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Haptics in Telerobotic Systems for Minimally Invasive Surgery

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9.1 Introduction

In the current practice of minimally invasive surgery (MIS) and therapy, a surgeon is faced with problems such as a lack of dexterity because of restricted port access to the surgical site, a lack of fine manipulation capability because of the long surgical instruments, visual problems including motion sickness and loss of localization, and significant degradation of touch sensation (haptic feedback) for the surgeon from the instrument and its contact with tissue. Some of the reasons for such degradation in the feedback of touch are that (1) the instruments include hinge mechanisms with significant friction, (2) the cannulae through which instruments are inserted introduce friction [6], and (3) the contact forces at the instrument tip can sometimes be very small, compared with the relatively large forces supplied by the arm, to move the instrument mass and the unsupported hand. As a result of this degradation in the haptic sensation for the surgeon, surgical tasks requiring accurate feeling of tissue characteristics such as palpation are difficult to perform in the minimally invasive mode.

The recent use of robots in surgical interventions has solved several of the above-mentioned problems associated with non-robotic surgery. For instance, the end tool of the *da Vinci*® Surgical (robotic) System (Intuitive Surgical, Sunnyvale, Calif.) includes a wrist that adds three rotations to the motions conventionally available in a minimally invasive environment, in order to improve the surgeon's dexterity. However, the current surgical robotic systems have not yet been successful in terms of restoring feedback of instrument/tissue contacts to the surgeon. While the *da Vinci* system is capable of providing force feedback to the surgeon in some directions, this feedback is of low quality and disabled by the manufacturer, mainly because in the absence of force sensors on the surgical tool the interactions between the robot and the patient's body are estimated from outside the patient and are consequently plagued by disturbances, bias, and noise caused by the entry port.

The absence of haptic feedback to the surgeon about instrument/tissue interactions is a safety concern in MIS. For instance, in a study involving minimally invasive cholecystectomy, it was observed that inappropriate and excessive application of force was a main cause of perforation of the gallbladder [2]. Such a safety concern is especially significant if visual feedback to the surgeon is degraded, e.g., if fluids from the patient's body cloud the camera lens or the instruments leave the limited field of view of the endoscopic camera. On the other hand, the presence of haptic feedback can provide the surgeon with the required perceptual information for optimal application of forces, thus reducing trauma to tissue. It can also shorten the task completion times by eliminating the need for prolonging the maneuvers and awaiting visual cues as to the strength of the grip, the softness of the tissue, etc. Last, for instruments with restricted maneuverability as in MIS, haptic feedback is expected to improve the precision of manipulation. Research has been done to evaluate the influence of haptic perception on human sensory and motor capabilities for several surgical tasks. For instance, the ability to sense the puncturing of different tissue layers during the needle insertion task improves when users receive haptic feedback [1]. Moreover, study of the effect of force feedback on performing blunt dissection has shown that it reduces the number of errors, the task completion time, and the magnitude of contact forces [14].

9.2 Mechanisms for Haptic Teleoperation

A master–slave system for robot-assisted MIS consists of three main parts: a robotic arm that holds and controls the endoscope, robotic arms that hold and actuate the surgical instruments, and a human–machine interface (HMI) for the surgical robot. In such a system, the surgeon operates using the HMI (the master), while the surgical robot (the slave) follows the surgeon's hand maneuvers transmitted from the HMI inside the patient's body. For feedback of instrument/tissue interactions to the surgeon's hand during master–slave teleoperation, it is imperative to have an HMI that can reflect forces to the surgeon's hand, in addition to a properly sensorized surgical tool that can measure its interaction with tissue. The master and slave subsystems of a haptic teleoperation system appropriate for use in a minimally invasive surgery/therapy environment are described next.

9.2.1 Haptic HMI (Master)

The possible motions for an endoscopic instrument excluding the tip's motions are limited to four: up and down rotation (pitch), side to side rotation (yaw), axial rotation (roll), and axial translation (insertion). In the haptic HMI shown in Fig. 9.1a, a PHANTOM 1.5A force feedback device (SensAble Technologies, Woburn, Mass.) is incorporated. A rigid shaft resembling an endoscopic instrument is passed through a fulcrum and attached to the PHANTOM's endpoint, causing the motions of the handles grasped by the surgeon to be similar to those in endoscopic manipulation and providing haptic feedback to the user in these directions. The haptic surgeon–robot interface includes two additional mechanisms placed on opposite sides of the fulcrum for maximum static balancing, which provide haptic feedback in the gripping and roll directions (see the close-up views 1 and 2 shown in Fig. 9.1a).

The maximum force that the haptic interface is able to apply against the user's hand in each of the three Cartesian directions is determined to be 14 N. In the gripping and roll directions, the maximum forces are 17 and 12 N, respectively. This means that the haptic interface can reflect large forces in all the five degrees of freedom if necessary, e.g., to provide the sensation of making contact with bone. In the haptic interface, the friction and gravity effects are determined and compensated for, such that the user does not feel any weight on his/her hand when the slave is not in contact with an object. This is important because, in MIS, the weight of an instrument hampers the accurate feeling of tissue properties by the surgeon. The workspace of the instrument covers a pitch angle of ±30°, a yaw angle of ±40°, a roll angle of ±180°, and an insertion depth of ±11 cm. Also, the finger loop's gripping angle ranges from 3 to 30° (handle open and shut). This workspace encompasses the 60° cone known to be typically reached by endoscopic instruments during generic surgical tasks [4]. For a detailed description of this haptic HMI, see Ref. [11].

9.2.2 Sensorized Robot (Slave)

As discussed before, the surgical instrument (called the end-effector) needs to be capable of measuring instrument/tissue interactions. Due to the constraint on incision size in endoscopic surgery, the diameter of the robotic end-effector should be less than 10 mm. This space limitation means, among other things, that the pivotal motions of the tip jaws (e.g., grasper jaws) need to be actuated by a linear motion, preferably placed outside the patient. Moreover, no sensor should be mounted directly on the tip jaws due to sterilizability reasons. An end-effector that complies with the above requirements is developed and attached to another PHANTOM device acting as the slave robot (Fig. 9.1b). Strain gauges are used to non-invasively measure the end-effector's interactions with tissue in all the five degrees of freedom. The end-effector has a multistage assembly for tip open/close actuation through a linear mechanism (see magni-

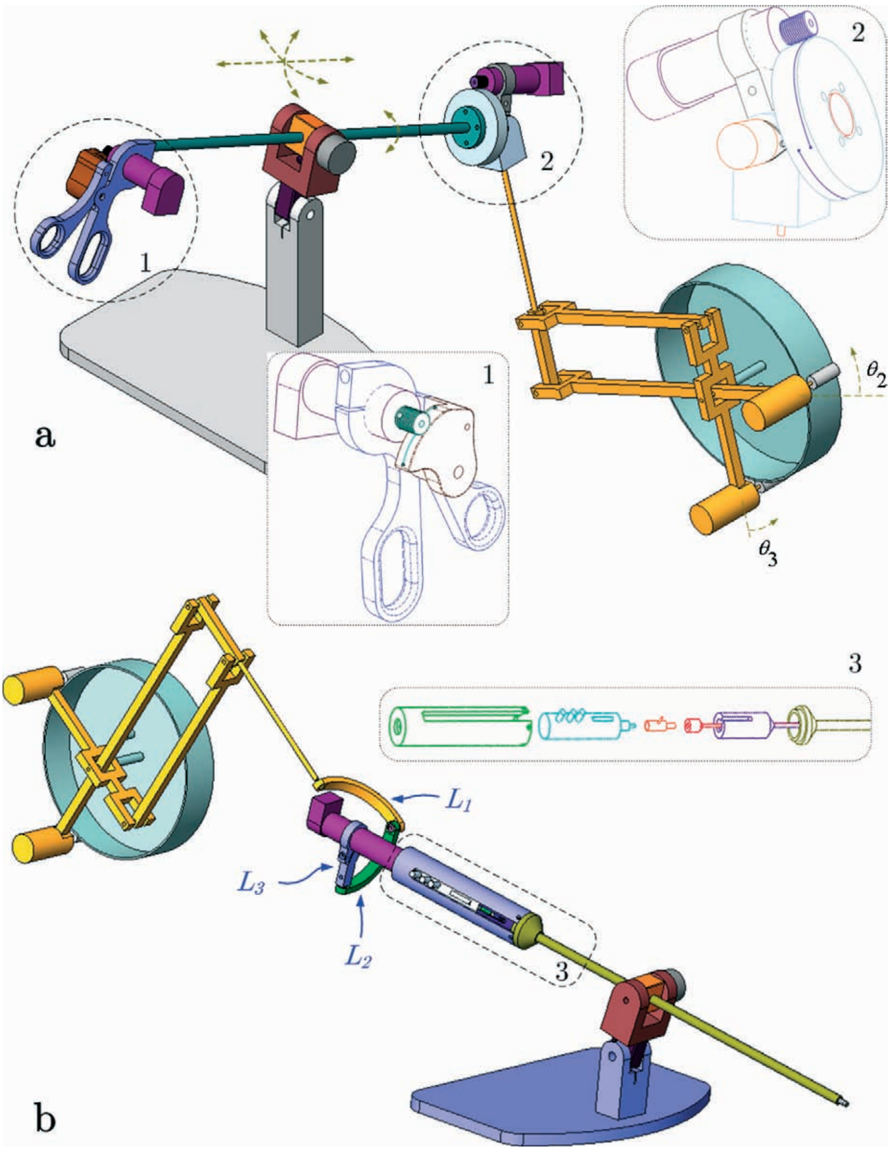

Fig. 9.1. **a** Haptic HMI (master), and **b** sensorized robot (slave) suitable for a minimally invasive environment

fied view 3 in Fig. 9.1b) and rotations about the main axis. A free wrist (made by links L_1, L_2, and L_3) is responsible for allowing the spherical motions of the end-effector centered at the entry point through the skin. For more information regarding this sensorized end-effector, see Ref. [8].

9.3 Communication and Control for Haptic Teleoperation

In a haptics-enabled telesurgical system, the flow of surgeon's hand motion and instrument/tissue contact data from the surgeon side to the patient side and vice versa require bilateral communication between the master and the slave. For this purpose, the virtual reality peripheral network (VRPN) was used to establish network-based communication such that the slave can be haptically telemanipulated from the master.

Consider the master–slave system block diagram of Fig. 9.2, in which θ_m, θ_s, τ_h, τ_e, τ_m, τ_s. M_m, and M_s are the master and the slave positions, the force (or torque) applied by the user's hand on the master, the force (or torque) applied by the slave on the remote object, the control commands (force or torque) sent to the master and the slave, and the master and the slave inertias, respectively. The goal of haptic teleoperation is to generate appropriate control commands τ_m and τ_s such that, regardless of the user and the object characteristics and behavior, there is correspondence between the master and the slave positions ($\theta_m = \theta_s$) and contact forces ($\tau_h = \tau_e$). This will ensure that the user has accurate perception of the object's compliance. The four-channel control architecture shown in Fig. 9.2 ensures the satisfaction of the above-mentioned *transparent teleoperation* requirements (provided the gains a_1 to a_4 are chosen such that $a_1 - a_3 = 1$ and $a_2 - a_4 = 1$). In our master–slave system, while the slave forces τ_e can be measured directly, thanks to the sensorized end-effector, we utilize the master's dynamical model to

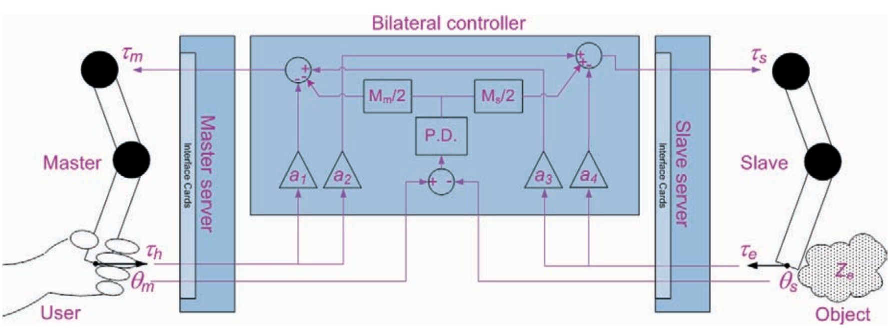

Fig. 9.2. Block diagram of four-channel haptic master–slave control

estimate the hand/master contact forces τ_h, as there is no force/torque sensor at the master. More details about this control method can be found in Ref. [12].

9.4 Experiments: Haptic Telerobotic Palpation of Soft Tissue

To assess the accuracy of transmission of task-related information to the surgeon's hand, we consider a palpation task. Palpation is frequently used by surgeons to estimate tissue characteristics and greatly depends on haptic sensation. In our palpation tests, a user moves the master such that the slave considerably indents a soft object made of foam material and then moves the master back and forth for 20 s, while the slave is still in contact with the object. With the four-channel bilateral controller described above, the slave closely follows the hand position and also exerts a force (torque) on the object that matches the force (torque) applied by the hand on the master (Fig. 9.3). This means that the teleoperation system is acting transparently in terms of transmitting to the user the force (torque) versus deformation characteristics of soft tissue and its mechanical impedance, which are critical to the tissue palpation task. Additional experiments with different soft objects showed that haptic feedback can successfully provide the user with the ability to distinguish between tissues with different stiffness when probing them robotically.

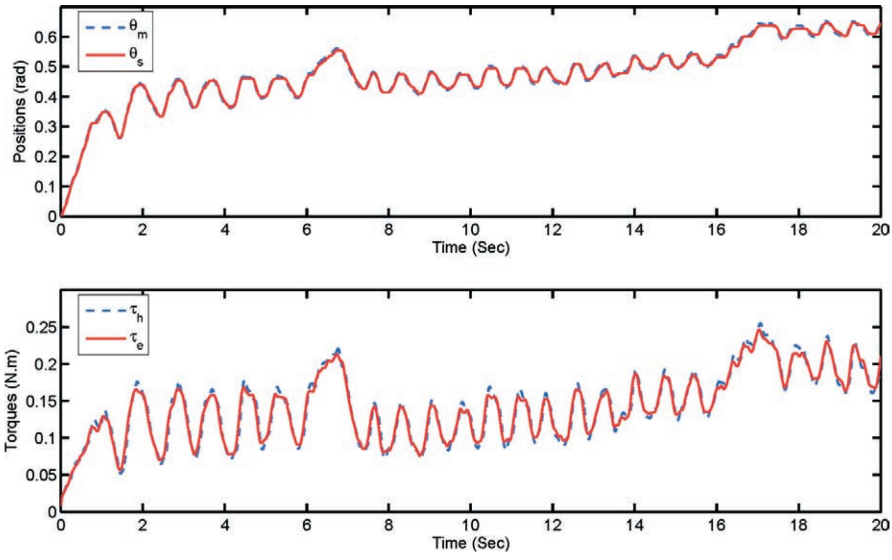

Fig. 9.3. Master–slave position and torque, after the slave is in contact with a soft object

9.5 Related Research Problems

9.5.1 Sensory Substitution for Haptic Feedback

It has been established that, due to major difficulties in design and technology, incorporating full haptic interaction in a complex surgical system such as the *da Vinci* demands fundamental system redesigns and upgrades, as well as long-term financial and research and development commitments from the manufacturer. However, in the short term and for some applications involving robotic surgery, it may be cost effective and advantageous to provide alternative modes of sensory feedback to the surgeon, e.g., as visual representation of haptic information. While force feedback remains a more intuitive means of relaying haptic information to the user, sensory substitution for haptic feedback may be able to provide sufficient feedback of an instrument's contact with tissue and improve surgical outcomes at a lower cost than haptic feedback itself.

Haptic feedback can be substituted in more than one way, for instance by providing the surgeon with auditory, graphical, or vibro-tactile cues about instrument/tissue contacts. For instance, graphical display of haptic information as overlaid on or beside the endoscope view can relay haptic information to the surgeon, simply based on the size and/or color of the visual stimuli and without the need for force reflection capability in the HMI (Fig. 9.4).

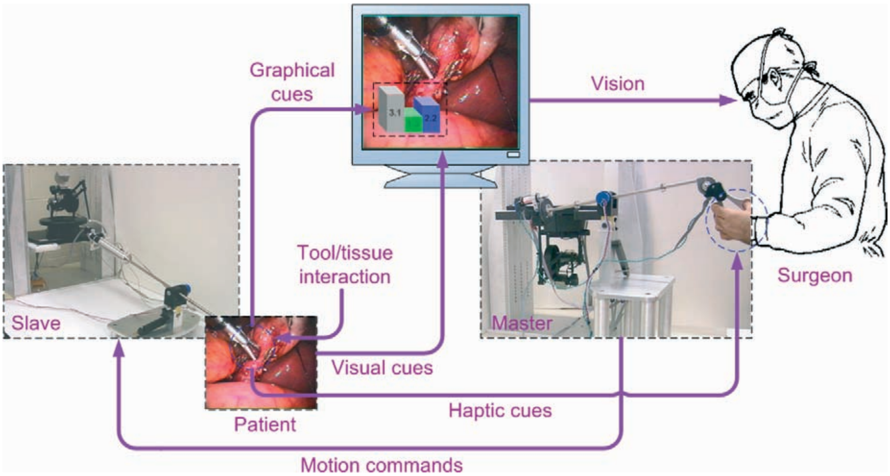

Fig. 9.4. Block diagram of master–slave teleoperation with several flows of sensory cues from the slave to the master

In the context of surgery, for manual operation and robotic teleoperation of a surgical-knot–tying task, the forces applied in the robotic mode were closer to the forces applied in the manual mode when the users were provided with auditory/graphical sensory substitution of haptic information [3]. In order to see the difference between sensory substitution and haptic feedback in the robotic mode itself, as shown in Fig. 9.5a, we used the master–slave system described earlier to compare the effect of haptic feedback with the effect of graphical feedback of haptic information for a lump localization task [10]. It was observed that the two feedback modalities resulted in comparable accuracies in finding the lump – an advantage of graphical feedback due to the lower system complexity required – while the task completion times were shorter with haptic feedback. The longer task time under graphical feedback was due to the fact that subjects had to constantly refer to the graphical display, in order to detect a significant variation in the contact force profile, which corresponded to a lump.

Utilizing the master–slave test bed, as shown in Fig. 9.5b, we also compared user performance for a telemanipulated soft-tissue stiffness discrimination task under visual (i.e., camera vision), haptic, and graphical modes [9]. Our goal was to study how effectively the graphical or haptic cues can replace a corrupted visual feedback. The motivation for studying this task is given by the fact that tissue palpation is one of the ways to detect cancerous tissue, which has a different stiffness compared to healthy tissue. It was found that graphical cueing leads to the highest rate of success in discriminating between two tissue

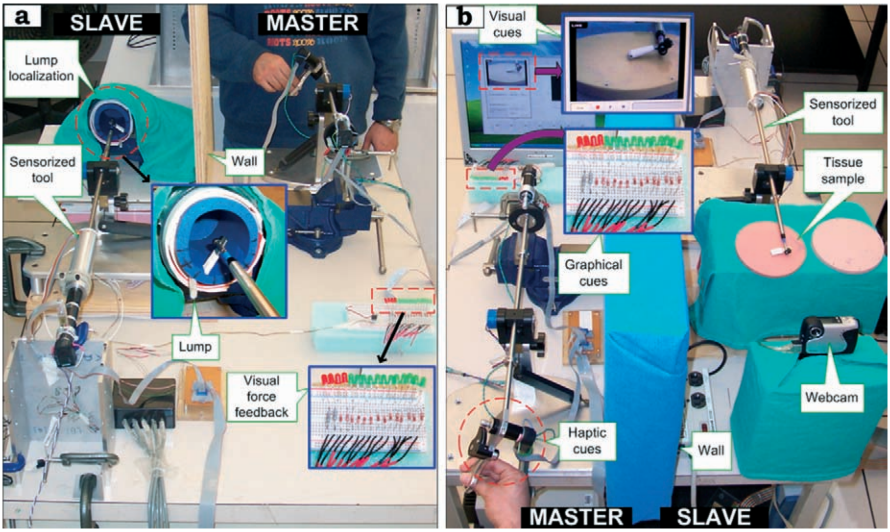

Fig. 9.5. Master–slave setup for performing **a** telemanipulated lump localization and **b** telemanipulated tissue stiffness discrimination

samples with different stiffness, while visual cueing incurs the highest risk of tissue damage (proportional to the energy delivered to tissue), which is because a subject would have to supply a significant amount of energy before tissue deformations are quantifiable.

9.5.2 Time-Delay Compensation in Haptic Teleoperation

An interesting control engineering problem is posed as a result of the presence of a non-negligible time delay in the communication media between the master and the slave. In the absence of haptic feedback to the surgeon, communication delays up to 600 ms have been found tolerable yet prolonging the completion times of surgical tasks [7]. In the presence of haptic feedback, however, such a delay can cause serious problems beyond merely slowing down the surgeon's maneuvers. In mild cases, the delay corrupts the feeling of the remote environments, as perceived by the user. In severe cases, it may make a teleoperation system unstable. We have used an approach based on passivity and wave theory to make the four-channel teleoperation architecture described earlier insensitive to time delays, by passifying the delayed communication channel [13]. As a result, stable teleoperation systems can be implemented with least interference on the user's perception of tissue characteristics.

9.5.3 Haptics-Assisted Training

In MIS, the limitations on the degrees of freedom and the surgeon's dexterity, the loss of tactile sensation, and the significant degradation in force sensation result in new perceptual-motor relationships, which are unfamiliar and challenging to learn. A possible solution to this learning challenge is to physically guide a trainee through the desired maneuver by force feedback from a haptic interface, thus helping the trainee to gain an objective understanding of the task required. Such haptics-assisted training can be done using shared control of two master HMIs and one slave robot [5]. One haptic device is held by the mentor, and the other is held by the trainee. The two haptic interfaces provide feedback forces to both the mentor and the trainee, proportional to the difference of their positions and inversely proportional to the control authority shared between them. At the beginning of the training, the slave robot is completely controlled by the mentor, and the trainee will receive large force feedback urging him/her to follow the mentor's motions. As the training progresses, the trainee takes over the control of the slave robot and receives less force feedback. Toward the end of training, the slave robot is completely controlled by the trainee, allowing the mentor to assess the skill level of the trainee by feeling the reflected forces. The same mode of training can be used for telesurgery, where the trainee will also gain hands-on experience on how to cope with delays in commands and audio/video signals.

9.6 Conclusion

A major deficiency of the current robot-assisted surgical systems is the lack of haptic feedback to the surgeon about instrument/tissue contacts. This chapter discussed the need for incorporating haptic interaction in robot-assisted interventions. To this end, a haptics-enabled surgeon–robot interface and a sensorized slave robot were described, which together form a master–slave teleoperator suitable for a minimally invasive environment. Using a four-channel haptic teleoperation control scheme and considering a soft-tissue palpation task, the transparency of the master–slave system in terms of accurate transmission of critical task-related information to the surgeon was experimentally validated. On the other hand, given that camera vision constitutes the only flow of data from the patient side to the surgeon side in the current surgical systems, it was discussed how alternative modalities for feedback of instrument/tissue interaction can improve task efficiency, while requiring a lower system complexity than haptic feedback.

Summary

Introduction

- A surgeon is faced with several problems in minimally invasive surgery (MIS) including degraded haptic feedback.
- Robots have solved several of the above-mentioned problems. Yet, haptic interaction is not restored in the currently available surgical robotic systems.
- The importance of haptics in master–slave surgery.

Mechanisms for Haptic Teleoperation

- A haptics-capable master interface and a sensorized slave robot are required.
  - Haptic master description.
  - Sensorized slave description.

Communication and Control

- The virtual reality peripheral network used for master–slave communication.

- The four-channel method used for haptic teleoperation control.

Experiments: Haptic Telerobotic Palpation of Soft Tissue

- Using the master–slave system and the communication/control scheme described earlier, soft-tissue palpation tests are done.
- Plots of the master and the slave positions and forces, indicating the high fidelity of teleoperation.

Related Research Problems

- Sensory substitution for haptic feedback:
  - When a haptics-capable master interface is not available, it may be useful to provide alternative modes of sensory feedback about tool/tissue interaction to the user.
- Time-delay compensation in haptic teleoperation:
  - Communication time delay in teleoperation can corrupt the feeling of the remote environment as perceived by the user.
- Haptics-assisted training:
  - Haptics can be used to guide a trainee through the desired maneuver, thus helping the trainee to gain a kinesthetic understanding of the task required.

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References

1. Gerovichev O, Marayong P, Okamura AM (2002) The effect of visual and haptic feedback on manual and teleoperated needle insertion. Proceedings of the 5th International Conference on Medical Image Computing and Computer Assisted Intervention, Tokyo, pp 147–154
2. Joice P, Hanna GB, Cuschieri A (1998) Errors enacted during endoscopic surgery – a human reliability analysis. Appl Ergon 29:409–414
3. Kitagawa M, Dokko D, Okamura AM et al (2005) Effect of sensory substitution on suture manipulation forces for robotic surgical systems. J Thorac Cardiovasc Surg 129:151–158

4. Lum MJH, Rosen J, Sinanan MN et al (2004) Kinematic optimization of a spherical mechanism for a minimally invasive surgical robot. Proceedings of IEEE International Conference on Robotics & Automation, New Orleans, pp 829–834
5. Nudehi SS, Mukherjee R, Ghodoussi M (2005) A shared-control approach to haptic interface design for minimally invasive telesurgical training. IEEE Trans Control Syst Technol 13(4):588–592
6. Picod G, Jambon AC, Vinatier D et al (2005) What can the operator actually feel when performing a laparoscopy? Surg Endosc 19:95–100
7. Rayman R, Primak S, Patel R et al (2005) Effects of latency on telesurgery: an experimental study. Proceedings of the 8th International Conference on Medical Image Computing and Computer Assisted Intervention, Palm Springs, Calif., pp 57–64
8. Tavakoli M, Patel RV, Moallem M (2005) Haptic interaction in robot-assisted endoscopic surgery: a sensorized end-effector. Int J Med Rob Comput Assist Surg 1:53–63
9. Tavakoli M, Aziminejad A, Patel RV et al (2006) Multi-sensory force/deformation cues for stiffness characterization in soft-tissue palpation. Proceedings of the 28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, New York, pp 837–840
10. Tavakoli M, Aziminejad A, Patel RV et al (2006) Tool/tissue interaction feedback modalities in robot-assisted lump localization. Proceedings of the 28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, New Yori, pp 3854–3857
11. Tavakoli M, Patel RV, Moallem M (2006) A Haptic interface for computer-integrated endoscopic surgery and training. Virtual Reality 9:160–176
12. Tavakoli M, Patel RV, Moallem M (2006) Bilateral control of a teleoperator for soft tissue palpation: design and experiments. Proceedings of the 2006 IEEE International Conference on Robotics and Automation, Orlando, Fla., pp 3280–3285
13. Tavakoli M, Aziminejad A, Patel RV et al (2007) Time delay compensation in four-channel bilateral teleoperation using wave variables. Submitted to the 2007 IEEE International Conference on Robotics and Automation, Rome
14. Wagner CR, Stylopoulos N, Howe R (2005) The role of force feedback in surgery: analysis of blunt dissection. Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando, Fla., pp 68–74