Applications of tactile sensors and displays in robotically-assisted minimally invasive surgery

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***Abstract*—Robotically Assisted Minimally Invasive Surgery (RMIS) applications have been shown to help with improving patient recovery times, reducing the duration of operation as well as minimizing trauma in patients. Recent years have seen an increase in the development of devices and external systems with the improve RMIS procedures. There is need for this kind of improvement as the procedure comes with drawbacks to the effectiveness of the surgeon. These could include impaired vision and haptic feedback otherwise available through direct manipulation. Various sensors and tactile display systems possess the potential to solve such problems and thereby further improve RMIS procedure. This paper makes a review of recent and past tactile technology with respect to RMIS applications from early endeavors designed to complement commercially available surgical systems to novel developments yet to be fully evaluated. In addition, a range of suggestions for areas on which to improve and directions for future research are provided.**

***Index Terms*—Tactile sensors, tactile display, haptic feedback, minimally invasive surgery.**

I. INTRODUCTION

Tactile sensors are devices designed to acquire tactile information (eg. Temperature, texture, vibration, shape, pressure) through physical contact whereas tactile displays convey such information to their respective receptors (eg. the skin). Generally tactile stimuli can be termed as any form of stimuli that can be transferred by palpation. Robot-assisted minimally invasive surgery (RMIS) typically involves the employment of remotely controlled tools or devices (robots) for surgical task that would typically be performed directly by the surgeon. Minimally invasive surgery (MIS) refers to procedures whereby the port of entry into the body is kept as small as possible. RMIS systems are typically either autonomous like the Robodoc (Curexo Technology Corporation, CA, USA) and the Cyber-Knife system (Accuray) or they are Master-Slave systems like the ZEUS and da Vinci Surgical Systems [1]. Robotic assistance in MIS procedures is beneficial to medical professionals (especially surgeons) because they can provide a high resolution view (digital), transfer of the work to robotic devices filters out natural hand tremors that could be caused by fatigue. Robotic assistance has been and continues to be successfully applied in processes such as hysterectomies, prostatectomies and thyroid surgeries [**?**]. RMIS has gained relatively more widespread use over the past decade, but the technique is currently operated in the absence of haptic feedback which is very important during tissue manipulation and the identification of tissue interaction forces. In recent years, advancements in sensing technology and robotics have brought about the development of tactile sensors specifically for use in minimally invasive surgery. The purpose of this paper is to present an overview of recent developments relevant to the application of tactile sensing and tactile displays in robotically-assisted minimally-invasive surgery as well as provide a discussion of possible areas for improvement and for future directions of studies in this field.

II. OVERVIEW OF CURRENT TACTILE SENSING AND DISPLAY TECHNOLOGY

A. Early Developments

To give a better understanding of the transition of the more recent tactile technologies, brief summaries of earlier tactile sensing developments will also be covered for their relevance to the topic.

1) Tactile feedback system mounted on to the da Vinci system: A 2009 report by King et al. [3] documented the development and evaluation of a complete tactile feedback system to be mounted onto the da Vinci surgical robotics system. The system consisted of a piezo-resistive force sensor, a signal control system and a pneumatic balloon functioning as the tactile display. The system was evaluated by a group of 16 novices and 4 experts performing peg transfer tasks. Three sets of experiment were performed varied by providing tactile feedback only in the middle set. It was revealed in the results that all participants used substantially less force all while completing the task with the suitable amount of grip required and that this improvement was exclusive the sets during which tactile feedback was provided. The system designed by King et al. is one the earlier and less complex systems designed with the purpose of providing tactile feedback during minimally-invasive surgery. The piezo resistive force sensors attached to the graspers of the da Vinci were commercially available Tekscan FlexiForce, modified and tested for linearity. They were attached at the upper and lower jaws of the Cadiere grasper Fig. 1.

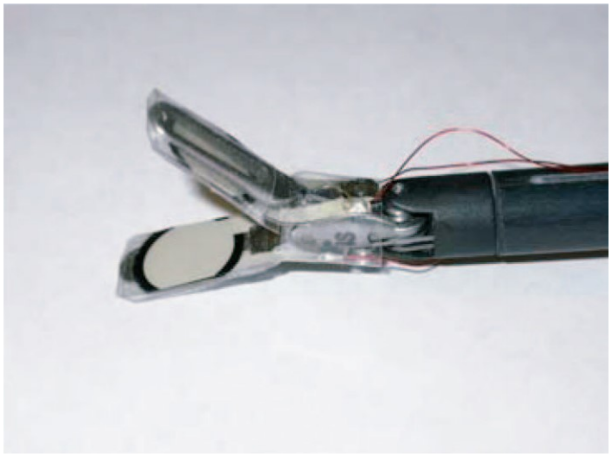

Fig. 1. Modified FlexiForce sensor mounted on the top and bottom jaws of the Cadiere grasper for the da Vinci System. Adapted from [3]

The voltage signal was processed by a control system which, using a digital signal processor and signal conditioning electronics, determined the inflation level corresponding to the input voltage and generate an output signal to effect the inflation. The signal was then relayed to the pneumatic balloon tactile display; a pair of hemispherical silicon balloons mounted at the master control to provide feedback to the thumb and index finger Fig. 2.

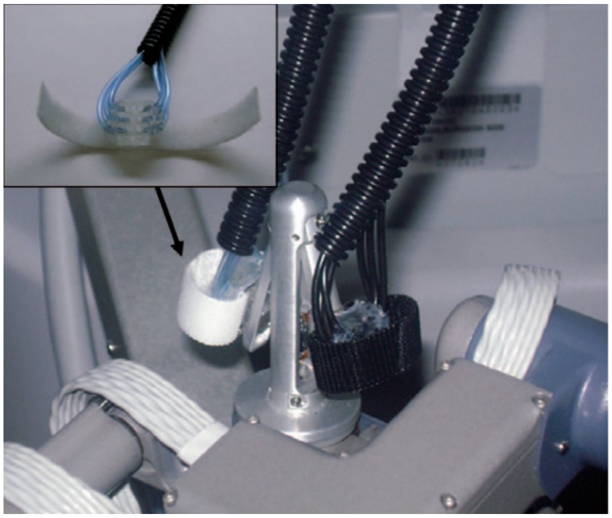

Fig. 2. Balloon tactile display with pneumatic tubing (inset) and balloon tactile displays mounted directly onto da Vinci master control for thumb and index finger. Adapted from [3].

Grip force and grip time were the main parameters measured and considered for evaluation. Overall, the results showed that the difference in force grip applied in the experiments with and without feedback was significant in all the participants. During the debriefing of the participants it was expressed by some that the force feedback provided no perceived improvement on and possibly worsened their performance of the task. It was suggested as well that recurrent practice or training with these kinds of systems could be integral to their adoption. This study, while pioneering, was limited by its small sample of participants and lack of extended testing. In addition to that, suggestions for improvements to the system itself include the application of an array based balloon inflation system. This could potentially provide a more accurate representation of surface forces in continuity.

2) Verrotouch: vibro-tactile feedback for da Vinci system: Designed by Kuchenbacker et al. in 2010 [4] , the VerroTouch is another (acceleration feedback) system designed to complement the da Vinci surgical system. The system provides tactile feedback to the surgeon by measuring and reproducing vibrations from contact interactions experienced by the grasper tools. Similarly to the system designed by King [1], the signals are relayed to the master controls of the system. The system included a MEMS-based accelerometer to detect the high frequency vibrations in the da Vinci tools. The sensors were attached to the patient-side manipulators in order not to interfere with tool or arm motion. Additionally, since they were placed within the drapes of the da Vinci, sterilization after surgery would not be required. The acceleration signals measured by the sensors mounted to the tool were transferred to the main receiving unit (MRU). Within the MRU, the signal is modified, amplified and filtered before being transferred to the vibration actuators. Two modules containing commercially available voice-coil actuators were mounted onto the da Vinci master handles in position to optimize signal transmission and minimize interference. A schematic of the integrated system is shown in Fig. 3.

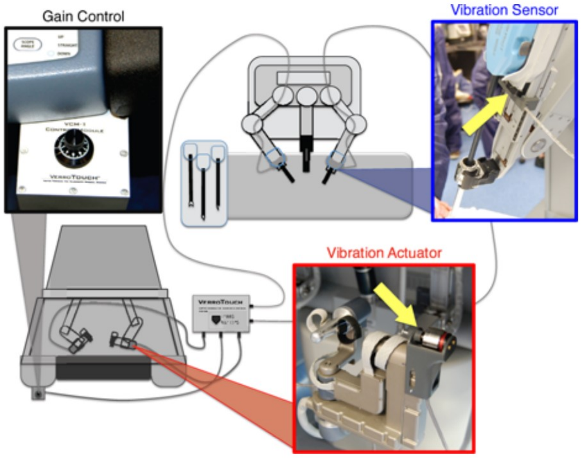

Fig. 3. Schematic of VerroTouch installed on an Intuitive da Vinci S surgical system. Adapted from [4].

Evaluation of the system was undertaken by analysis of a number of tasks involving interaction with a number of objects of different shape and size. Acceleration data obtained at the master controls (master) and da Vinci needle driver (slave) were compared and contrasted. The frequency and acceleration-time diagrams of the master generally matched those of the slave magnified by a factor of 15 (Fig. 4). During testing, participants were capable of experiencing texture of rough surfaces and the duration of the contact period. They also provided a qualitative rating of different aspects of the system through a questionnaire survey. Different for the previous study, this evaluation included tool contact acceleration feedback via audio as well. Additionally, it was restricted to surgeons (novice and expert) making for a small sample. The tasks performed were simple manipulation like peg transfer, needle pass and suturing. Analysis was done using analysis-of-variance (ANOVA).

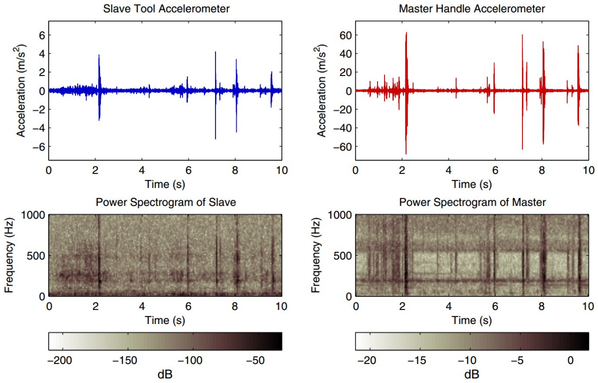

Fig. 4. Sample frequency- and time-domain data recorded during experiment. Adapted from [4].

It was found from statistical analysis that the provision of feedback did not result in any significant improvement (or effect) on task performance with regards to force, completion time and acceleration. Survey ratings mentioned an improved awareness or concentration. Once again, as with the study by King [3], comprehensive analysis was deterred by a small sample size thus considerable inter-subject variation. Finally, with regards to the system itself, it was shown that the filtration of the signal made signal deduction difficult thus the VerroTouch would be would be best suited to interactions involving harder material. There is currently no evidence of any documented improvement of this system, originally documented in 2011.

B. Recent Development

1) Improved three-axis pneumatic tactile display: More recently, in 2016, an improved three axis pneumatic display was designed by Yun et al. [5]. Basically, this proposed system consisted of a balloon array for normal force haptic stimulation and four lateral balloons for tangential stimulation as well. Testing went so far as to validate and demonstrate the accurate control of tangential displacement by the system. The design itself is comprised of an outer frame within which is the pneumatic balloon array for the normal pressure surrounded on alternating sides by flexible printed circuit board (FPCB) capacitive sensors for the x- and y-axes. These are controlled by balloon set in the side walls of the device to provide tangential displacement Fig. 5.

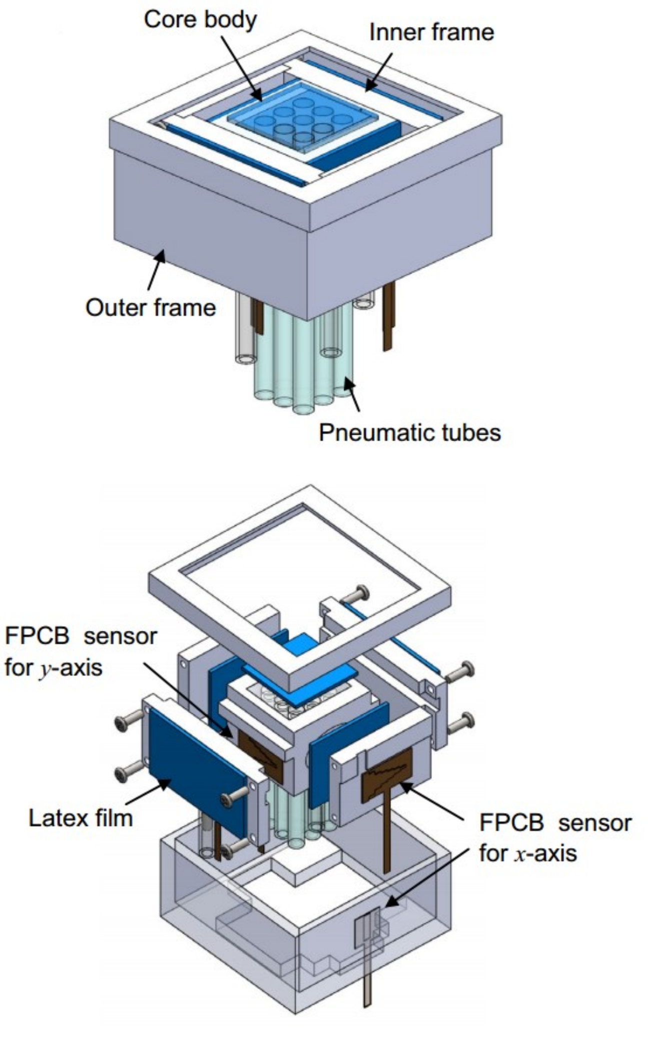

Fig. 5. Diagram of proposed 3-axis haptic de. Adapted from [5].

This proposal can be seen as an improvement on the work of King et al [3] in that it provides tangential in addition to normal force feedback. The device demonstrated further improves on previous work of the author by incorporating capacitive position sensors to monitor the accuracy of tangential movement and minimize the influence of normal pressure. The major difference between this and the previous developments is that each balloon was controlled and actuated individually using electro-pneumatic regulators. While the study was ultimately an evaluation of the device accuracy, it showed potential for improvement of assisted minimally invasive surgery with its relatively small and simple design. The proposed display device, however, was not tested or evaluated for human use.

2) Tactile feedback via magneto-rheological (MR) sponge cell: Also in 2016, Kim et al. investigated tactile feedback by use of a proposed magneto-rheological (MR) cell [6]. The underlying principle in this application is its capability to mimic visco-elastic sensation of real organs. The system was tested to investigate how accurately tactile motion and response due to a human fingertip could be represented by the MR sponge cell mimicking different kinds of materials. This could be useful for remote palpation exercises as shown in Fig. 6.

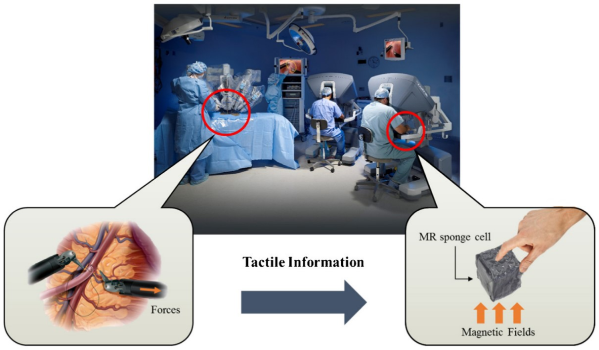

Fig. 6. Theoretical application of MR cell in telerobotic palpation. Adapted from [6]

The application of the cell was tested using a 3-axis robot on three different pork specimens (Fig. 7). Subjected to various electromagnetic conditions, the MR cell was loaded as determined by the beam bundle model of the human finger. The test specimen (cubes of pork, pork rind, and pork heart) were tested individually. To determine force relaxation properties, the stress response of each material under steady strain was measured. The relaxation times derived from this were then compared with the relaxation times of the MR cell under different voltages to determine at what voltage the MR cell was most identical to the material being operated.

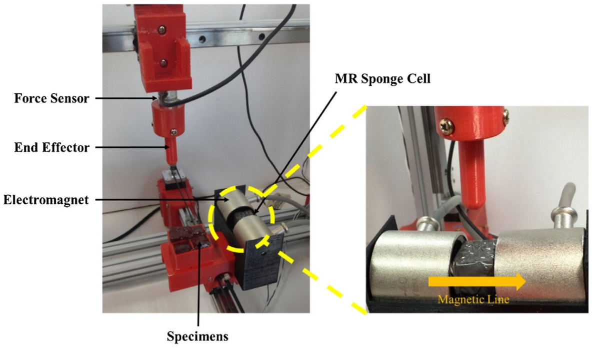

Fig. 7. Operational parts of 3-axis robotic testing mechanism. Adapted from [6].

The experimentation results showed that the MR cell could mimic relaxation times and equilibrium forces depending on the magnetic field and voltage under which it was operated. Limitations to this study include its lack of a comprehensive way of modelling a human fingerâĂŹs examination of surfaces and effective methods for its integration into surgical systems. In addition to that, for this method of material examination to be applicable, the MR cell would have to be tested and calibrated for different material leaving a lot of room for incongruence.

3) Palpation probe for locating subcutaneous structuresl: Of special interest to the present study is a palpation probe designed by McKinley et al. in 2015 [7] . The highlights of this work include that it is. A low-cost single-use probe that can detect subcutaneous structure like blood vessels by continuous measurement of tip deflection with respect to a known spring constant. Senses relative differences in reaction force by measuring tip deflection with respect to a known spring constant. In this specific application the deflections were measured by incremental magnetic Hall Effect position sensor. The system was tested on fabricated tissue phantom but limited to normal indentation in very controlled situations. This kind of device can be used in surgery for surface examination and characterization where access is limited.

C. Artificial Tactile Feedback

In light of the research, there are some alternative approaches to providing tactile feedback which include providing the tactile information to senses other than touch. This could include but is not limited to visual, auditory or temperature based representation of stimuli. In 2015, Shostek et al. [8] experimented on the use of a feedback system in which tactile feedback, specifically pressure distribution as well as force magnitude and opening angle were displayed graphically alongside the visualization of the operation area in the endoscopic screen. The grasper is fitted with two sensors on the forceps jaw as well as an angle sensor on the joint of the handle and a strain gauge. Special software was developed to display the measurements on the screen as an overlay (Fig. 8). The visualizations available include pressure distribution, numerical parameters and a pictogram of the forceps with operating angle. Sensor information acquired and transmitted via Bluetooth technology to a remote computer. Testing on an experimental setup validated the operation of the forceps and angle sensors. Participants in the operational evaluation agreed on the benefits of having the option of that information available.

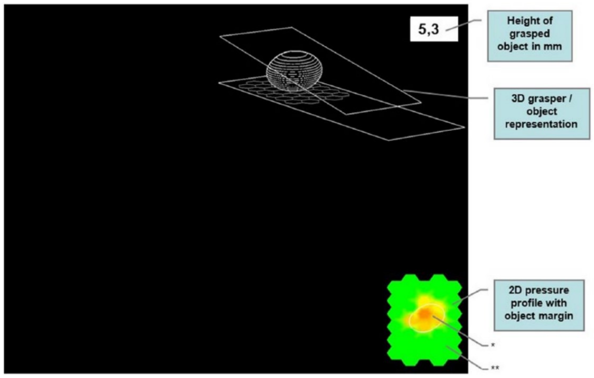

Fig. 8. Example of overlayed graphical tactile data. Adapted from [8].

The benefit of this study and this proposed artificial feedback system in general, is its low production-material cost. It was shown to have a combined cost of 22.5 per use, which is, at least theoretically, very cost-effective. Limitations, however, could be addressed by the inclusion of preclinical treatments with a larger number of participants who are surgeons as well as some qualitative analysis on its effectiveness. Another artificial tactile feedback system involves the use of thermal imaging to estimate brain tumor parameters developed by Sadeghi et al. in 2015 [9] . A novelty assisted surgery robot was developed to palpate tissue surface (continuously) to derive comprehensive temperature variation. The basis of this new development lies in the knowledge that temperature distribution serves as an indicator of existence of a tumor, specifically a malignant one. In that specific study, a finite element approach was used to simulate the experiment in which an agar phantom model containing a resistance heater was used to simulate a brain with a tumor. With regards to surgical applications, this provides a relatively accurate, completely non-invasive, imaging of subcutaneous masses and possibly other medical issues. This kind of technology could as well be used during operation for real time visualization.

D. Additional note-worthy tactile sensing and display developments

Aside from sensing and feedback systems presented within this paper, there have been some studies presenting tactile display technology intended for different purposes but possessing the potential to be applied to minimally invasive surgery. One of these is a system that was designed by Watanabe et al. in 2012 [10] . This system makes use of MEMS actuator arrays and hydraulic displacement system with an incompressible fluid (Fig. 9). The device evaluation showed it being capable of outputting and allowing users to perceive soft and rough textures depending on the variation in the actuators. This and a number of other similar systems have not been developed for use with robotic assisted surgery but have the potential to be i.e. with advancements in miniaturization and design.

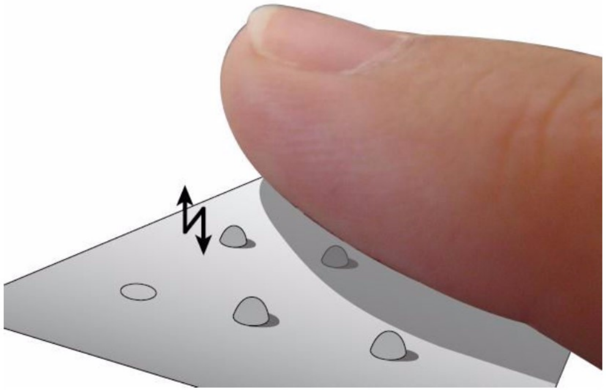

Fig. 9. Schematic of tactile array display. Adapted from [10].

Additional noteworthy developments related to RMIS and tactile sensing and display include an artificial tactile-based artery clamping robot developed by Pahlavan et al. [11] . The device was shown to be capable of circling an artery to separate it from its environment. The system uses sensors to detect contact between the links of the robot and the tissue. The path of the robot is thus defined by keeping contact with the tissue autonomously to achieve tissue separation where necessary and especially in cases of minimal access surgery. Robo-Tac-BMI is a Breast Mass Identifier making use of an indentation probe and a visualization system. During examination, test points and corresponding tension-relaxation curves are obtained and used to extract stiffness parameters of the material being investigated. This is one of the more readily available proprietary medical devices that has been useful in surgery. This technology also has the potential to provide additional mechanical properties as opposed to other technologies like sonography [12].

III. Drawbacks and Areas of Improvement

From the research presented in this paper, one could argue that there is a substantial capacity for improvement in the field of tactile sensing, especially for application in Minimally Invasive Surgery. Suggestions for improvement and further research can be categorised by the aspect to which they are applied. Firstly, with regards to the design of devices, it has been shown that modern design are feasible in very small dimensions. Further research should be directed towards optimizing sensors and feedback systems both size and for placement on the surgical tool. Additionally, minimizing energy leaks and injections that could impede on the accuracy of the readings. The aim should be to achieve insulation from the operative environment as this would also help with hygiene and sterilization issues. Another relatively uncovered area of improvement is the signal modification and transfer and associated computational error. A number of the papers presented document experiments that are overly simplified. While it is common knowledge that such specialized research comes at a high cost, the widespread adoption of robotically assisted surgery technology greatly relies on there being comprehensive studies demonstrating its effectiveness. Future studies and evaluations of tactile sensing or feedback systems ought to consider the use of larger samples with more experienced practitioners. Finally, there should be a focus on MRI and biocompatibility of these devices. It is crucial to the health of patients that the devices used in surgery not be a danger by way of infection.

IV. Conclusion

Having a force feedback during robotic surgery provides the surgeon with a realistic perception of the surgical site, which in turn improves the performance of the surgeon.This paper highlighted the recent developments in tactile sensing and display not covered in similar reviews. In addition the suggestions made ought to be a step in the right direction towards the improvement of RMIS in general. Although there are still barriers toward application of the tactile in clinical operations, but the ongoing researches in this field are promising which in near future would equiped surgeons with a realistic force sensing during surgery.

REFERENCES

[1] Nima Enayati, Elena De Momi, and Giancarlo Ferrigno. Haptics in robot-assisted surgery: challenges and benefits. *IEEE reviews in biomedical engineering*, 9:49–65, 2016.

[2] Sudipta Roy and Charles Evans. Overview of robotic colorectal surgery: Current and future practical developments. *World journal of gastrointestinal surgery*, 8(2):143, 2016.

[3] Chih-Hung King, Martin O Culjat, Miguel L Franco, Catherine E Lewis, Erik P Dutson, Warren S Grundfest, and James W Bisley. Tactile feedback induces reduced grasping force in robot-assisted surgery. *IEEE transactions on haptics*, 2(2):103–110, 2009.

[4] Katherine Kuchenbecker, Jamie Gewirtz, William McMahan, Dorsey Standish, Paul Martin, Jonathan Bohren, Pierre Mendoza, and David Lee. Verrotouch: high-frequency acceleration feedback for telerobotic surgery. *Haptics: Generating and perceiving tangible sensations*, pages 189–196, 2010.

[5] Seokpyo Yun, Jihyung Yoo, Soochul Lim, Joonah Park, Hyung-Kew Lee, and Kwang-Seok Yun. Three-axis pneumatic tactile display with integrated capacitive sensors for feedback control. *Microsystem Technologies*, 22(2):275–282, 2016.

[6] Soomin Kim, Pyunghwa Kim, Chun-Yong Park, and Seung-Bok Choi. A new tactile device using magneto-rheological sponge cells for medical applications: Experimental investigation. *Sensors and Actuators A: Physical*, 239:61–69, 2016.

[7] Stephen McKinley, Animesh Garg, Siddarth Sen, Rishi Kapadia, Adithyavairavan Murali, Kirk Nichols, Susan Lim, Sachin Patil, Pieter Abbeel, Allison M Okamura, et al. A single-use haptic palpation probe for locating subcutaneous blood vessels in robot-assisted minimally invasive surgery. In *Automation Science and Engineering (CASE), 2015 IEEE International Conference on*, pages 1151–1158. IEEE, 2015.

[8] Sebastian Schostek, Melanie Zimmermann, Marc O Schurr, and Ruediger L Prosst. Design and performance of a low-cost telemetric laparoscopic tactile grasper. *Surgical innovation*, 23(3):291–297, 2016.

[9] M Sadeghi-Goughari, A Mojra, and S Sadeghi. Parameter estimation of brain tumors using intraoperative thermal imaging based on artificial tactile sensing in conjunction with artificial neural network. *Journal of Physics D: Applied Physics*, 49(7):075404, 2016.

[10] Junpei Watanabe, Hiroaki Ishikawa, Xavier Arouette, and Norihisa Miki. Surface texture and pseudo tactile sensation displayed by a mems-based tactile display. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, pages 4150–4155. IEEE, 2012.

[11] Pedram Pahlavan, Siamak Najarian, Javad Dargahi, and Majid Moini. A proof-of-principle robot with potential for the development of a hand-held tactile instrument for minimally-invasive artery cross-clamping. *Journal of medical engineering & technology*, 38(6):295–301, 2014.

[12] Afsaneh Mojra, Siamak Najarian, Seyed Mohsen Towliat Kashani, Farzad Panahi, and Morteza Ali Tehrani. A novel robotic tactile mass detector with application in clinical breast examination. *Minimally Invasive Therapy & Allied Technologies*, 21(3):210–221, 2012.