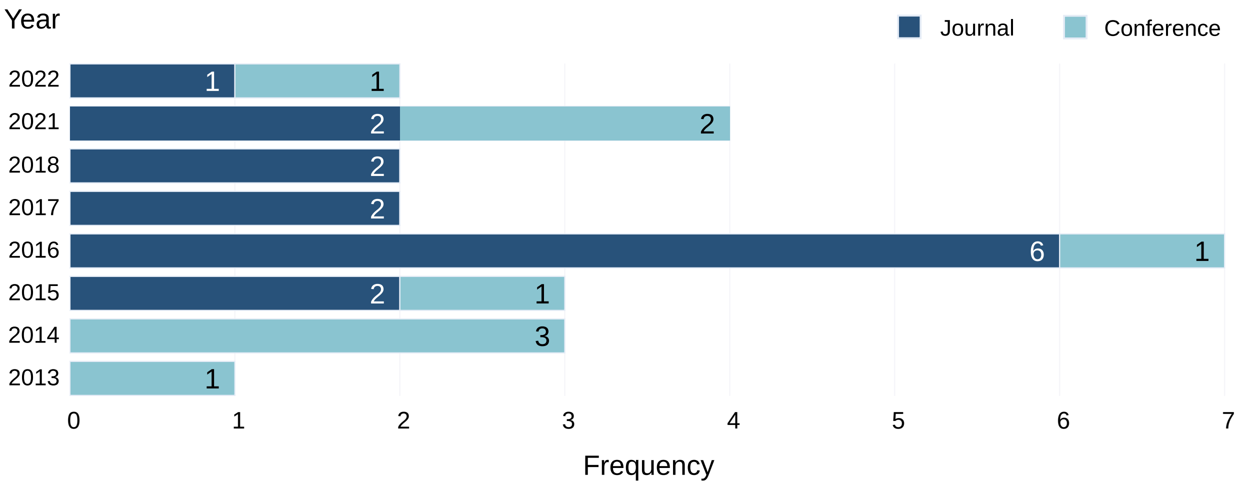

Figure 3. Number of publications per year for the last ten years.

For the years not included in the figure, no publications were found. Although there is increasing interest in robot-assisted surgical technologies, less attention has been paid to enhance current conventional laparoscopic surgery with tactile feedback, as indicated by the limited number of publications. The necessity of tactile sensing as a prerequisite to study tactile displays makes the development of new devices more difficult, as tactile sensing in minimally invasive surgery presents its own challenges [17].

3.2. Tactile Display Modalities

From the articles reviewed, we classify the proposed tactile displays into two categories based on the need for skin contact:

- Skin tactile displays: Skin deformation is used. Three modalities for tactile feedback display are considered: vibrotactile devices, skin indentation devices, and grip feedback devices,
- Non-contact tactile displays: Propose the use of visualizations of tactile information (e.g., pressure maps). Some also include a visual representation of the interaction forces.

The following sections will discuss the most relevant aspects of the reviewed work.

3.3. Skin Tactile Displays

Skin tactile displays rely on the stimulation of the mechanoreceptors found in the skin. We subclassify these devices into three categories: vibrotactile, skin indentation, and grip feedback displays. Table 3 summarizes the modality, the target application, the sensor and actuator used, the location of the feedback, and the experimental validation used (phantom models or experiments ex-vivo).

Table 3. Skin tactile displays.

Authors	Date	Modality	Application	Sensor	Actuator	Feedback Location	Phantom	Ex-Vivo
Tanaka et al. [18,19]	2014	Vibrotactile	Tissue stiffness discrimination	Acoustic	Voice coil actuator	Handpalm	X	-
Kurita et al. [20] and Sawada et al. [21]	2016	Vibrotactile	Tissue stiffness discrimination and suturing	Piezoelectric	PZT actuator	Handpalm	X	X
Hoskings et al. [22]	2016	Vibrotactile	Tissue stiffness discrimination	6-axis Force/Torque	Voice coil actuator and piezoelectric	Upperarm and forearm	X	-
Howard et al. [23–25]	2016	Vibrotactile	Guidance	6-axis Force/Torque	ERM vibration motor	Handpalm	X	-
Tanaka et al. [26,27]	2016	Skin indentation	Tissue stiffness discrimination	Acoustic	Rigid tactor	Forearm	X	-
Fukuda et al. [28]	2018	Skin indentation	Tissue stiffness discrimination	Acoustic	Voice coil motor	Foot	X	-
Ly et al. [29–31]	2021	Skin indentation	Tissue stiffness discrimination	Acoustic	Pneumatic actuator	Fingertip	X	-
Udo et al. [30–32]	2021	Skin indentation	Tissue stiffness discrimination	three-axis force	Pneumatic actuator	Fingertips	X	-
Aguirre et al. [33]	2022	Grip feedback	Tissue manipulation	Sensorless	Compliant mechanism	Fingertips	X	-

Vibrotactile devices have been commonly preferred for displaying tactile information due to their low cost and versatility. Tanaka et al. [18,19] utilized a voice coil motor to generate vibrations in real time to the user's palm proportional to the interaction forces obtained from an acoustic sensor mounted on a laparoscopic tooltip. Feedback is applied to the opposite hand that holds the surgical tool to avoid noise amplification. The experimental results of a lump detection task in a phantom model showed that lump perception improves after selecting adequate feedback gains. The effect of stochastic resonance (SR) on tactile displays has been explored in [20–22]. Kurita et al. [20] proposed improved sensorimotor capabilities for laparoscopic surgical tools based on SR. A lead zirconate titanate (PZT) actuator is used as a vibration source that generates white noise vibrations to tactile receptors located at the base of the thumb. They experimented with touch detection, texture discrimination, and tumor detection and showed improvements in user tactile sensitivity. Furthermore, the proposed device can be easily attached to conventional laparoscopic tools. Sawada et al. [21] included suturing and knot tying tasks in ex vivo experiments with similar results (Figure 4A). Hoskins et al. [22] studied the combination of vibrotactile feedback with stochastic resonance (SR) for lump detection. A force sensor was mounted on a laparoscopic tool to measure the force interaction between the tool and the tissue. The vibrotactile device was placed in the user's upper arm, and the stochastic resonance device was placed in the forearm as shown in Figure 4B. Their results showed a significant improvement in the detection accuracy for the group that used only the stochastic resonance device, due to SR signals amplifying the existing mechanical vibrations between the surgical tool and the phantom tissue. Howard et al. provide a detailed study that compares visual feedback in combination with four vibration patterns for tactile stimulation [24]: continuous, fixed pulse length, varying pulse length and interval, and fixed pulse interval. The combination of visual force feedback and continuous vibrotactile feedback provided the best performance for precision and task execution speed, while using only vibrotactile feedback showed poor performance compared to the use of only visual force feedback. In later works, they proposed this combination of vibrotactile feedback and visual feedback for navigation assistance in high-precision path tracking [23,25]. Deviations from the target path are presented to the user as bar graphs combined with tactile cues from vibration motors shown in Figure 4C. Experimental results concluded that visual with tactile feedback significantly increases user performance in tracking a target path.

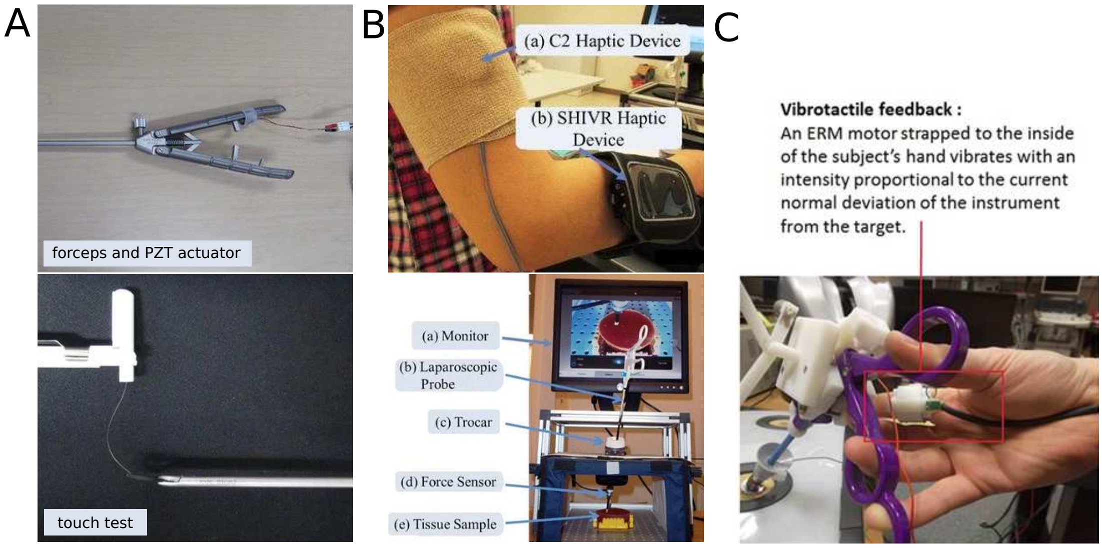

Figure 4. Vibrotactile devices. (**A**) stochastic resonance for laparoscopic surgical instruments [21]; (**B**) combination of vibrotactile (upper arm) and stochastic resonance (forearm) stimulations for lump detection [22]; (**C**) vibrotactile feedback for tool guidance [25].

Skin deformation has been proposed to recreate tactile information by direct stimulation of the skin mechanoreceptors. Deformation can be achieved through rigid tactors pushing against the skin to reproduce normal forces, or through deformable interfaces generating non-uniform force distributions, Tanaka et al. [26,27] proposed the use of a rigid tactor in contact with the forearm to generate skin indentation according to the forces sensed from a tactile acoustic sensor located at the tip of a grasping forceps. Fukuda et al. [28] performed a comparative analysis between various tactile feedback modalities for tumor detection applications. They also used an acoustic tactile sensor placed on the tip of a laparoscopic tool. The tactile feedback is achieved by a rubber attached to a voice coil motor generating normal forces on the upper side of the user's foot as shown in Figure 5A. Placing the tactile device on the foot avoids the need for sterilization. A phantom of the stomach is built to resemble the characteristic of the actual stomach wall and a tumor inserted into the inner layers. The results of the experiment showed that the tactile feedback of the foot does not increase the detection sensitivities with respect to visual feedback alone, but the combination of both reduces the overall forces and the scanning speed. In a subsequent work, Fukuda et al. [29] developed a tactile pneumatic ring for the localization of gastric tumors. An acoustic tactile sensor is used to acquire the interaction forces with a laparoscopic tool, and instantaneous feedback is generated over the user's finger by a portable pneumatic drive unit inflating a silicon rubber membrane. The proposed pneumatic ring shown in Figure 5B has advantages in terms of being lightweight, cost-effective, disposable, and sterilizable. In a multi-day experiment, the use of the pneumatic ring contributes to reducing the tumor localization error. Subsequent work [30,31] improved the design and included an additional actuator to generate shear force feedback. Udo et al. [32] developed a dual-structure pneumatic tactile display to reproduce the pressure detected in a softness detection probe. The dual structure characteristic provides central and peripheral stimulation at the fingertip.

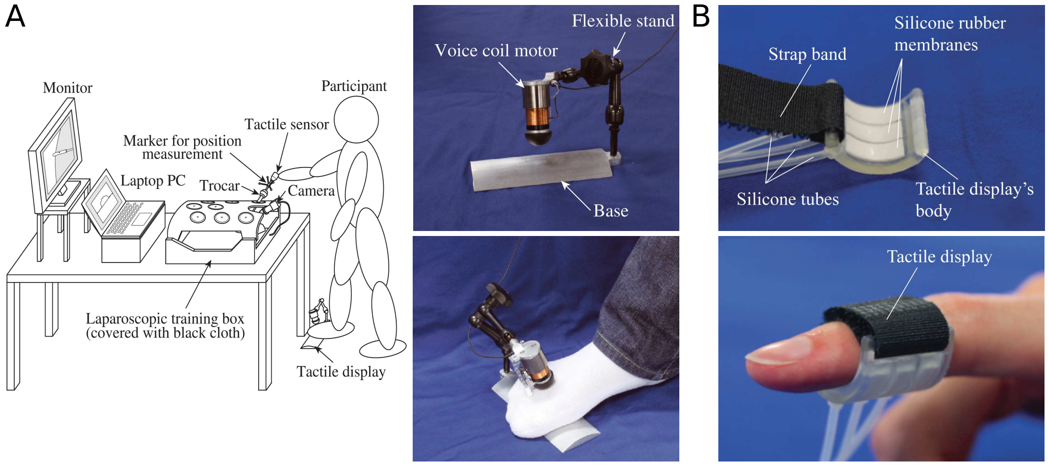

Figure 5. Skin indentation devices. (**A**) rigid tactor applies normal force to the foot [28]; (**B**) pneumatic ring proposed by Ly et al. [30].

The force feedback provided directly to the user's hand holding the surgical instrument when grasping a tissue has also been explored in [33]. Aguirre et al. proposed a laparoscopic grasper based on a contact-aided compliant mechanism (CCM) made of superelastic nickel titanium material, which is capable of showing multimodal stiffness behavior. Their concept aims to replace the rigid tooltip of conventional tools, which produces large grip forces for small handle displacements, with a compliant design that provides enhanced grip force feedback by amplifying the forces felt in the handle.

3.4. Non-Contact Tactile Displays

Non-contact tactile displays take advantage of visualization tools to display tactile information (e.g., pressure maps). Table 4 summarizes the main aspects of the work that propose visual displays as tactile feedback.

Wiederer et al. [34] developed a tactile sensor based on polymer-based circuit tracks (PBCTs) that can be placed at the tip of laparoscopic tools. The sensor force and pressure output were presented to the user through 3D color coded bar graphs as shown in Figure 6. Experiments on tumor detection in ex vivo livers showed a high success rate. Beccani et al. [35] propose a wireless tissue stiffness probe for natural orifice translumenal endoscopic surgery (NOTES). The probe creates stiffness distribution maps by combining the position and pressure of the probe obtained from accelerometers and a pressure sensor, respectively. Their experimental validation of the palpation task in a transcolonic NOTES procedure in a swine liver showed that it was possible to distinguish different levels of stiffness. Afshari et al. [36] proposed a laparoscopic probe to discriminate tissue stiffness. The probe is intended to be used for lump detection applications. The force and displacement of the probe tip are acquired by a combination of load cells and Hall sensors and presented to the user through a tactile monitoring system. Their validation included discriminating stiffness levels in phantom tissues and detecting lumps in a sheep kidney sample. Naidu et al. [37–39] developed a wireless palpation instrument with a piezoresistive sensor placed at the tip of the tool. A 2D pressure map of the sensor surface is shown to the user along with a level bar that indicates the average pressure measured. Experiments included the location of tumors in phantom models and ex vivo tissue samples.

Wang et al. [40,41] proposed a tactile sensor integrated with a fiber Bragg grating (FBG) at the tip of a laparoscopic tool to record the interactions forces of the tools. The average force is presented to the surgeon on an external screen. Comparison between novice and experienced surgeons showed that the use of visual force display allows novices to achieve grip force levels similar to those of experienced surgeons.

Table 4. Non-contact tactile displays.

Authors	Date	Application	Sensor Type	Visualization Parameters	Phantom	Ex-Vivo
Wiederer et al. [34]	2015	Tissue stiffness discrimination	PBCTs based sensor	3D color-coded bar graphs indicating palpation force	-	X
Beccani et al. [35]	2016	Tissue stiffness discrimination	Pressure sensor	Endoscope position and pressure exerted over tissues	-	X
Afshari et al. [36]	2017	Tissue stiffness discrimination	Force and magnetic sensors	Interaction forces and displacements	X	X
Naidu et al. [37,38] and Escoto et al. [39]	2016	Tissue stiffness discrimination	Piezoresistive sensor	2D pressure map and average pressure level	X	X
Wang et al. [40,41]	2022	Tissue stiffness discrimination	fiber Bragg gratings (FBG) based sensor	Gripping force from the tactile sensor	X	X

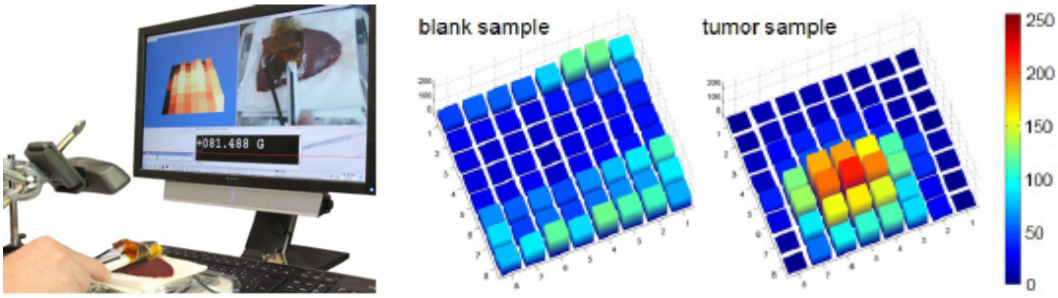

Figure 6. Pressure and force represented as a 3D color coded grid and bar graphs [34].

4. Discussion

In LS, surgeons must perceive the characteristics of organs and tissues using surgical instruments. Tactile feedback is fundamental for the execution of force-related surgical tasks, such as palpation, knotting, or tissue manipulation. In this section, we discuss the applications and challenges for tactile displays in conventional LS.

4.1. Applications in Laparoscopic Surgery

Experimental results have shown that the addition of tactile feedback increases overall performance in common surgical tasks, with applications in palpation, tissue manipulation, suturing, and guidance tasks.

4.1.1. Palpation

Tumors are generally more rigid than surrounded tissues, and therefore a higher pressure intensity could be used for tumor detection. Most of the works included in this review have focused on the palpation task to discriminate tissue stiffness. Rigid tactors have been proposed to reproduce stiffness as a normal force applied over the user's finger, arm, or foot. The need to mount the actuators on the surgeon's body, skin exposure, and minimal tactile information transmission could limit its applicability in real scenarios. In the case of vibrotactile feedback, specific vibration patterns appear to be more effective than others for the palpation task [24]. The benefits of using different patterns in other LS tasks remain unexplored. Furthermore, feedback gain is also an important parameter that should be adjusted according to the level of user perception [19]. Comparison studies between tactile feedback on the skin and visual tactile feedback showed a preference for visual display of tactile information. However, multimodal display, in which both forms of feedback are presented simultaneously, appears to be more effective [23,25].

4.1.2. Tissue manipulation

Manipulation of tissues and organs is based on a good estimation of their dynamic characteristics, such as stiffness and elasticity. Surgeons generally use grip force feedback to estimate these characteristics. Amplification of grip forces has been proposed [33] by innovative designs of compliant mechanisms without the need for a sensor. The reliability and robustness of the proposed design in real surgical scenarios still require further studies.

4.1.3. Suturing

Control of tension forces in suturing and knot tying tasks is required to avoid damaging delicate tissues. Stochastic resonance (SR) has been explored for this application [21]. The use of SR improved the participant's assessment scores in terms of total score and needle position due to improvements in tactile sensitivity when holding a needle. However, experiments ex vivo did not show improvement in tissue damage and large-scale experiments are still required.

4.1.4. Guidance

Vibrotactile cues have also been explored to guide the movement of surgical tools along predefined constraints, for example, in the case of resection paths [23]. Well-tuned vibration patterns significantly improve performance in a guidance task. Only corrections are provided as vibrotactile information, and ways of including directional information have not yet been studied.

4.2. Challenges in the Development of Tactile Displays

In contrast to kinesthetic feedback, the complexity and various forms of tactile sensations make the development of tactile displays for LS quite challenging. To be implemented on conventional laparoscopic tools, tactile displays must overcome challenges similar to those for tactile sensing:

- Transparency: The tactile display should provide tactile information to the surgeon in a natural and seamless way to avoid increasing the surgeon's cognitive workload.
- Compactability: Size of the tactile display must be able to be included in the surgical workspace without constraining the surgeon's movement.
- Weight: The weight of the display should not affect the manipulation of the surgical tool and should not increase the surgeon's effort. The selection of external actuators and its location are critical to reduce the overall weight of the device.
- Time delay: The time delay between tactile sensing and tactile feedback rendering reduces its effectiveness.
- Safety: Forces generated must be kept within a safe range to avoid injuring the surgeon.
- Adjustable: Each user requires different levels of stimulation, and adjustable perception is desirable.
- Sterilizable: Tactile displays mounted close to the surgical workspace (e.g., surgical tool or surgeon's hands) must be sterilized.
- Reusability: To reduce costs, surgical instruments are commonly reused multiple times before being discarded. In the same way, tactile displays should be designed to last for many uses. Single-use devices could eliminate the need for cleaning or sterilization but increase costs and have a high environmental impact.

5. Conclusions

In conventional laparoscopic surgery, the surgeon is directly in control of the surgical instruments, and some kinesthetic haptic feedback is still preserved by transmission of forces along the instrument shaft. On the other hand, tactile sensing, fundamental for discriminating characteristics of tissue and organs, is completely lost. A large number of studies have shown that the recreation of tactile feedback can enhance a surgeon's performance during minimally invasive surgical tasks. Unlike robot-assisted minimally invasive surgery, where the surgeon is physically removed from the patient, conventional laparoscopic surgery requires tactile displays to overcome several additional challenges to be used in the operating room. This systematic review aimed to identify which tactile display technologies have been proposed and experimentally validated for the restoration of tactile sensations during conventional laparoscopic surgical tasks. We discuss the tactile feedback modalities used, the target surgical applications, and the experimental results found.

Note that there are several limitations to this systematic review. First, only four scholarly databases were included in the search, and relevant studies stored in other databases or repositories were not taken into account. In addition, this review is limited to studies that include experimental validation in LS conditions in phantom or ex vivo environments. Therefore, novel tactile display technologies that have the potential to be used in conventional LS but have not explored LS applications have not been considered. Finally, only studies reported in English were included.

The lack of an increasing trend in the number of studies compared to tactile sensing in surgical applications indicates that tactile display remains a challenging and open problem. We hope that this review contributes to the development of more research in the area of tactile feedback for conventional laparoscopic surgery by discussing the current state of the art and identifying the remaining challenges.

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