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SURGICAL ENDOSCOPY
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Methods and mechanisms for contact feedback in a robot-assisted minimally invasive environment

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Abstract. Providing a surgeon with information regarding contacts made between instruments and tissue during robot-assisted interventions can improve task efficiency and reliability. In this report, different methods for feedback of such information to the surgeon are discussed. It is hypothesized that various methods of contact feedback have the potential to enhance performance in a robot-assisted minimally invasive environment. To verify the hypothesis, novel mechanisms needed for incorporating contact feedback were designed, including a surgeon–robot interface with full force feedback capabilities and a surgical end-effector with full force sensing capabilities, that are suitable for minimally invasive applications. These two mechanisms were used to form a robotic "master–slave" test bed for studying the effect of contact feedback on the system and user performance. Using the master–slave system, experiments for surgical tasks involving soft tissue palpation were conducted. The performance of the master–slave system was validated in terms of criteria that assess the accurate transmission of task-related information to the surgeon, which is critical in the context of soft tissue surgical applications. Moreover, using a set of experiments involving human subjects, the performance of several users in carrying out the task was compared among different methods of contact feedback.

Key words: Contact feedback — Haptic interface — Master–slave surgery — Robot-assisted surgery — Sensorized end-effector — Sensory substitution

Despite the benefits that endoscopic surgery brings, namely, reduced trauma, postoperative pain, and hospital stay for the patient, it has inherent drawbacks and pitfalls in terms of the surgeon's motor functioning and sensory capabilities. These drawbacks include a lack of dexterity on the part of the surgeon because of restricted access to the surgical site [8], a lack of fine manipulation capability because of the long instruments, and visual problems including motion sickness, loss of localization, and awkward hand–eye coordination [1, 2].

Another important obstacle in endoscopic surgery is the significant degradation of kinesthetic/force feedback (haptic feedback) to the surgeon from the instrument and its contact with tissue. This degradation occurs because the instruments include hinge mechanisms with significant friction, because the cannulas through which instruments are inserted introduce friction [21], because pivoting at the entry point causes the forces at the two ends of instruments from contacts with the tissue and the hand to vary with the insertion depth (lever ratio) and thus to be mismatched, and because the contact forces at the instrument tip can sometimes be negligible compared with the relatively large forces supplied by the arm to move the instrument mass and the unsupported hand [31]. As a result of the significantly degraded haptic sensation for the surgeon, surgical tasks requiring accurate feeling of tissue characteristics, such as palpation, are difficult for the surgeon to perform endoscopically.

To tackle several of the aforementioned limitations, robots recently have been introduced in surgical interventions [5, 13, 29]. The currently available surgical robotic systems for minimally invasive surgery (the da Vinci and the Zeus systems, Intuitive Surgical Inc., Sunnyvale, CA [1]) solve several problems of endoscopic surgery. For example, the end-effector of the da Vinci robot includes a dexterous wrist that adds three rotations to the motions conventionally available in a minimally invasive environment. The robot also allows precise movements by filtering out hand tremors and scaling down hand motions up to a factor of 5:1. Furthermore, it achieves stable three-dimensional vision with good eye–hand instrument alignment as the surgeon grasps the instrument controls placed below the fixed binocular viewer. An upgraded version of the Zeus

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also has laparoscopic instruments with wrist capabilities, provides motion scaling, and offers three-dimensional vision. However, the Zeus system is being phased out.

Several studies have compared the performance of robot-assisted and conventional surgeries [14, 22]. However, the robotic systems have not yet been successful in restoring feedback of instrument–tissue contacts to the surgeon. Although the da Vinci system is capable of providing force feedback in some of the available degrees of freedom, this feedback is of low quality and disabled by the manufacturer.[1] The Zeus system does not provide any haptic feedback to the surgeon. The lack of feedback to the surgeon regarding instrument–tissue interactions can cause complications such as accidental puncturing of blood vessels or tissue damage [11, 25]. Indeed, lack of haptic feedback is regarded as a safety concern in endoscopic surgery because it is potentially dangerous if instruments leave the endoscopic camera's limited field of view. Furthermore, the endoscopic view, which easily can deteriorate because of fluids from the patient's body on the camera lens, can make it difficult for the surgeon to detect any tissue damage in the absence of haptic feedback.

This report is organized as follows. The Methods for Contact Feedback section discusses the methods and requirements for incorporating contact feedback into a minimally invasive environment (i.e., surgery or therapy) using a master–slave robotic system in which the movements of a surgical robot (the slave) are controlled via a surgeon–robot interface (the master). The Mechanisms for Contact Feedback section presents the master and slave mechanisms consisting of a force-reflective user interface and a sensorized surgical end-effector. The Experiments section presents a brief overview of our master–slave test bed for studying haptic feedback during endoscopic surgery and a short discussion of bilateral control and communication issues. Tests were conducted to evaluate the usefulness of haptic feedback during the master–slave operation on soft tissue (Case Study 1), and to compare surgical task performance for the different methods of contact feedback (Case Study 2). The final section contains some concluding remarks.

Methods for contact feedback

In the following discussion, the methods for contact feedback in a minimally invasive environment are explained, as well as the requirements and benefits of each.

Haptic feedback

In master–slave teleoperation with force reflection (haptic feedback), the surgeon operates from and receives force feedback via a surgeon–robot interface (the master), with a surgical robot (the slave) mimicking the surgeon's hand maneuvers inside the patient's body. In theory, a reflection of instrument–tissue interactions to the surgeon's hand can be attained without force sensing at the patient's side and simply by keeping the positions of the master and the slave close to one another at all times. With this position-based scheme, however, the perception of forces by the surgeon is sluggish, delayed, and of inferior quality, as compared with the use of a force sensor to measure instrument–tissue contact forces [23].

Requirements

All other techniques for master–slave force reflection share a common need for patient-side force information [16, 23]. If a surgical robot is not equipped with a sensor to measure the instrument–tissue contact forces, as is the case with the da Vinci system, the forces may be estimated from outside the patient. This approach, however, leads to inaccuracies in haptic feedback because the estimation is significantly plagued by disturbances, bias, and noise caused by the entry port. Indeed, study of robot-assisted suturing has shown that estimation of instrument tip interactions from robot joint torques is of little value [18]. Therefore, the following two devices are needed at the sides of the surgeon and patient for haptics-based operation in an endoscopic surgery environment: (1) a force reflective surgeon–robot interface that transmits the hand movements to the surgical robot and the instrument–tissue interactions to the surgeon's hand, and (2) an endoscopic instrument properly sensorized to measure the contact forces that act as the end-effector of the surgical robot. The significance of haptic feedback in the master–slave operation, hereafter termed "teleoperation," to perform surgical tasks is discussed next.

Benefits

Studies investigating the effect of haptic feedback on various object manipulation and target acquisition tasks have shown that it improves the performance and efficiency of teleoperation by reducing the contact force levels; the sum of squared forces, which is proportional to the energy consumption; the task completion time; and the number of errors [3, 10, 24]. Similarly, in surgical teleoperation, haptic feedback can provide the surgeon with the perceptual information required for optimal application of forces, thus reducing trauma to tissue. It also can 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, and the like. Finally, for instruments with restricted maneuverability, as in endoscopic surgery, haptic feedback is expected to improve the precision of manipulation.

Research has been conducted to evaluate the impact 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 [9]. Moreover, study of the effect that force feedback has on the performance of blunt dissection shows that it reduces the number of errors, the task completion time, and the magnitude of contact forces [32].

Sensory substitution for haptic feedback

It has been established that because of 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., visual representation of haptic information). Whereas force feedback remains a more intuitive means of relaying haptic information to the user, sensory substitution for haptic feedback can provide sufficient feedback of an instrument's contact with tissue under certain conditions. Therefore, it is hypothesized that surgical outcomes can be improved by replacing haptic feedback with other sensory cues (sensory substitution), or by complementing haptic feedback with other sensory cues (sensory augmentation).

[1] As discussed later, the main reason for this is that any contact made between the da Vinci's instruments and the patient's body is estimated from outside the patient rather than through direct measurement from inside.

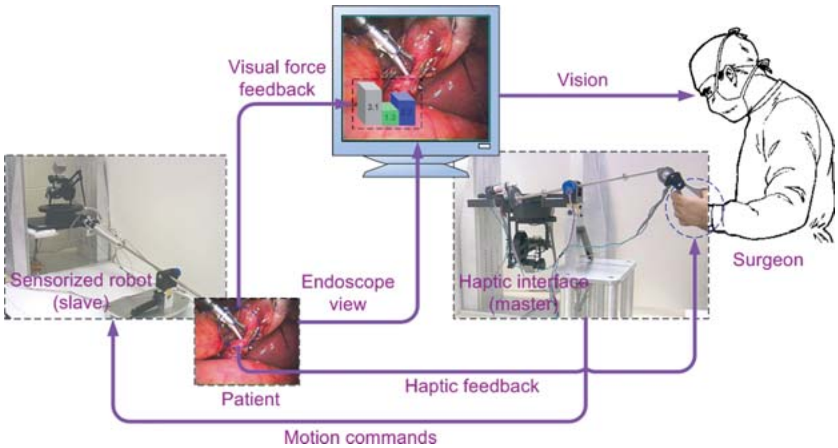

Fig. 1. Sensory substitution/augmentation for haptic feedback.

Requirements

Haptic feedback can be substituted in more than one way, for instance, by providing the surgeon with auditory, visual, or vibrotactile cues about instrument–tissue contacts. However, the substitute feedback channel must be intuitive and must provide straightforward mapping to haptic information. It should have minimum background noise and a fairly large bandwidth (communication capacity). In the context of surgical applications, substitution of haptic information with auditory signals (in the form of different auditory tones) is not favored by surgeons because it may interfere with the conversations among the surgical team, It also provides only single-event reports rather than continuous real-time information about instrument–tissue contacts. In general, surgeons also are not familiar with vibrotactile inputs (in the form of different vibration intensities). However, visual display of haptic information (visual force feedback) as overlaid on or beside the endoscope view can relay haptic information to the surgeon based simply on the size or color of the visual stimuli.

Figure 1 shows how haptic feedback can be substituted or augmented by corresponding visual information in master–slave surgery. Visual feedback of contact forces is provided using a bar indicator whose height varies with the magnitude of forces, similar to the bar display added to a research version of the Zeus system for showing gripping forces.

Benefits

A study investigating the effect of sensory substitution for a peg-in-hole insertion task has shown that both visual feedback and vibrotactile feedback of haptic information can reduce peak forces, as compared with the case in which no feedback of haptic information is provided to the users [6]. Moreover, findings have shown that visual sensory substitution improves a user's sensitivity for detecting small forces by allowing the use of high feedback gains without a slowing of hand movements [19].

These studies were not performed in the context of surgical applications. 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/visual sensory substitution of haptic information [15]. It would be interesting to see the difference between sensory substitution and haptic feedback in the robotic mode itself.

Mechanisms for contact feedback

This section discusses the design of our force reflective user interface and sensorized endoscopic robot.

Haptic user interface (master)

The possible motions of an endoscopic instrument relative to the incision point are limited to four (excluding the tip's motions): up and down rotation (pitch), side-to-side rotation (yaw), axial rotation (roll), and axial translation (insertion). As a result of the limitation on the surgeon's dexterity in addition to other limitations, endoscopic surgery involves perceptual–motor relationships that may be unfamiliar to a surgeon and may require training [30]. On the other hand, robot-assisted surgery requires more skills on the part of the surgeon and involves a slow learning curve [12]. Therefore, we decided to have the surgeon–robot interface configured to involve the same motions as in conventional endoscopic surgery to provide a natural feel to the surgeon, and to preserve the geometric relationships and motor skills for which an endoscopic surgeon is trained. Such an interface would favor exploiting the surgeon's past cognitive and motor skills while bringing about the unique advantages of robot-assisted surgery (e.g. scaling of instrument–tissue interactions, filtering of hand tremors).

A possible arrangement for the haptic interface is shown in Fig. 2a. This interface is capable of providing a user with force sensation, sensation regarding surface roughness, and kinesthetic sensation of an object's elasticity. The PHANToM 1.5A force feedback device (Sensable Technologies Inc., Woburn, MA) is integrated into the user interface. A rigid shaft resembling an endoscopic instrument is passed through a fulcrum and attached to the PHANToM's end point, causing the motions of the handles grasped by the surgeon to resemble those in endoscopic manipulation. The three-dimensional Cartesian workspace of the PHANToM spans the pitch, yaw, and insertion motions of the instrument, providing force feedback and position measurement in these three directions.

Two additional mechanisms are incorporated in the surgeon–robot interface to reflect forces in the roll and gripping directions. The two cable-capstan mechanisms, shown in Figs. 2b and c, have been placed intentionally on opposite sides of the fulcrum to have as much static balancing as possible.

The zero position for the haptic interface is defined in which the endoscopic instrument is horizontal and the PHANToM's arms are at right angles. As the instrument starts reaching out to the intended body part, its

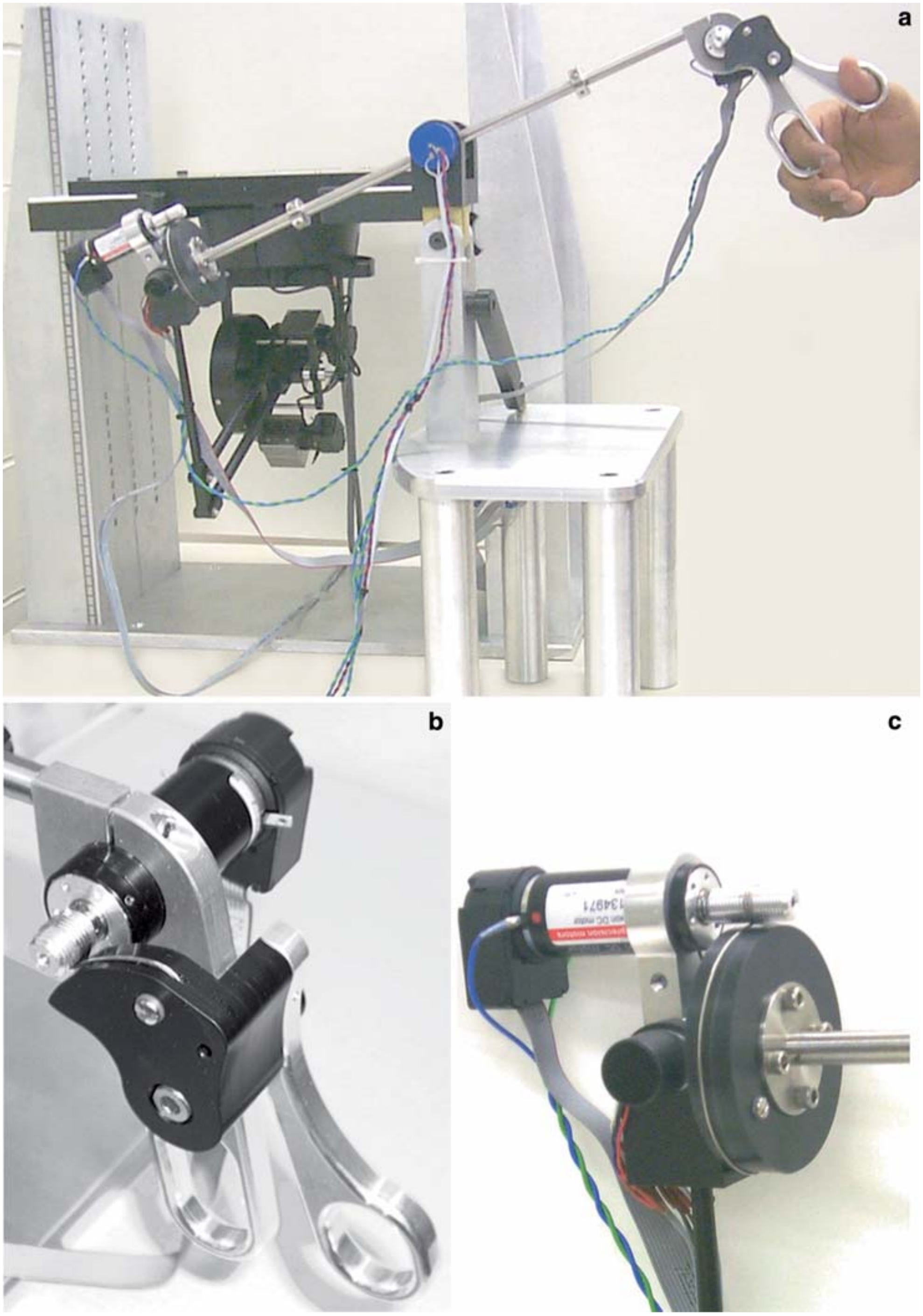

Fig. 2. (**a**) Haptic user interface for endoscopic interventions. Mechanisms for force reflection in the finger loops (**b**) and the roll mechanism (**c**).

end point sweeps the space below it (Fig. 2). With this workspace, the upside-down orientation of the PHANToM ensures better conditioning of the Jacobian matrix of the haptic display, and therefore higher control accuracy. For the configuration shown in Fig. 2, the workspace of the instrument covers a pitch angle of $\pm 30°$ (elbow up and down), a yaw angle of $\pm 40°$ (elbow left and right), a roll angle of $\pm 180°$ (rotation about the instrument axis), and an insertion depth of ± 11 cm (displacement along the instrument axis). Also, the finger loop's gripping angle ranges from 0° to 30° (handle open and shut).

On the other hand, for generic surgical tasks such as tissue handling, tissue dissection, and suturing performed *in vivo* by a number of surgeons in a minimally invasive environment, the instruments were found 95% of the time to be inside a 60° cone whose tip was located at the fulcrum [17]. Therefore, the workspace of the haptic user interface encompasses the space typically reached by endoscopic instruments.

The maximum force that the haptic interface is able to apply against the user's hand in each of the three Cartesian directions (F_x, F_y, and F_z) is determined to be 14 N. For the two additional force feedback mechanisms, the low-inertia and low-friction DC motors selected have sufficient power to exert 17 N in the gripping direction and 12 N in the roll direction. Therefore, the haptic interface can reflect large forces in all the five degrees of freedom if necessary (e.g., to provide the sensation of hitting a bone). In the haptic interface, the friction and gravity effects are determined and compensated such that the user does not feel any weight on his or her hand when the slave is not in contact with an object. This is important because in endoscopic surgery, the weight of an instrument hampers the accurate feeling of tissue properties by the surgeon. Tavakoli et al. [27] provide a detailed description of this haptic display.

Sensorized surgical end-effector (slave)

As discussed in the Haptic Feedback section, the surgical instrument (termed the "end-effector") must be capable of measuring instrument–tissue interactions. Because of constraint on incision size in endoscopic surgery, the diameter of the robotic end-effector, including all required sensors and the tip actuator, should be less than 10 mm. Therefore, the end-effector design must take the following issues into account.

- The available multi-axis force/torque sensors cannot be used because, as a result of their size, they will stay outside the patient, picking up unwanted abdominal wall friction and stiffness at the trocar site and causing distortions in the sensation of forces.
- Because of the limited space, the pivotal motions of the tip jaws (e.g., grasper jaws) need to be actuated by a linear motion, preferably placed outside the patient.
- The sensor measuring contact between the tip and the tissue should not be mounted directly on the tip jaws because for the device to be sterilizable, it is desirable to use tips that can be detached and discarded after use.

An end-effector that complies with the preceding requirements has been developed and attached to another PHANToM device acting as the slave robot (Fig. 3a). We have tackled the aforementioned requirements by noninvasive measurement of instrument–tissue contact forces/torques using strain gauges integrated into the end-effector, noninvasive actuation of a detachable tip using a linear motor, and noninvasive measurement of the tip interactions with tissue (during grasping, cutting, and the like) using a single-axis load cell. The end-effector has a multistage assembly for tip open/close actuation and rotations about the main axis (Fig. 3b). 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 (constrained isocenter). At the other end of the end-effector, a fulcrum is placed at the trocar to support the end-effector such that its movements do not damage the surrounding tissue.

If the wrist is not to be used, the end-effector can be attached to a robot such as the da Vinci that provides spherical movement at a remote center of motion located at the entry point. Possible maneuvers of the instrument involve lateral and axial force interactions at the distal end when tissue is pushed or pulled, and torsional moment interactions that can occur, for example, during suturing. In addition, the tip interacts with tissue as a result of the open/close motions of the jaws. Measurement for each of these interactions is made possible by one of the strain gauges shown in Figs. 3c–f. Tavakoli et al. [26] provide more information about this end-effector.

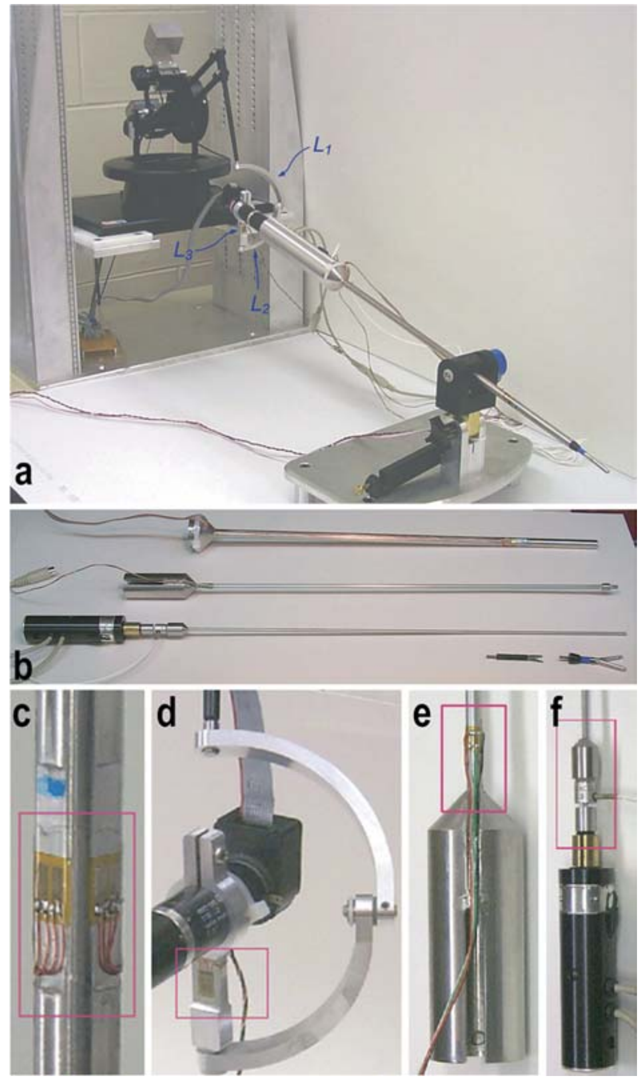

Fig. 3. **a** Sensorized slave robot including the end-effector, the wrist, the twist motor, and the tip actuation assembly. **b** Details of the tip actuation assembly: the three tubes and two different detachable tips. **c** Gauges to measure bending moments. **d** Gauges to measure axial forces. **e** A gauge to measure torsional moment. **f** A load cell to find tip forces.

Master–slave control and communication

In haptic master–slave control, the goal is to generate appropriate control commands such that, regardless of the user and (remote) object characteristics and behaviors, there is correspondence between the measured

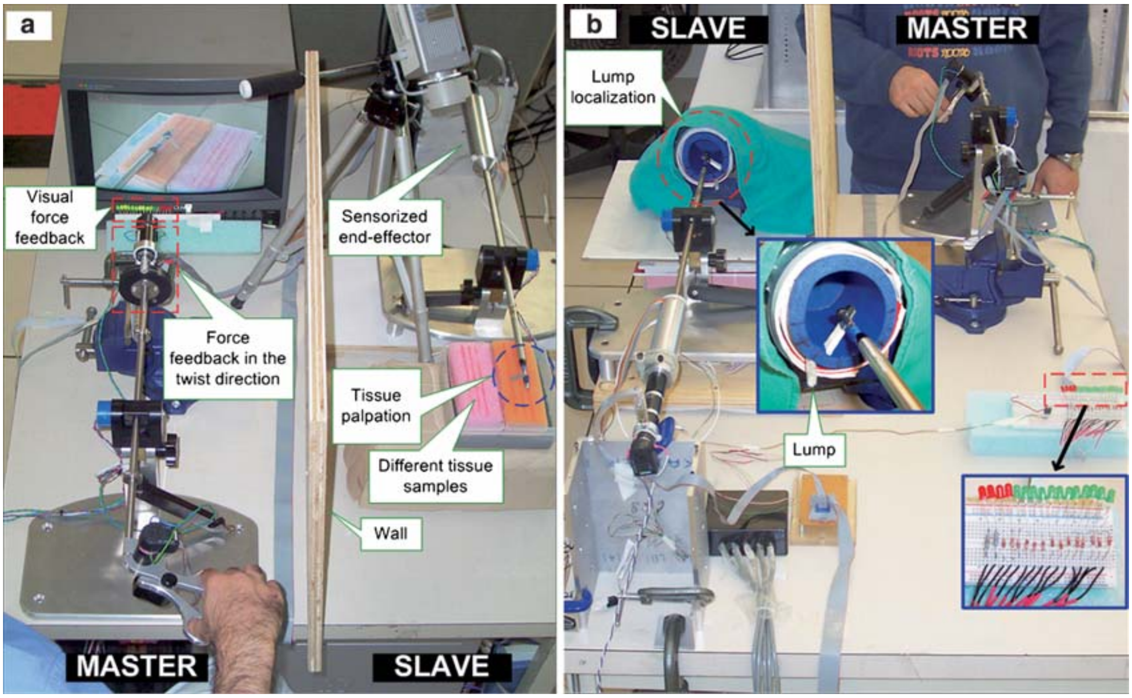

Fig. 4. Master–slave setup for performing telemanipulated tissue palpation (**a**) and lump localization (**b**).

positions and the measured contact forces at the master and the slave. This will ensure that the user has accurate perception of the object's compliance. We have used a four-channel architecture for teleoperation control that uses weighted summations of the master and slave forces as well as the difference between the positions of the master and the slave. Yokokohji and Yoshikawa [33] provide more information about this control strategy.

The Virtual Reality Peripheral Network (VRPN) [28] has been used to establish network-based communication such that the slave can be telemanipulated from the master. The VRPN provides a network transparent and device-independent interface to virtual reality peripherals. Two personal computers (PCs) (Pentium 4, 2.8 GHz) are placed next to the master and slave. Through their interface cards, these two computers input and output measured variables and control commands, respectively. A third PC, which runs the algorithms for bilateral control at a rate of 1,000 Hz, communicates in each sampling time through the VRPN with the two local PCs for data exchange. The proximity of the master–slave system components results in negligible communication latency.

Experiments

The master–slave system discussed in this report is a useful test bed for investigating the effects of force feedback in master–slave teleoperation for soft tissue applications. Using the master–slave system, teleoperation experiments involving the tissue palpation task were conducted. Palpation is used frequently by surgeons to estimate tissue characteristics, and its effectiveness depends greatly on haptic sensations. For the experiments described in this report, the master and slave subsystems, capable of operation in all five motions available in endoscopic surgery, were constrained for force reflective teleoperation in the twist direction only (i.e., rotations about the instrument axis). The user twisted the master, causing the slave to probe the tissue using a small rigid beam attached to the slave end-effector (Fig. 4). The instrument interactions with tissue were in the form of torques about the slave instrument axis. This contact torque was measured by the gauge shown in Fig. 3e, and reflected to the user via the force feedback mechanism shown in Fig. 2c.

In the two case studies that follow, the contact feedback methods were evaluated and compared based on the transparency of the master–slave system in transmitting critical task-related information to the user in the context of a soft tissue surgical task. For experiments involving visual sensory substitution for haptic feedback, 16 light-emitting diodes, which formed a bar indicator for the magnitude of forces, were located beside the screen that showed the tissue site to the user (Fig. 4).

Case study 1: Force feedback during tissue palpation

In this study, the user moves the master such that the slave considerably indents a soft object, then moves the master back and forth for 20 s while the slave still is in contact with the object (Fig. 4a). For these tests, we used an object made of packaging foam material in addition to an artificial silicon-based tissue phantom

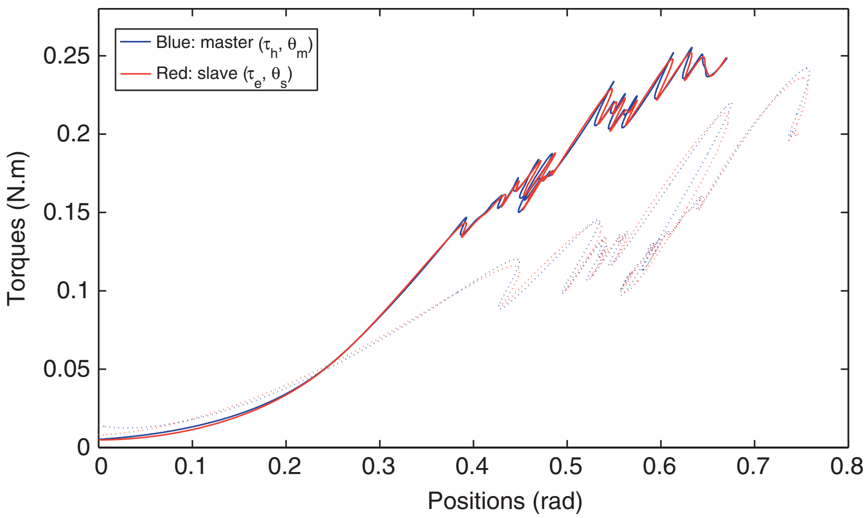

Fig. 5. Contact mode profile of the torque position relationship measured at the slave and as perceived by the user for the silicon-based phantom (*solid*) and for the foam object (*dotted*).

(from the Chamberlain Group LLC [4]) with greater stiffness than the foam material.

Results

When the slave interacts with the foam object and the silicon-based object, the contact torques and deformations, as measured at the slave (τ_e, θ_s) and as perceived by the user (τ_h, θ_m), are plotted in comparison with each other (Fig. 5).[2] Figure 5 shows that the slave closely follows the hand position, exerting a force on the object that matches the force applied by the hand on the master. Because the torque deformation graphs are quite close for each object, the master–slave system acts transparently in terms of transmitting to the user the contact force/torque versus the deflection characteristics of soft tissue, which is critical to the tissue palpation task. As a result, force feedback provides users with an accurate perception of the compliance of each soft object. Moreover, haptic feedback provides users with the ability to distinguish between the two tissues when probing them robotically.

Case study 2: Visual force feedback versus force feedback during lump localization

Experiments involving human subjects that compare the performance of users in a surgical knot-tying task between manual operation and robotic operation with auditory/visual sensory substitution for haptic feedback [15] have been reported previously in the literature. The issue we address is the difference in terms of performance between haptic feedback and visual substitution for haptic feedback during robotic operation. The task considered in this case study was localization of an embedded lump in a compliant environment.

[2] The relationship between the indenting force/torque and the deformation of biologic tissue, such as liver, is linear for small deformations [7], but tends to become nonlinear (2nd order) for large deformations [20]. As can be seen, the data collected from the silicon-based phantom is in good agreement with a second order stress–strain relationship, implying that it closely approximates real tissue.

Experiment design

Six subjects (2 men and 4 women) ages 24 to 34 years participated in our experiments. The subjects were engineering science students with little to average exposure to haptic feedback and visual substitution for haptic feedback. The task was to locate a rigid lump embedded at an unknown location in a finite-stiffness homogeneous tissue model made from rubber. Lump localization was based on exploring the model and receiving haptic feedback using the master–slave model described in this report (Fig. 4b).

The lump was placed in one of five locations at approximately 34°, 65°, 92°, 124°, and 158° with respect to the horizon. The size of the lump (5 mm) was chosen such that users could detect the lump in a reasonable amount of time.

The subjects' primary goal was defined as pinpointing the lump by centering the slave end-effector on it. The subjects were told that the task completion time was a secondary performance metric that needed to be minimized, yet they could take their time if it helped them to minimize the primary performance metric (i.e., localization error). A task was considered complete when the subject signaled verbally that the lump was found.

Each subject performed two sets of tests with a short break between them. In each test, each of the five lump locations was presented twice to the subject: once in the presence of visual force feedback (VFF) about the levels of instrument–tissue interaction and once in the presence of force feedback (FF). Therefore, each test comprised 10 trials (i.e., 10 combinations of lump location and feedback mode). The trials within a test were presented in a randomized order to the subjects. Before the experiments, each subject was given three or four practice trials until he or she felt comfortable with the operation of the master–slave system.

To keep tissue deformation cues from playing a role in lump localization, the subjects did not have camera vision from the slave side. Also, to mask any audio feedback that could result from the friction between the tissue model and the slave's end-effector, the subjects wore headphones that played music loud enough to mask any external sounds. Each lump localization trial started from orientation of the master handle (and the slave's end-effector) such that it was horizontal, followed by twisting of the handle to explore the tissue until the handle was again horizontal on the other side (equal to a wrist rotation of +180° for the user).

In each trial of each test, the contact forces between the instrument and the tissue were recorded. Before the experiments, each subject was briefed that our goal was to compare the user performance under visual force feedback and kinesthetic force feedback. Unlike most of the previous studies on sensory substitution, which have considered task completion time as the only metric for performance comparisons, we chose lump localization accuracy as the primary metric and the task times as a secondary factor for comparison. We also compared the energy supplied to tissue under VFF and FF because lower energy corresponds to less trauma and probably less damage to tissue.

Results

The bar graph of Fig. 6a displays the statistics of the slave's final end-effector positions for the different lump locations. The error bars show that there is consistency among the subjects in the detected position of each lump (small standard deviations). Table 1 contains the means and standard deviations of the position errors in lump localization for the five lump locations. The values of the mean position errors in Table 1 suggest that VFF achieves higher levels of localization accuracy. To test this hypothesis and to determine the nature of variations in the position errors, we used a two-tailed *t*-test and obtained the null hypothesis probability in this case for the five lump locations. The probability of the results assuming the null hypothesis $\mu_1 = \mu_2$ for lump locations 1 to 5 were $p < 0.002$, $0.02 < p < 0.05$, $p > 0.2$, $p > 0.2$, and $p > 0.2$, respectively.

These results indicate that for lump locations 3, 4, and 5, there is no significant difference in mean localization error between VFF and FF. This might be partly attributable to the fact that the subjects experienced some difficulty localizing the first two lump positions because they were too close to the starting point of the slave. To investigate the accuracy of lump localization further, we performed a one-way analysis of variance (ANOVA) test to determine the localization error statistics of the five lump locations for both VFF and FF ($F[4,82] = 0.4589$, $p > 0.5$ for VFF, and $F[4,82] = 3.31$, $p < 0.05$ for FF). These results indicate that the localization error means do not vary significantly across the five lump locations for VFF, but vary significantly for FF.

Figure 6b depicts the statistics of the time (s) taken to localize a lump in each of the five locations. As a general observation, the mean localization time is significantly longer with VFF than with FF (267%, 192%, 201%, 151%, and 195% for lump locations 1 to 5, respectively). Right-tailed *t*-tests comparing VFF and

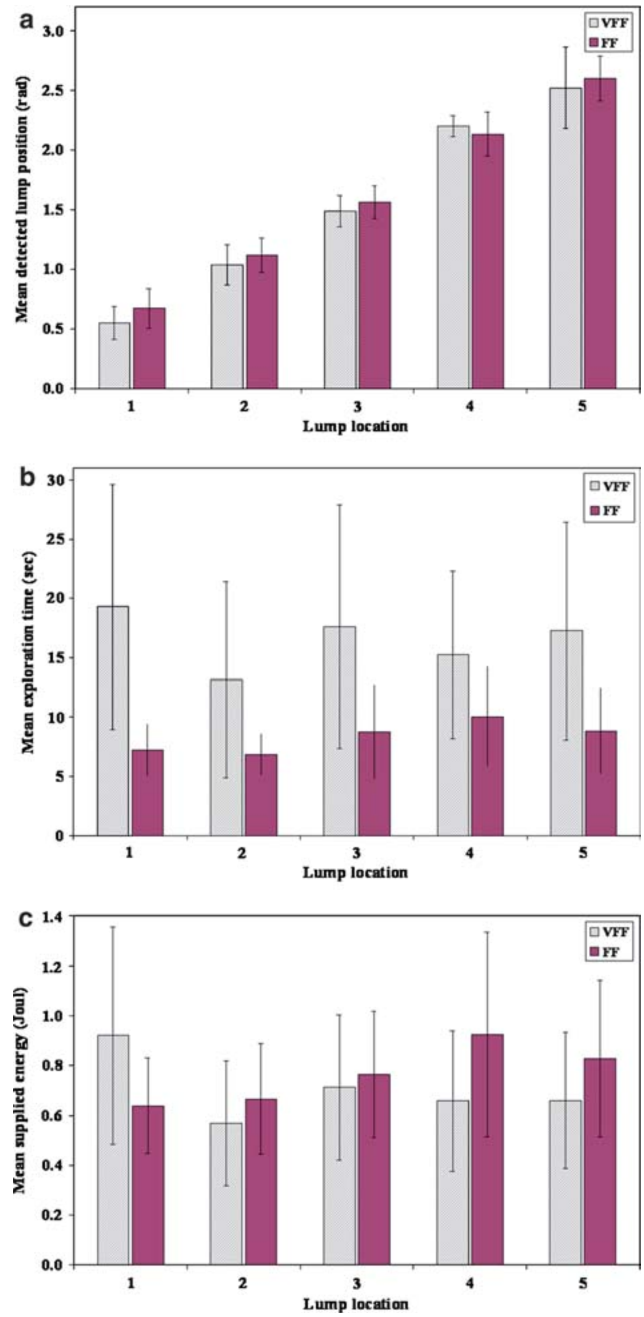

Fig. 6. **a** Mean detected lump position (rad). **b** Mean exploration time (s). **c** Mean energy supplied to the tissue (Joule). Error bars show standard deviations.

FF for localization times of each lump location confirm this observation ($p < 0.0005$, $p < 0.0050$, $p < 0.0005$, $p < 0.0050$, and $p < 0.0005$ for lump locations classes 1 to 5, respectively). Subjects were instructed to localize the lumps as accurately as possible regardless of the exploration time, which justifies the high levels of standard deviation in the localization time statistics.

Figure 6c depicts the statistics of the energy (Joules) supplied to the tissue during lump localization for each of the five lump locations with VFF and FF. Excluding the first location, FF-based lump localization seems to supply more energy than VFF-based lump localization. Again, we tested this hypothesis by means of a right-

Table 1. Lump localization error statistics

	Lump location	1	2	3	4	5
Feedback mode						
VFF	Mean absolute position error (rad)	0.009	0.003	0.026	0.009	0.005
	Standard deviation of position errors	0.091	0.079	0.084	0.069	0.072
FF	Mean absolute position error (rad)	0.123	0.078	0.049	0.022	0.010
	Standard deviation of position errors	0.108	0.103	0.150	0.167	0.150

VFF, visual force feedback; FF, force feedback

tailed *t*-test ($p < 0.025$, $0.1 < p$, $0.1 < p$, $p < 0.025$, and $p < 0.05$ for lump locations 1 to 5, respectively). These results show that the mean of the energy supplied to tissue under VFF and FF varies significantly for lump locations 1, 4, and 5. A one-way ANOVA test for the energy yields $F(4,82) = 2.96$, $p < 0.05$ for VFF and $F(4,82) = 2.812$, $p < 0.05$ for FF, which indicate significant variations across the five lump locations for both VFF and FF.

Discussion

Our objective in this case study was to compare lump localization performance using a telemanipulated master–slave system between two different feedback modalities: haptic feedback and visual substitution for haptic feedback. The following trends were observed:

- The subjects were 100% successful in localizing the lumps under both VFF and FF, with position errors significantly less than half the average distance between the lumps. No consistent trend was observed in favor of either approach with respect to localization accuracy except for a weak tendency for better accuracy with VFF. Considering the lower system complexity required for implementing VFF, even an equivalent level of accuracy can be regarded as an advantage for VFF. However, with VFF, a user can perform well only if the sensitivity and resolution of the visual display is sufficiently high for small variations in the reflected force to become discernible.
- The exploration time for VFF is considerably longer than for FF. This observation is justifiable given the fact that with VFF, the subjects must refer constantly to the visual display to see the exerted force. Therefore, although the provision of visual feedback about instrument–tissue interaction is useful for the purpose of lump localization, the corresponding task times are longer because of the need for cognitive processing by the users. This conclusion is consistent with previous results for the teleoperation of nonsurgical tasks [19]. From the user's point of view, VFF's moderate need for human processing and interpretation, especially for dexterous tasks, in which the user must keep track of several visual indicators and switch his or her attention between them without getting distracted from the main surgical task, may be a major drawback, particularly for lengthy procedures (sensory overload).
- With regard to the energy supplied to the tissue by the user, the results are not consistently in favor of either VFF or FF. The higher levels of supplied energy under FF for two locations (out of five) seems to result from the fact that the localization ability under FF is proportional to the slave's velocity. In contrast, the slower the slave moves, the higher the localization ability will be under VFF.

Concluding remarks and future work

This report started by elaborating on the need for incorporating contact feedback into robot-assisted interventions. To this end, a haptics-enabled surgeon–robot interface and a sensorized surgical end-effector were developed that together form a master–slave teleoperator suitable for endoscopic surgery and therapy applications. The master–slave system was used as a test bed for studying the effect of contact feedback in the context of soft tissue applications. Using a four-channel haptic teleoperation control scheme, the transparency of the master–slave system was experimentally validated for a soft tissue palpation task.

Additionally, for a lump localization task, performance comparisons were made for situations in which visual feedback substituted for haptic feedback of contact information. It was observed that localization accuracy is comparable between VFF and FF, meaning that for cases in which a haptic user interface is not available, visual force feedback can adequately and cost effectively substitute for force feedback. However, this comes at the expense of longer task completion times for VFF.

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