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Computerized Endoscopic Surgical Grasper

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Abstract. We report a computerized endoscopic surgical grasper with computer control and a force feedback (haptic) user interface. The system uses standard unmodified grasper shafts and tips. The device can control grasping forces either by direct surgeon control, via teleoperation, or under software control. In this paper, we test an automated palpation function in which the grasper measures mechanical properties of the grasped tissue by applying a programmed series of squeezes. Experimental results show the ability to discriminate between the normal tissues of small bowel, lung, spleen, liver, colon, and stomach. We anticipate applications in telesurgery, clinical endoscopic surgery, surgical training, and research.

1. Introduction

As endoscopic procedures have rapidly grown in volume, surgeons have lost the ability to palpate tissues and organs. The corresponding diagnostic information is lost. Two components of this palpation information are tactile and kinesthetic information. Their combined use is referred to as haptic perception. Early work explored automated palpation with an external robot (1). Tactile sensors have been applied to endoscopic graspers which are coupled to tactile displays (2, 3). These systems aim to enable the surgeon to discriminate textural or time varying features of the patient via endoscopic tools. Morimoto et al., (4) have described an instrumented Babcock grasper which measured forces and torques at the tool-tissue interaction point, but did not measure or control grasping force.

The importance of haptic feedback to safe performance of surgery cannot be overstated. Although color, texture, and visible aspects of tissue deformation in the surgical field convey important anatomic information, palpation is critical to identifying otherwise obscure tissue planes, arterial pulsations, and regions of tissue thickening that may signify pathology such as infection or cancer. Safe tissue handling requires tissue manipulation that is both secure and nondamaging to the tissues. Much of the art of surgery and the implicit learning curve for traditional surgical technique depend on training to refine and educate the sense of

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touch. Training for endoscopic surgery is even more difficult because of the remote nature of videoendoscopic tissue manipulation. Indeed, recent literature emphasizes the importance of tactile feedback for accurate targeting of primary (5, 6, 7) and metastatic cancer (8, 9, 10, 11) and identifying therapeutic margins for curative resection (6, 12, 13). The loss of palpation for localization may seriously limit the efficacy and safety of minimally invasive treatment in some operative fields (11).

1.1. Purpose

This project aims to develop and characterize a grasper capable of restoring a degree of kinesthetic information to the surgeon about the tissue being grasped. The following goals were laid out:

1) Improve the ability of the endoscopic surgeon to feel mechanical properties of tissues such as compliance.

2) Make minimal changes to the form and function of existing surgical graspers to reduce cost, complexity, and certification difficulties. Avoid adding sensors and wiring to the tool tip.

3) Take advantage of the declining cost of computer control.

Our system is designed to support both manual and automatic palpation. For reasons of space, this report will describe mainly the automatic function.

2. Methods

The present grasper (Fig. 1) is a re-design of the handle end of an existing stainless steel, reusable, interchangeable grasper. The tool head consists of the tool shaft mount, electro-

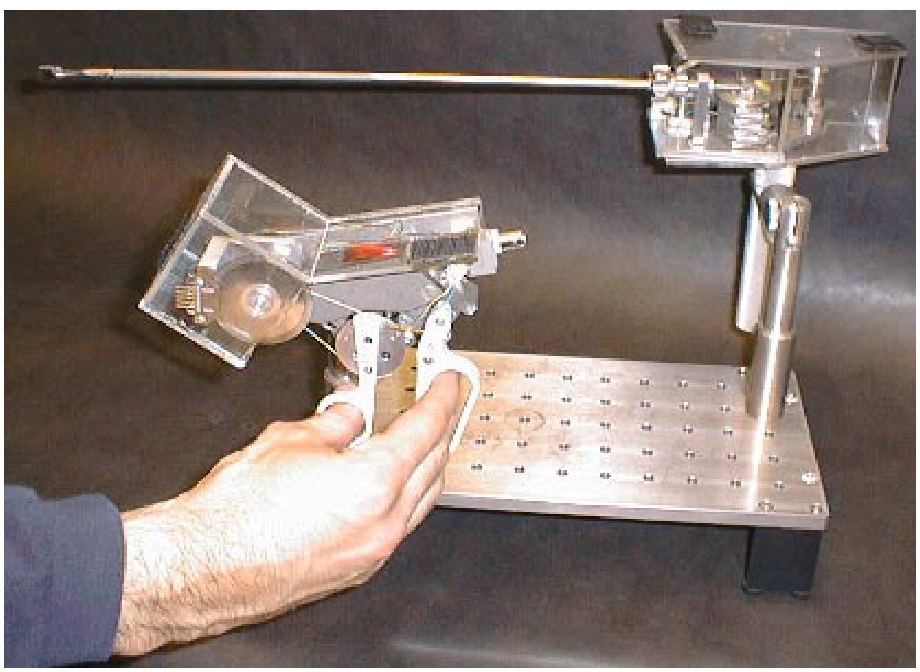

Figure 1. Photo of the current design of the computer controlled endoscopic grasper mounted on its storage base.

magnetic actuator (see below), and an optical encoder position transducer. These elements are mounted on a handle for the surgeon which can be attached and detached from a base. Also on the base is a separate user interface consisting of finger loops taken from another grasper. The distal finger loop is connected to an actuator/encoder pair identical to those on the tool shaft. To increase sensing resolution, the encoder wheels are connected to the actuation axes via pulleys and a kevlar drive belt having a multiplication ratio of 1:3.6. As a consequence, both master and slave have 1400 quadrature position counts over the full 0.6 radian (34.4 degrees) motion range.

The actuators are flat coil actuators modified from hard disk drive head positioning actuators. In an earlier prototype, the actuators were taken directly from 5.25 inch (133mm) hard drives. Hard disk drive head actuators have many advantages for precision robotics and force feedback devices (15). However in this application, the actuators' maximum torque of 0.1NM at 2.0 amps (based on steady state coil temperature of 93 deg. C) did not produce convincing subjective grasping sensations. The actuator magnets were replaced with custom made Nd-Fe-B magnets having approximately triple the energy product of the AlNiCo magnets used in the disk drive actuator (14). The coil and bearing assembly was retained. To realize the full flux increase from the new magnets, we built new frames from high permeability iron to prevent backing iron saturation. The new actuator magnets and frames increased the torque output to 0.3 NM but preserved the desirable qualities of low torque ripple, low friction, and low backdriving inertia.

The laparoscopic instrument used in these experiments is a stainless steel atraumatic Babcock grasper (Carl Storz Inc., model # 30420 BL) with a square jaw grasping surface area measuring 9 x 9 mm. The tool shaft is 5 mm in diameter and 38 cm long from the proximal attachment to the instrument tip. The shaft and mount allow 360 degree rotation of the tool about its long axis. The proximal end of the instrument shaft is clamped to a supporting post on the slave handle. The push rod operating the jaws is linked to the electromagnetic actuator via a ball and socket joint. This system allows easy change of shaft length, diameter, and tool tip conformations. Laparoscopic tools compatible with the mounting system are readily available from various manufacturers.

3. Control

The control system supports both bi-lateral force reflecting teleoperation of the grasper jaws, and programmed automatic operation for tissue characterization. Proportional-derivative (PD) controllers were designed for both the master and slave using a linear dynamic model of the device and conventional control techniques (16). Integral feedback is not desirable in position error based force feedback control because it creates a time varying force feedback under conditions of steady state contact.

The force feedback controller is based on the well known bi-lateral, position error based, teleoperation system (17). In this design, the measured position of each side serves as the reference position input for the other.

A desirable quality of force feedback systems is a high effective stiffness between master and slave sides. In the position error based architecture, this requirement can be translated into the need for a high value of the proportional feedback gain, Kp (18). An additional controller design constraint is introduced from the actuator limit of 0.3NM maximum torque. Experience shows that users feel a subjective loss of contact sensations when a force feedback device saturates at its maximum force output. There is thus a trade-off between Kp and the deflection at which saturation occurs. For high values of Kp, the user will feel high effective stiffness, but saturation will occur at relatively smaller position errors. We set the position error corresponding to the saturation point at one quarter of the motion travel range which in turn sets

$$K_P = \frac{Imax}{0.16rad} = 12.6 \tag{1}$$

The remaining parameter Kd was determined by placing the dominant closed loop pole for an 8 ms settling time constant and a damping ratio of 0.5. For the slave, this design method resulted in an unstable controller, possibly because of backlash in its mechanism. An acceptable controller was recomputed with a lower initial Kp value.The resulting gains are given in Table 1.

Table 1: Controller Parameters

	$K_P\left(\frac{NM}{rad}\right)$	$K_d\left(\frac{NM\sec}{rad}\right)$
Master	12.6	0.05
Slave	9.6	0.04

3.1. Automatic Palpation Mode

Because the grasper is computer controlled, the possibility exists to create automated grasping and palpation functions in software. This could be used for automating surgical functions such as grasping with a pre-set force level, or for quantitative, automated palpation in which the deflection and force measurements are analyzed to extract information about tissue mechanical properties. Our initial experiments were designed to evaluate the information which can be obtained by driving the slave position controller with a sinusoidal displacement command while recording position, position error, and torque command. Other testing modes will be evaluated in future work such as applying a torque command and recording displacement. In the experiments reported here, three cycles of a 1 Hz sinusoidal displacement were applied as the desired position input to the slave controller. The amplitude of the sinusoid corresponded to full opening and closing of the jaws (0.6 rad).

Full analysis of the solid mechanics of the Babcock grasper interacting with organ tissue is beyond the scope of this paper, but compared to other types of surgical grasping instruments, the geometry of the Babcock tool suggests that it creates a relatively uniform stress distribution under the contact sites. In a future report (19) we will describe the analysis method in more detail.

Torque vs. displacement data were first isolated in time to the segment involving initial contact and compressive displacement. Next, considering the grasper mechanism, and a modified version of the theory proposed by Fung (20) for viscoelastic material, the torque-displacement data measured at the handle were transformed to the uniaxial compression stress-length ratio. Then, the stress-length ratio data were fitted, using the Least-Square method, with Eqn. 2.

$$\sigma = -\beta\,(e^{\alpha(1-\lambda)} - 1) \qquad (2)$$

$$\sigma = \frac{F}{A} \qquad (3)$$

$$\lambda = \frac{L}{L_0} \qquad (4)$$

where: α and β are parameters, λ is the compression length ratio, σ the uniaxial compression stress [Pa], A the compression cross section area $[m^2]$, L the Length of the material compressed by the load [m]. L_0 is the length of the material at zero load [m], and F is the compression force applied by grasper tip [N]. The resulting parameters α and β are features of the tissue as computed from the graspers measurements. Generally speaking, higher values of α and β describe "stiffer" tissues.

Protocols for anesthetic management, euthanasia, and survival procedures were reviewed and approved by the Animal Care Committee of the University of Washington and the Animal Use Review Division of the U. S Army Veterinary Corps.

In addition to pig tissues, five different latex materials were examined. For the purpose of further discussion they were designated MAT1, MAT2, MAT3, MAT4, MAT5. All the latex materials were shaped in the same cylindrical form with a diameter of 13 mm and a length of 45 mm. The above designation was referred to each material by a subjective estimation of its stiffness where MAT1 is the softest material and MAT5 is the stiffest material. MAT1 to MAT4 can be considered viscoelastic materials representing artificial replication of soft tissues while MAT5 can be defined as a solid which exhibits the upper limit of physiological stiffness and can simulate the bone tissue.

4. Results

To analyze the data recorded by the automatic palpation function, the stress-length ratio curves for the compression phase of each material squeeze (tissues and latex) were fit with the exponential function (Eqn. 2) using the least squares method.

Most of the recorded data were well fit by (Eqn. 2). The quality of the numerical fit was verified by using the correlation ratio factor, R^2. The computed R^2 values were typically very close to one ($R^2 > 0.999$), indicating very high quality of fit between (Eqn. 2) and the experimental data. Two exceptions with relatively lower R^2 values ($R^2 > 0.99$) were the colon tissue and the stomach. Those tissues exhibited different type of compression characteristics especially at lower compression length ratios.

Since the software generated three squeeze/open cycles, there were three squeezes recorded 1 second apart for each grasp. Tissues typically got stiffer in the second and third squeezes of each sequence.

Scatter plots were made of the α and β parameters for the pig tissue and latex material (Fig 2). Data formed into clusters. Each cluster consists of nine data points. Rectangles defined by the univariate standard deviations computed from the organ data clusters did not overlap except for lung and spleen. These variances are partly due to the stiffening of tissues under repeated compression as described above.

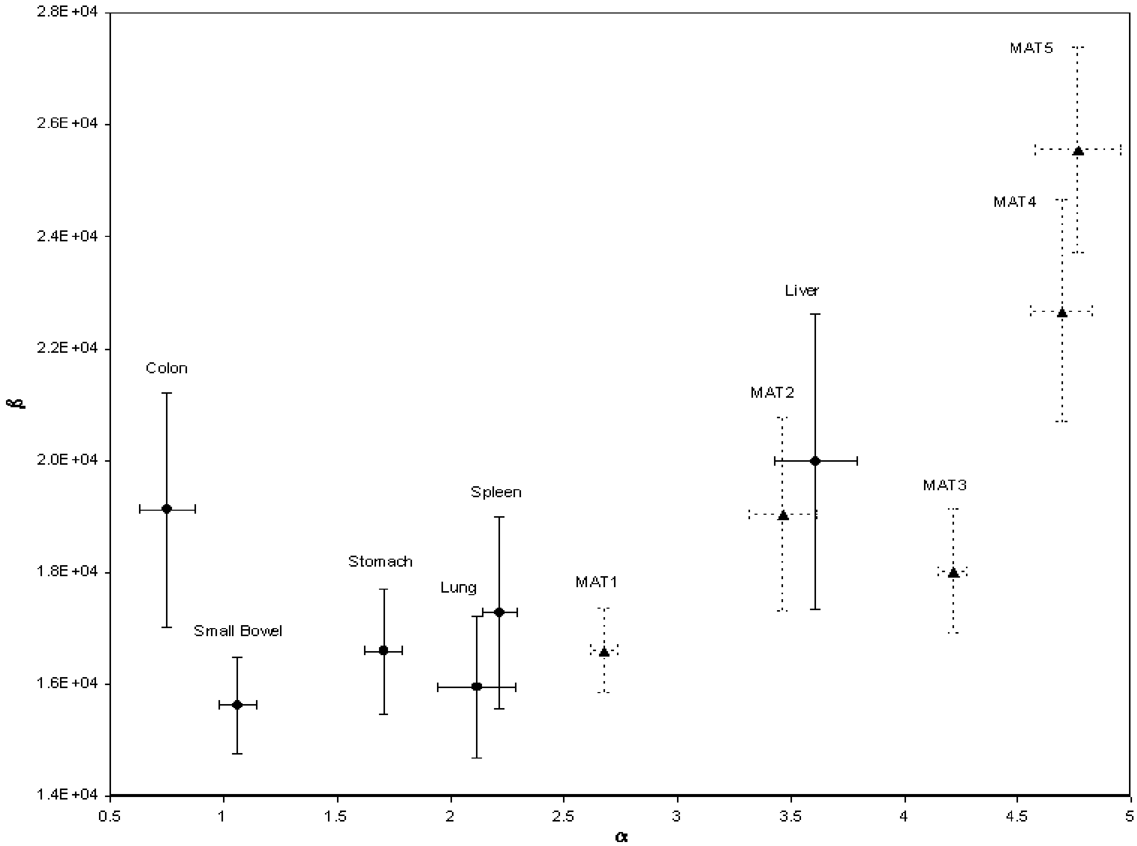

Figure 2. Scatter plot of the curve fitting parameters (Alpha, Beta) for different pig tissues (solid) and latex materials (dashed).

5. Conclusions and Discussion

We have reported a modified surgical grasper capable of controlling the force or displacement of jaw opening with interchangeable tools. To minimize cost and complexity, the system works with existing interchangeable re-usable tools. The controller was designed to maximize position control gain while preserving stability under unloaded conditions.

Initial tests revealed promising performance in the ability to reliably distinguish different tissue mechanical properties in the automated mode. In the future, we plan to measure its ability to distinguish pathological tissue from normal. An additional benefit to this project is an improved ability to characterize artificial materials for use in disposable organ simulators for surgical training. For example, Figure 2 indicates that “MAT2” might be a suitable material for simulating liver.

In additional preliminary experiments, beyond the scope of this paper, surgeons were able to distinguish the same tissues using the instrument in the teleoperated mode. A future study will quantify this ability in detail.

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