ORIGINAL ARTICLE

Haptic interaction in robot-assisted endoscopic surgery: a sensorized end-effector

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Abstract
Conventional endoscopic surgery has some drawbacks that can be addressed by using robots. The robotic systems used for surgery are still in their infancy. A major deficiency is the lack of haptic feedback to the surgeon. In this paper, the benefits of haptic feedback in robot-assisted surgery are discussed. A novel robotic end-effector is then described that meets the requirements of endoscopic surgery and is sensorized for force/torque feedback. The endoscopic end-effector is capable of non-invasively measuring its interaction with tissue in all the degrees of freedom available during endoscopic manipulation. It is also capable of remotely actuating a tip and measuring its interaction with the environment without using any sensors on the jaws. The sensorized end-effector can be used as the last arm of a surgical robot to incorporate haptic feedback and/or to evaluate skills and learning curves of residents and surgeons in endoscopic surgery.

Keywords: Endoscopic surgery, robot-assisted surgery, endoscopic end-effector, force feedback, haptic perception, perceptual-motor skills

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INTRODUCTION
With endoscopic surgery, in which an endoscope and endoscopic instruments are inserted into the body cavity through small incisions, the trauma to the body, the postoperative pain and the length of hospital stay are reduced significantly compared to open surgery. However, endoscopic surgery has inherent drawbacks and pitfalls with respect to sensory and motor aspects, as discussed in the following section.

Limitations of endoscopic surgery
The following are some areas in which endoscopic surgery shows limitations:

Observation: The camera platform is unstable and vibrates because of the assistant's hand tremor, resulting in visual interruptions and possible motion sickness [(1)]. Hand-eye coordination is awkward and disorients the surgeon [(2)].

Ergonomics: The surgeon is not in a comfortable position and gets fatigued [(3)].

Manipulation: The surgeon's hand tremor is magnified by the long instruments, making it difficult to achieve fine manipulation of objects. The surgeon cannot rest their wrist on a surface to reduce tremors.

Dexterity: Because the endoscopic instrument pivots about an entry point, it has limited degrees of freedom, hampering fluid rotations of the surgeon's wrist and consequently the dexterity of the motion. This is especially significant when performing complex tasks such as suturing, in which case the surgeon is forced to extend the translational movements of the arm and forearm to compensate for the shortage of rotational degrees of freedom for the wrist [4].

Tactility/Kinesthesis: The surgeon cannot access the surgical field directly, thereby losing the tactile (cutaneous) perception resulting from direct touch. Also, the surgeon has a limited and distorted kinesthetic/force perception of the instrument and its interaction with tissue. The reasons for this are: (1) the cannulae through which instruments are inserted introduce friction, (2) the instrument pivoted at the entry point has a mechanical advantage that varies with the insertion depth, causing the instrument's interactions with the tissue and the hand to vary and be mismatched, and (3) the contact forces at the instrument tip can sometimes be negligible compared to the relatively large forces required to move the instrument mass and the unsupported hand and arm [5].

The need for robot-assisted surgery

Robots have found extensive use in "assisting" surgical interventions despite the challenges they create, for example, the possible collisions of different arms [6–9]. Using robots and computers to assist in endoscopic surgery is a step towards overcoming some of the difficulties mentioned above. For instance, in terms of visual steadiness, robotic camera holders can outperform human camera holders without compromising the operation time and even with cost savings [10, 11]. Moreover, robotic positioners can control the endoscope based entirely on the surgeon's facial motions and without verbal, hand or foot commands, paving the way for solo surgery [12].

Master-slave robotic surgery

The idea of performing surgery in a master-slave robotic mode, where the movements of a surgical robot (slave) are controlled via a surgeon's console (master), takes robot-assisted surgery into a new era in which robots are given a more significant role. Master-slave robotic operation can solve many of the problems encountered in conventional surgery in the following ways:

Ergonomics: The surgeon becomes less fatigued sitting at a comfortable and ergonomic console.

Manipulation: To improve manipulation precision and to make both hands equally dominant, motions of the hand can be scaled down and natural hand tremors can be filtered out.

Dexterity: The surgeon's dexterity can be improved by means of articulated wrist-like mini-robotic attachments at the end of the instruments [13].

Tactility/Kinesthesis: Any contact between the instrument and tissue can be reflected to the surgeon's hand by incorporating appropriate sensors and actuators at the patient side and the surgeon side respectively. The interaction forces can be scaled up prior to being reflected to the user, in order to make even the smallest contact perceivable to the unsupported hand.

Furthermore, robotic surgery can be done with the surgeon operating from a distant location [14].

State of the art

The currently available robotic surgical systems (the Zeus and the da Vinci systems, Intuitive Surgical Inc., USA, www.intuitivesurgical.com [1]) provide most of the above-mentioned benefits, but as yet they do not provide feedback of tactile/force (haptic) sensations that are so crucial for the surgeon. The significance of haptic feedback in master-slave operation (also referred to as "teleoperation") is discussed in the following section.

Significance of haptic perception in master-slave operation

Transparency of a master-slave system measures the extent to which a user feels as if they are directly interacting with the environment while actually performing a task in teleoperation mode. Transparency depends on how well the slave-environment interactions are reflected to the user's hand by the master console. Ideally, with haptic feedback in robotic surgery, the surgeon is unable to discriminate between moving the actual surgical instrument and manipulating the console.

General teleoperation

Studies on the effect of force feedback on various object manipulation and target acquisition tasks have revealed that force feedback helps the performance and efficiency of teleoperation by reducing the peak magnitude of contact forces (and trauma to the tissue in the case of surgery), the sum of squared forces and thus the energy consumption, the task completion time, and the number of errors [15–17]. Similarly, analysis of reach-to-grasp movements towards graphic objects in a virtual environment has demonstrated that haptic feedback about object contact can improve movement time and peak velocity (i.e., lower and higher respectively) [18]. According to Fitt's law [19], the movement time has a direct relationship with the index of difficulty of a motor task and, therefore, a shorter movement time means that haptic feedback has made the task more intuitive. Additionally, there is other literature on the importance of haptic feedback in user interfaces in the context of shortening task completion times and improving perceptional/motor capabilities of the human operator [20, 21].

Robotic surgery

Haptic perception, as crucial as it is for teleoperation in general, is even more important in performing surgical tasks. Haptic feedback can complement sensory modalities such as vision [22] and, therefore, can counterbalance the restricted camera vision in minimally invasive surgery. Haptic feedback can also affect the three main metrics of motor functioning (i.e., precision, speed and force [23]) during surgery as discussed next. With regard to precision, haptic feedback is very important in performing surgical tasks with complex kinematics [22] and can enhance precision when using instruments with limited manoeuvrability, as is the case in minimally invasive surgery. As for speed, lack of haptic feedback causes the surgeon to slow down their manoeuvres and wait for visual cues as to the strength of the grip, the softness of the tissue, etc., prolonging the operation and hampering the natural conduct of the operation.

A study of the effect of force feedback on performing blunt dissection [24] has shown that force feedback can reduce contact forces, task completion time and number of errors. Also, trials on a uni-manual suturing task in a virtual environment have shown that force feedback can reduce the peak force application and the stitch completion time and can improve the "straightness" of the stitch [25]. Moreover, in needle insertion tasks, the ability to detect the puncturing of different tissue layers is improved when users receive haptic feedback [26]. Palpation is another procedure frequently used by surgeons to estimate tissue characteristics and locate blood vessels. Without haptic perception and thereby palpation capability, excessive forces may be applied by the surgeon causing complications such as accidental puncturing of blood vessels or tissue damage [27, 28].

To restore the perception of forces, the surgical instrument needs to be sensorized to measure instrument/tissue interactions. Such an instrument (the end-effector), which is the subject of this paper, can be used with a surgical robot and a force-reflective console to incorporate force perception in robotic surgery. The applicability of the end-effector is discussed further in the following section.

Perceptual-motor skills study

The sensorized end-effector developed in this paper can also be used for research purposes, for example, to study the sensory and motor skills of residents and surgeons. In endoscopic manipulation, the reduced dexterity, the loss of tactile sensation and the significant degradation in force sensation result in new perceptual-motor relationships that are unfamiliar, challenging, and must be learned [29]. An endoscopic end-effector, which measures its interactions with tissue, can be used to objectively assess the skill levels and the learning curves of users. In fact, novice and experienced surgeons leave different force/torque and temporal statistical signatures while manipulating and dissecting tissue [30]. Therefore, the sensorized end-effector discussed in this paper can be used with a surgical robotic system as a training tool to help surgical residents learn how to best exert forces and torques on tissue in various surgical manoeuvres and correct any problem that may arise.

The required skills for endoscopic surgery take longer than normal to master. The prolonged learning period for perceptual-motor skills is partly due to the disrupted hand-eye coordination experienced during endoscopic manipulation as the perspective is not updated with the surgeon's head movements [31]. A study done in a virtual environment using Fitt's tapping task, in which subjects tap back and forth between two objects, concludes that force feedback can improve performance when the perspective is incorrect [32]. This suggests that force feedback may assist the surgeon's adaptation to an incorrect viewpoint through recalibration of the eye-to-hand mapping and, therefore, accelerate the learning process for endoscopic surgery.

METHODS, MATERIALS AND RESULTS

To provide the surgeon with force perception during robotic endoscopic surgery, the following two devices are needed at the patient and surgeon sides:

a) An endoscopic surgical instrument that acts as the last arm (end-effector) of the slave surgical robot and is properly sensorized to measure instrument/tissue interactions in the form of forces or torques.
b) A force-reflective interface that mediates between the surgeon and the robot, transferring hand movement commands to the robot and instrument/tissue interaction measurements to the surgeon's hand.

Our research concerns restoring force (and torque) feedback to the surgeon. Tactile feedback, which involves stimulation of cutaneous receptors to perceive mechanical, thermal and other cutaneous stimuli at the skin surface, is a much more difficult task. While some research is underway to develop tactile sensors for minimally invasive surgery [33], the lack of a human-robot interface that effectively displays cutaneous stimuli to the hand is a significant impediment. In this paper, we discuss a robotic endoscopic end-effector that measures any force/torque interaction it has through contact with its environment. In parallel, we are conducting research on a user interface with force/torque feedback capabilities that can be used in endoscopic manipulation [34].

Force reflection methods

In principle, force feedback in a master-slave system is possible even without force sensing at the slave side. In fact, a real-time control algorithm mutually minimizing the position/orientation error between the master and the slave manipulators can provide some force sensation to the user manipulating the master. This scheme, called position error based force reflection, accounts for an inferior teleoperation transparency as compared to force reflection using a force sensor at the slave side [35]. Additionally, the perception of forces is sluggish and delayed.

To explore the above comment further, we set up an experiment in which two PHANTOM haptic devices (SensAble Technologies Inc., www.sensable.com) act as the master and the slave, and are controlled using the position error based scheme. The setup was used to qualitatively examine whether the palpation of soft objects can be done effectively using this method of force reflection. Our experiments showed that due to the compliance of the low-stiffness object, the position error between the master and slave robots is small. Since the force reflected to the user is proportional to this position error, in order to have a perceivable force, the corresponding gain should be high. Indeed, if the gain is not high enough, the user may damage the tissue by incurring excessive deformation because insufficient forces are being transmitted to the user's hand. A high gain, however, causes some force to be reflected to the hand even when the slave robot is moving in free space due to any control inaccuracies. Therefore, with a tradeoff on the force feedback gain, the dynamic range of perceivable forces is limited.

The surgeon's console of the da Vinci surgical system has force feedback capability in some degrees of freedom. This force feedback, however, is of low quality and therefore has been disabled. The main reason is that no force sensing capability is present at the end-effector of the robot; instead the contact forces are estimated from outside the patient. The unwanted consequences of the estimation of contacts from outside the patient are picking up disturbance forces at the entry port, and biased and noisy force feedback.

Other techniques for master-slave force reflection share a common need for slave-environment force measurements [35, 36]. With such techniques and with an end-effector properly sensorized to measure all interactions it has with the tissue from inside the patient, the adverse effects of sensorless force feedback are excluded from the haptic teleoperation loop.

Design requirements

Developing a robotic end-effector that is sensorized and actuated in accordance with the requirements of endoscopic surgery involves some challenges. Due to the constraint on incision size in endoscopic surgery, the diameter of the portion of the end-effector that enters the body including all required sensors/actuators should be less than 10 mm. The following is a list of issues to be considered in designing a robotic endoscopic end-effector:

a) The available sensors that measure forces and torques in all six degrees of freedom (three translational and three rotational) are wider than

10 mm* and, therefore, cannot enter the body. Being located outside the patient causes the sensors to pick up unwanted abdominal wall friction and stiffness at the trocar site, causing distortions in the sensation of forces.

b) Due to the limited amount of space, the pivotal motions of the tip jaws (e.g. grasper jaws) need to be actuated by a linear motion from outside the patient. This also poses another challenge related to the previous requirement: if a force sensor is ever used, it must be hollow to accommodate the rod whose linear motions actuate the tip.

c) The sensor measuring the force applied by the tip's jaws on the tissue should not be mounted directly on the jaws because, for sterilizability reasons, it is desirable to use tips that can be detached and disposed of after use.

We tackle the first problem by non-invasive measurements of interactions using strain gauges that are integrated into the endoscopic end-effector. For the second and third requirements, a mechanism consisting of a linear motor and a load cell is used to remotely actuate a detachable tip and measure its interactions with tissue.

Twist and tip motions

Twist motion and free wrist

Regardless of the kinematic properties of a surgical robot, a mechanism for the roll motion (twist about the main axis) of the end-effector is needed. In Figure 1a, a geared motor/encoder combination responsible for twisting the instrument is placed at the base of the assembly. A free wrist (made by links L_1, L_2 and L_3 in Figure 1a) is attached to the roll motor and is built such that if the motor faces resistance while trying to rotate the instrument (and the tissue), the wrist will not twist into itself. This is simply because the axes of the motor and the joint connecting links L_1 and L_2 do not ever align in the workspace ($-90^\circ <$ yaw angle $< 90^\circ$). The reason for having the wrist is given in the Discussion section.

Tip actuation

The tools used in endoscopic surgery to grasp, cut, or dissect tissue have their jaws pivotally moved relative to one another by a linear motion actuator. For the end-effector developed here, the elements of the assembly for tip actuation (open/close motion) as well as two detachable scissors and grasper tips are shown in Figure 1b. There are three concentric tubes – outer, middle and inner. The inner tube is displaced with respect to the middle one by a linear motor (Zaber Technologies Inc., Canada, www.zaber.com), in order to control the tip jaws. The reason for having an additional outer tube is discussed in the Interaction Measurements section. Figures 1c and 1d show an exploded view of the overall end-effector and a sectional view of the tip actuation assembly.

Tip model

To control the jaw's angular position, it is necessary to find its relationship with the linear displacement that actuates it. The sketch of an atraumatic forceps tip (Fundus grasper 3211, Microline Inc., USA, www.microlineinc.com) is shown in Figure 2. Here, $\alpha = \theta + \alpha_0$ and the jaw angle θ can be found from the linear displacement x using the equation

$$\sin(\theta + \alpha_0) = \frac{L}{D - x} \qquad (1)$$

Tip model identification

The parameters α_0, L and D of equation (1) for the specified tool tip have to be found empirically. An experiment was set up in which the linear motor moved the tip to 30 positions (corresponding to the angle between the two jaws of the tip ranging from 0 to 63°) and the linear position x as well as the angle 2θ were registered. Then, a non-linear minimization (Gauss-Newton method) was used to find the values for α_0, L and D that best satisfied equation (1). The mean values for the resulting parameter estimates obtained using four trials are listed in Table 1. A consistency measure has been defined as the ratio of the standard deviation of the estimates to their mean value. Small consistency measures for the estimated parameters promise a good match with the actual values. The value of d was separately determined to be 22 mm.

Interaction measurements

Having obtained the position model (1) of the tip, we need to determine the force model. From

*A miniature force sensor that is 12.5 mm in diameter and is intended for measuring small contact forces at the tip of a microsurgical instrument is the subject of recent research [37]; however, it is only capable of measuring forces in three dimensions.

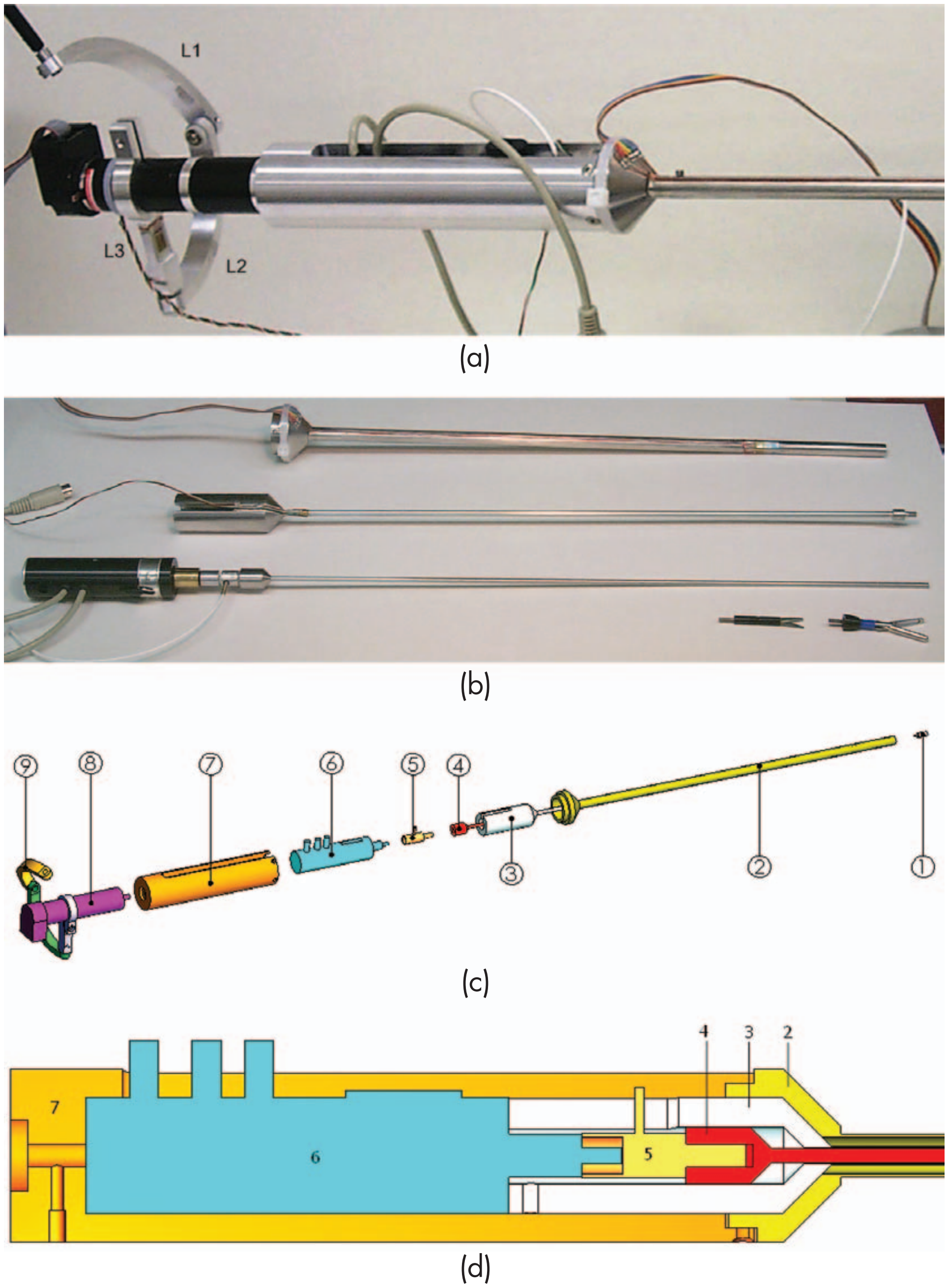


Figure 1 From top (a) The overall end-effector including the wrist, twist motor and tip actuation assembly, (b) details of the tip actuation assembly: the three tubes and two different detachable tips, (c) an exploded view of (a), and (d) a sectional view of (b). In (c) and (d): (1) tip, (2) outer tube, (3) middle tube, (4) inner tube, (5) load cell, (6) linear motor, (7) outer housing, (8) twist motor, and (9) free wrist.

Figure 2, the balance of moments about the pivot point leads to $F_j d = (F_m \sin\alpha)((D - x)\cos\alpha)$. Using equation (1) and $\alpha = \theta + \alpha_0$, the following force propagation model is obtained:

$$F_j = F_m \frac{L\cos(\theta + \alpha_0)}{d} \qquad (2)$$

Equation (2) demonstrates that it is possible to determine the force F_j, applied by the jaws on the tissue, based on the linear tension/compression F_m measurable by a single-axis load cell. Using the parameter estimates of Table 1, the nonlinear relationship between F_m/F_j and the jaw angle θ is depicted in Figure 3. A load cell was attached between the linear motor shaft and the inner tube (Figure 4a) to measure F_m so that equation (2) can be solved for F_j.

Possible manoeuvres of the instrument involve lateral and axial interactions at the distal end,

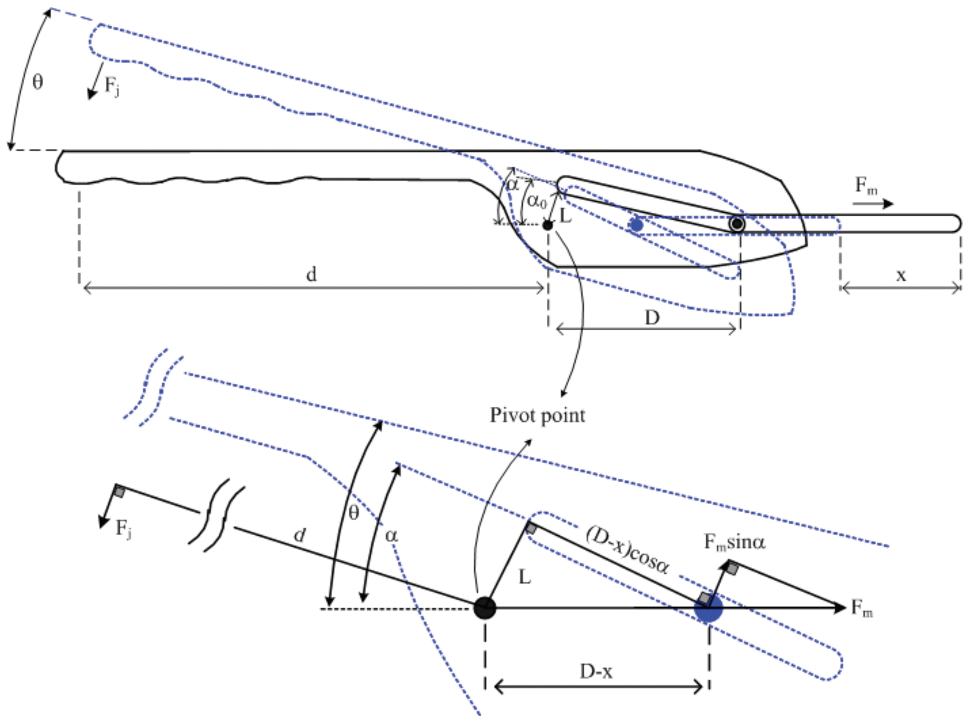


Figure 2 Surgical grasper mechanism and a close-up.

occurring when pushing or pulling on tissue, and torsional interactions that can happen, for example, during suturing. Assuming that the instrument axis is defined by z, the above interactions, i.e. the instrument endpoint forces (f_x f_y f_z) and the twist moment τ_z, can be determined from the measurements of all moments (τ_x τ_y τ_z) and the axial force f_z, provided that interactions only occur at the end point of the instrument. Several strain gauges are used to non-invasively measure all of these interactions with the tissue:

- Strain gauges are placed on opposite sides of the surface of the outer tube such that any lateral force at the endpoint causes tension in one strain gauge and compression in the other (Figure 4b). These full-bridged gauges register the two bending moments τ_x and τ_y.
- Compressional/tensional axial force f_z is registered by the full-bridged strain gauges placed on the opposite sides of link L_3 of the 2-dof wrist (Figure 4c). This wrist is responsible for the spherical motions of the end-effector centered at the entry point through the skin (see the Discussion section).
- The twist moment τ_z is measured by the torque gauge placed on the middle tube (Figure 4d) as the tip's outer body threads onto it.

Table 1 Grasper tip parameter estimates

	Mean	Standard deviation/Mean
α_0	25.15°	2.1 %
L	2.34 mm	3.9 %
D	5.91 mm	1.7 %

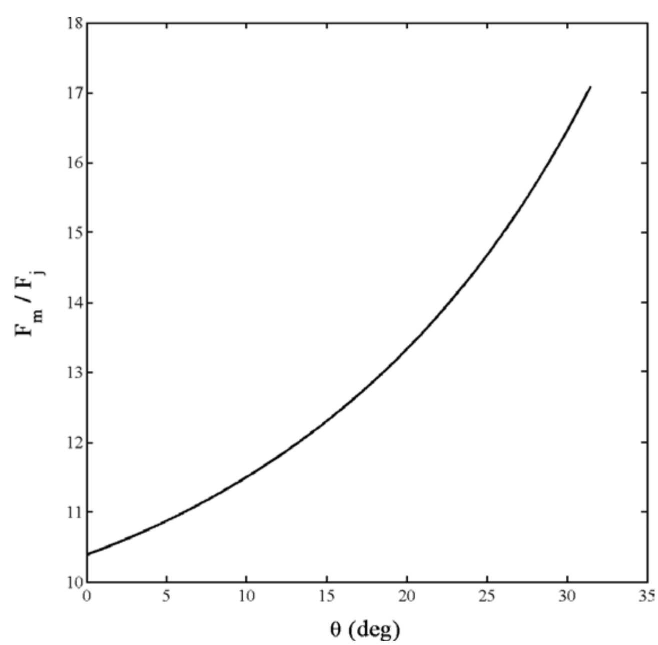


Figure 3 The ratio of axial and tip forces vs. the jaw angle.

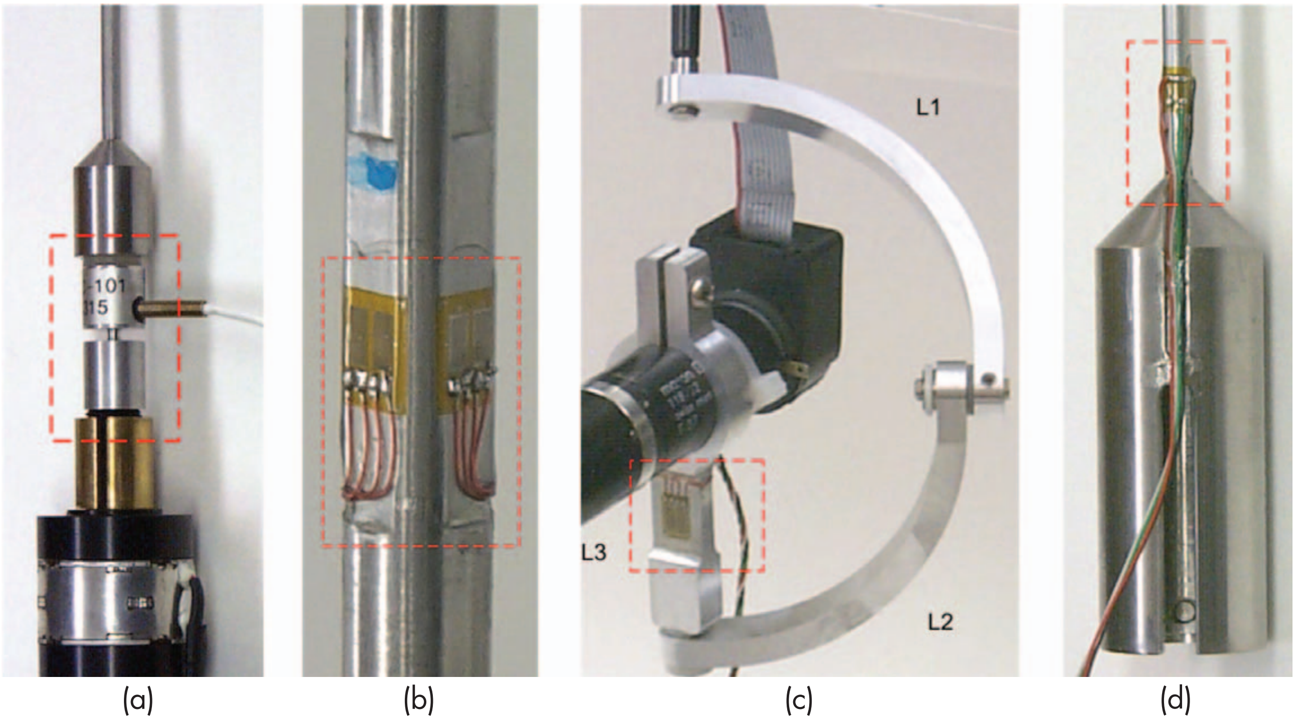


Figure 4 From left to right: (a) load cell to find the tip forces, (b) gauges to measure the bending moments, (c) gauges to measure the axial forces, and (d) gauge to measure the torsional moments.

Note that each of the above strain gauges is in a transverse arrangement with respect to others and, therefore, is sensitive only in the intended direction.

The reason for having three tubes in the end-effector assembly becomes clear here. This arrangement isolates the differential force that actuates the tip from the measurements in other directions. More specifically, the middle tube, which floats between the inner and outer tubes, prevents the differential inner tube/middle tube force from affecting the strain gauges mounted on the outer tube for measuring lateral forces.

Strain gauge calibration

The strain gauges are calibrated by finding the relationship between the output voltages and the forces/torques applied at the tool end-point. For example, to calibrate the axial force gauge shown in Figure 4c, different masses were attached to the assembly held in the vertical position and the resulting voltage readings were recorded. In this particular case, there is a no-load voltage present due to the weight of the motor. The least-squares method was used to find a line that best describes these data points in the voltage versus axial force plane. Table 2 shows the parameter estimates α and β in $V = \alpha f_z + \beta$ where V is the voltage readout and f_z is the axial compression or tension force. Figure 5 shows the data points for the four experiments where the assembly has been under tension and the linear fit is as shown in Table 2. The calibration of the other strain gauges is done in a similar manner.

Table 2 $V - f_z$ relationship parameter estimates

		Mean	Standard deviation/Mean
Compression	α	2.58×10^{-1}	5.5%
	β	-7.09×10^{-1}	8.1%
Tension	α	3.48×10^{-1}	4.5%
	β	-1.48×10^{-1}	31.8%

DISCUSSION

The endoscopic end-effector can be used with or without the free wrist (made by links L_1, L_2 and L_3 in Figure 1a) depending on the kinematic properties of the surgical robot. With the wrist, the end-effector can be used with any robot that provides positioning in 3D space and with a spherical-joint fulcrum placed at the trocar to form a constrained isocenter. The fulcrum supports the end-effector so that its movements do not damage the tissue near the trocar. Without the wrist, the end-effector should be used with a robot that provides spherical movement at a Remote Center of Motion (RCM) located at the entry point. As the motion sequence

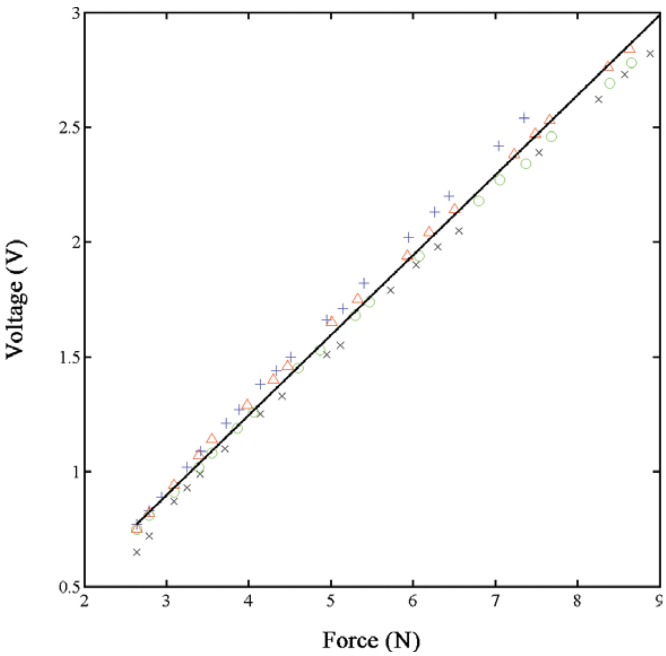


Figure 5 The experimental $V - f_z$ data points for the four experiments (plus, cross, triangle, circle) and the least-squares linear fit (solid line) during tension.

for the da Vinci robot shows (Figure 6), this manipulator simulates a spherical joint by providing two rotations and one translation (insertion) centered at a fixed point along the instrument (coincident with the entry point), such that the instrument tip can be positioned anywhere inside a cone. A summary of surgical robotic systems and their characteristics including the number of degrees of freedom and whether they provide an RCM is given by Taylor and Stoianovici [6].

When using the end-effector in a master-slave system, one issue to consider is how to use the tip's position and force models. In a handheld endoscopic instrument, there is a difference between the jaw's angular position (or force/torque interaction) and the handle's angular position (or force/torque interaction). For example, in a Carl Storz Babcock grasper instrument, there is a gain of 1.2 between the angular positions of the tip and the handpiece while the transfer function between the interactions is more involved [38]. In a robotic master-slave setting, where the surgical end-effector's tip is controlled by a handle at the surgeon's console, it is important to preserve the same tip/handle relationships to minimize the perceptual and motor mappings that an endoscopic surgeon would have to learn to perform robotic endoscopic surgery.

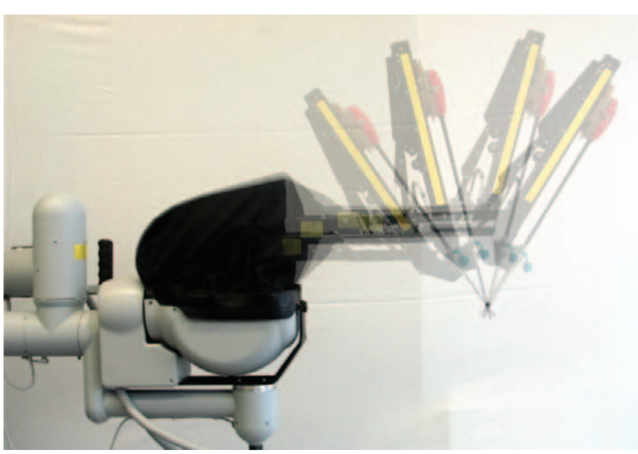


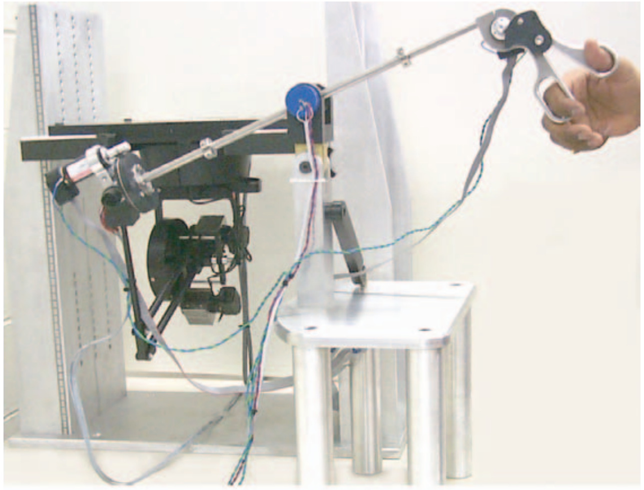
Figure 6 The remote center of motion (RCM) created by the da Vinci robot.

CONCLUDING REMARKS AND FUTURE DIRECTIONS

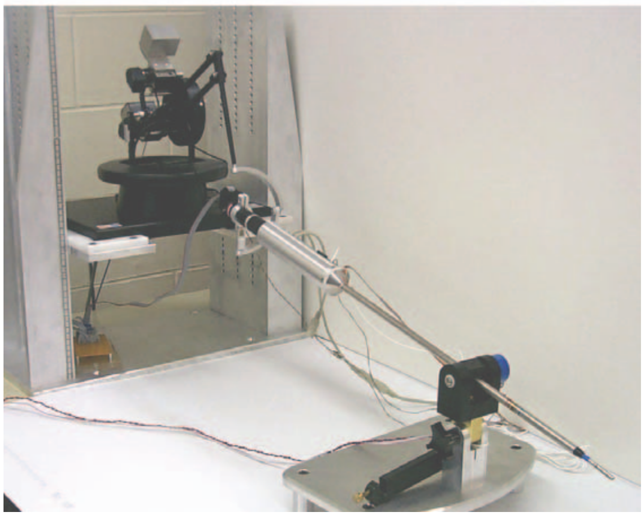
The incorporation of haptic feedback is a logical next stage for robotic surgical systems. It makes robotic surgery and therapy more efficient, accurate and reliable, and the surgeon's task more intuitive. The endoscopic robotic end-effector presented in this paper is capable of measuring tool/tissue interaction in all five degrees of freedom present in endoscopic operations (pitch, yaw, roll, insertion and grasping/cutting/dissecting). The three-stage instrument assembly and its strain gauge sensors provide a non-invasive, efficient solution to the problems posed by the incision size constraint in minimally invasive surgery. The end-effector features remote actuation of a tip and the measurement of tip interactions with tissue (grasping forces, etc.) without using sensors on the jaws.

The end-effector is capable of using disposable, detachable tips of all functionalities. Thin wires running from the strain gauges measuring lateral forces (Figure 4b) back to the base of the end-effector can be placed in the tiny groves made on the outer shaft surface and then covered by a sterilized coat, or they can run inside the instrument in the space between the outer and the middle tubes. All other wires are far from the tip of the instrument. Nevertheless, the sterilizability of the end-effector needs to be investigated more fully before it can be considered for use in clinical trials.

As part of our ongoing research, we have developed a robotic master-slave test bed to study haptics-based interaction in a minimally invasive environment (see Figure 7). A force-reflective



(a)



(b)

Figure 7 (a) Master subsystem and (b) slave subsystem.

master console (Figure 7a) capable of providing haptic feedback in all degrees of freedom available during endoscopic manipulation has been developed [34]. The sensorized end-effector and the free wrist discussed in this paper are used at the slave side (Figure 7b). The PHANTOM haptic device used on the slave side acts merely as a robotic manipulator. The user is able to manipulate the master causing the slave to execute a desired motion of the endoscopic instrument and at the same time receives haptic feedback via the master interface. The developed master-slave system is a useful test bed to investigate the performance and effectiveness of different master-slave control schemes. The Virtual Reality Peripheral Network (VRPN) [39] has been used to establish network-based communication between the master and slave subsystems so that the slave can be telemanipulated by the user sitting at the master console at a distant location. Therefore, the system is also useful in exploring the effects of communication latency on the stability and performance of the haptics-based master-slave system and finding techniques to compensate for time delay in a real-time, human-in-the-loop telemanipulation.

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