Force-Feedback Grasper Helps Restore Sense of Touch in Minimally Invasive Surgery

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The age of minimally invasive surgery has brought forth astounding changes in the health care field. Less pain and quicker patient recovery have been demonstrated with several types of operations that were once performed by an open technique. With these changes have come reports of complications. The decreased sense of touch is just one of several limitations inherent to current techniques of minimally invasive surgery that limit detection of subtle or unapparent lesions on palpation, such as common duct stones and liver lesions. The purpose of this study is to demonstrate the ability of a force-feedback–equipped grasper to restore some of the sense of touch that is lost in minimally invasive surgery. To demonstrate this ability, we created six silicone phantoms of identical dimensions but graded compliance, and asked 10 subjects to place them in increasing/decreasing order of compliance. They used three tools (their dominant gloved hand, a standard laparoscopic Babcock grasper, and our force-feedback device fitted with the identical Babcock grasper) to rate the compliance of the samples in a blinded fashion. These conditions thus approximated the conditions of open surgery, minimally invasive surgery, and minimally invasive surgery fitted with a force-sensing device, in terms of palpating tissues. Five surgeons skilled in minimally invasive surgery and five nonsurgeons participated in the study. The results indicate that the force-feedback device is significantly ($P < 0.05$) better than a standard Babcock grasper at rating tissue compliance, but was not as successful as a gloved hand (mean of squared errors = 1.06, 3.15, and 0.25, respectively). There was no significant difference between surgeons and nonsurgeons in rating compliance. We conclude that this force-feedback instrument is able to partially restore the sense of touch in minimally invasive surgery. This restored ability may thus potentially result in more efficient operations with improved diagnostic capabilities and fewer complications during minimally invasive surgery. (J Gastrointest Surg 1999;3:278-285.)

Key words: Haptic, surgical simulation, force feedback, touch

The current age of minimally invasive surgery has brought forth astounding changes in the health care system. Patients have benefited by faster recovery,[1-4] less patient discomfort,[5,6] and improved cosmesis because of the smaller incisions. Insurance companies and employers alike have also benefited by way of shorter hospital stays[7-9] resulting in lower hospital charges[10,11] and a quicker return to work.[12] Unfortunately this new technology has also been accompanied by reports of endoscopic complications such as gastrointestinal and colon perforation, as well as injuries to other organs.[13] In addition, some diagnostic information may be lost when endoscopic surgery is performed[14] because of the inability of the surgeon to feel the tissues with the hand. This may result in underestimated or unrecognized tissue inflammation or inability to detect solid and hollow organ masses. The preceding disadvantages of minimally invasive surgery are a result (at least in part) of the need to use long instruments that leave the surgeon at a mechanical disadvantage in terms of the haptic interface or sense of touch. Other investigators have proposed ways to improve the haptic feedback in minimally invasive surgery by incorporating a sleeve,[14] which allows passage of the hand into the abdomen, but this requires a larger incision, thus partly defeating the purpose of minimally invasive surgery. Visual cues can supply information on tissue deformation and com-

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pliance,[15,16] but the information is highly subjective and incomplete.

To address the deficit of haptic feedback during minimally invasive surgery, we have designed and tested an endoscopic grasper with force-feedback capabilities,[17] to improve the sense of touch in minimally invasive surgery. This prototype instrument is our initial attempt to enhance the sense of touch during minimally invasive surgery.

MATERIAL AND METHODS

Computerized Grasper Design

The grasper design utilizes "master" and "slave" components, which are linked by a computer interface. The master component is manipulated by the surgeon through a standard set of endoscopic finger loops. By this movement the surgeon determines the corresponding position of the instrument tool tip on the slave component. The driving force to move the tool tip is an electromagnetic coil actuator on the slave. The position of the tool tip and finger loops is measured by identical optical encoder position sensors on the master and slave. Thus, as the surgeon manipulates the finger loops on the master, the position is measured by the master position sensor. This position is then transferred via the computer interface to the slave position sensor, and the slave actuator then moves the tool tip to the corresponding position of the finger loops. The force-feedback capability (haptic interface or sense of touch) of this device is produced by a second and identical actuator on the master which is linked to the finger loops. Therefore as the slave actuator creates a force to move the tool tip and compress whatever is in the tool tip, the identical force is generated in the master actuator, which is linked to the surgeon's hand by means of the finger loops. This constant and simultaneous interplay of position and force between the master and slave is outlined in Fig. 1.

The computer interface allows transmission of signals of position and force between the master and slave. In addition, it also allows real-time display and recording of force and position data, and thus allows one to measure how much force is required to displace a tissue a given distance. The computer interface also has the capability to perform a task with the slave in an automated preprogrammed manner (no involvement of master) or in a bimanual mode (response of the slave is controlled by the action of the master). The force-feedback mode is the bimanual mode. More technical aspects of the grasper system have been described in detail previously.[17]

The tool tip used throughout the experiments consisted of a nondisposable endoscopic Babcock grasper tip and shaft with a tool tip surface area of 9 × 9 mm. The prototype is displayed in Figs. 2 and 3.

Creation and Objective Testing of Silicone Phantoms

Six silicone phantoms of uniform shape and color (15 mm diameter × 150 mm length cylinders) but of varying compliance (Fig. 4) were custom manufactured by a local private company (Simulab Inc., Seattle, Wash.). The compliance of the materials was altered by varying the percentage by weight of the catalyst during manufacture of the phantoms. To ob-

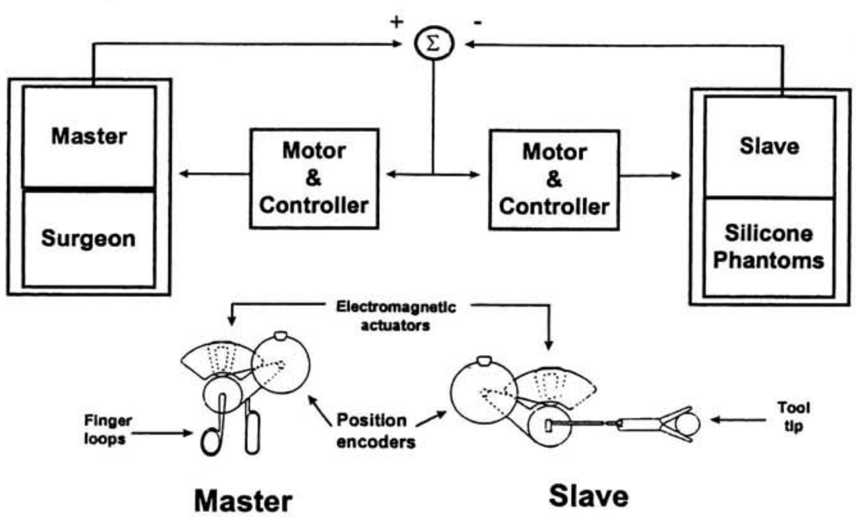

Fig. 1. Flow diagram for interaction of master and slave components of the grasper system. Optical encoder position sensors and electromagnetic actuators are identical on the master and slave components.

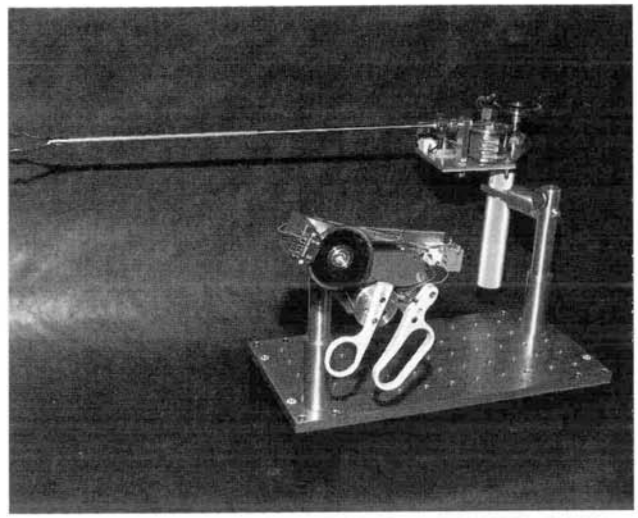

Fig. 2. Master and slave components of the computerized grasper. Both parts can be detached from the metal base as needed.

A B C D

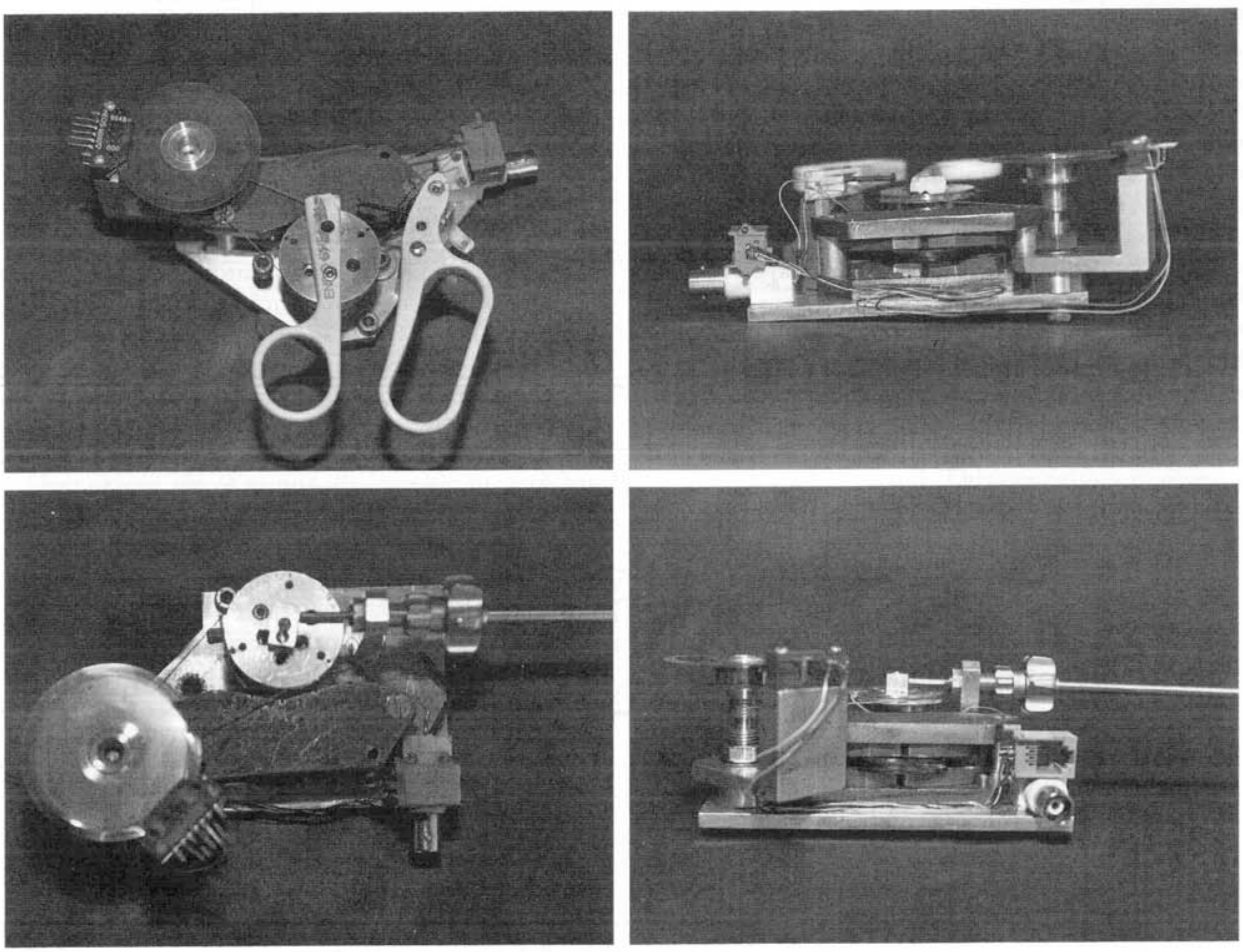

Fig. 3. Detailed views of the master (**A** and **B**) and slave (**C** and **D**) components. Each component contains an actuator and position sensor.

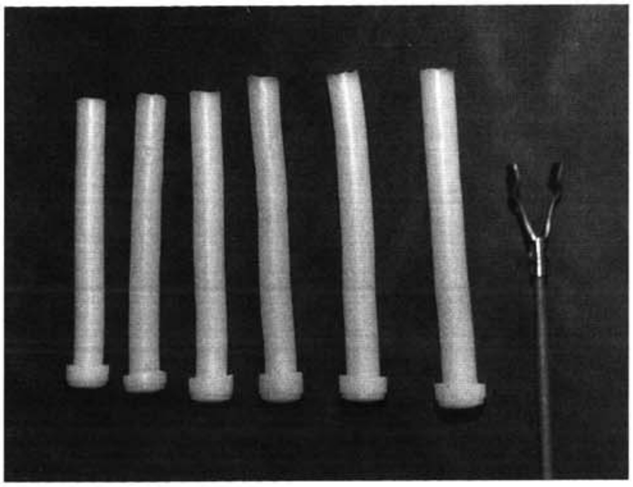

Fig. 4. Photograph of the six silicone phantoms of graded compliance. Dimensions are identical for each of the six phantoms.

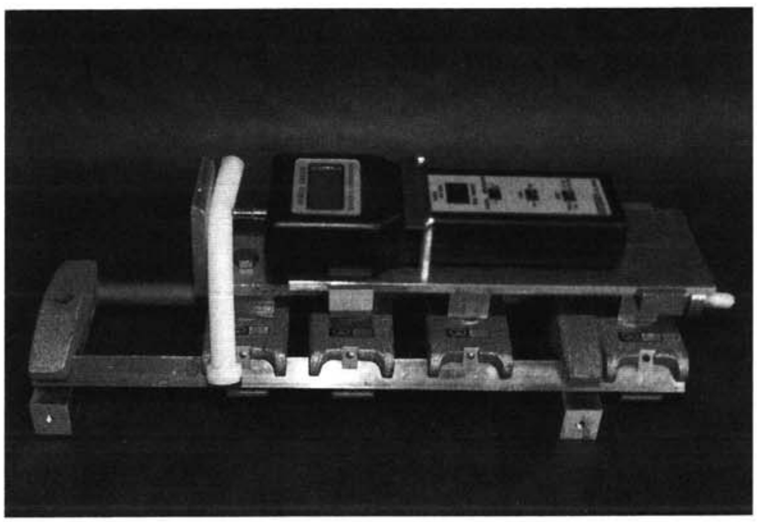

Fig. 5. Device used to carry out objective stress/compression studies of the six silicone phantoms.

tain an objective measure of the compliance ratings, the phantoms were subjected to stress/compression testing. This was performed by sequentially compressing each phantom in increments of 1.1 mm over a total distance of 9.9 mm using a device that held and compressed the materials. We measured the force required to compress the materials by means of a force meter attached to the compression device (Fig. 5). Testing was performed three times on each silicone phantom. The data were used to construct stress/compression curves for each phantom (Fig. 6).

Subjective Compliance Rating of Silicone Phantoms

To test for possible improvement in haptic feedback by the force-feedback grasper compared to a standard laparoscopic instrument, we performed experiments as outlined below. Ten subjects (five experienced laparoscopic surgeons and five electrical engineers with experience in haptic technology) performed palpation experiments on the six silicone phantoms. Subjects were asked to place the phantoms in the correct order of increasing or decreasing compliance. This was performed a total of four times for each palpation tool used. The three tools for palpation included a dominant surgical gloved hand (simulating open surgery palpation), a standard 10 mm nondisposable laparoscopic Babcock grasper (simulating endoscopic surgical palpation), and an identical Babcock grasper tip fitted to our force-feedback device in the bimanual mode (simulating possibly improved endoscopic surgical palpation). Subjects were allowed a 3-minute unblinded practice period for each

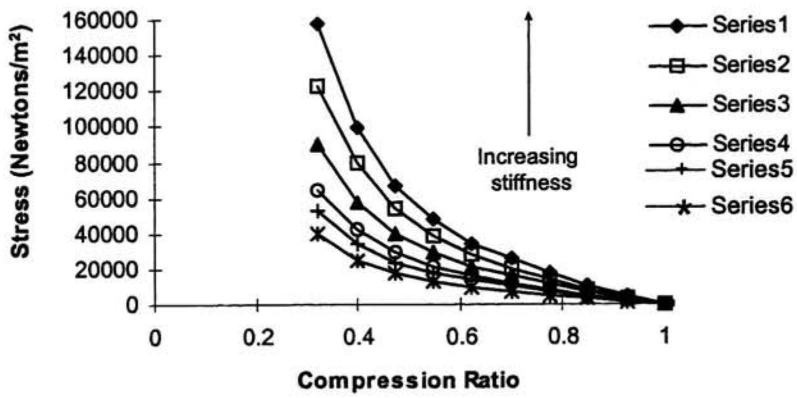

Fig. 6. Stress/compression ratios for each of the six silicone phantoms. Standard deviations (not shown) indicate minimal to no overlap, even at the low end of the compression ratio, although this is not appreciated on the graph secondary to the large y-scale.

of the three tools so they could become aquainted with the palpation of the phantoms. The phantoms were presented to the subjects in random order, and the order was changed on each presentation. The phantoms were assigned a number of 1 through 6 (1 = hardest, 6 = softest) based on the preceding objective compliance testing. Subjects attempted to choose the correct order. The difference of the chosen order (subjective) from the known order (objective) was then squared to give a positive integer for each choice. Each squared value was summed, and the total divided by six (6 phantoms) to yield the mean squared error. Testing resulted in a total of 12 rounds of compliance ratings for each of the six phantoms for each subject (a possibility of 72 errors in compliance rating for each subject and 720 possible errors for the 10 subjects). Although the tool type obviously could not be blinded, the subjects were not allowed to visualize any interaction of the tool type/phantom interface. Likewise the subjects were not allowed to visualize any part of the three tools or phantoms during the experiments; thus visual cues were eliminated in their subjective evaluation of phantom compliance.

Data Analysis

Objective stress/compression ratio curves were generated from 36 data points for each silicone phantom after graduated compression. A best curve fit using Matlab (The MathWorks, Inc., Natick, Mass.) was used to construct the stress/compression curves.

Subjective compliance ratings of the six silicone phantoms by 10 subjects were scored as the mean of the squared difference (error) of the subjective order from the known correct order as described previously. Results were analyzed with a two-tailed t test with significance reported as a P value of ≤ 0.05.

RESULTS

Data points for the six different silicone phantoms generated from compression of the samples were fitted to the stress/compression curves as illustrated in Fig. 6. Increasing stress is applied to the samples (y-axis) in to produce a given compression ratio. Series 1 is thus the hardest material (least compliance) and series 6 is the softest silicone phantom (greatest compliance). This serves as the basis for comparing the subjective rating of the silicone phantoms by the 10 subjects to the correct order of varying compliance.

Fig. 7 depicts the mean of the squared errors of the subjective order of compliance (compared to the known order) for surgeons and nonsurgeons for each of the three tool types. Although the nonsurgeons (electrical engineers with extensive experience in haptic technology) appeared to have fewer errors in determining the correct order (lower error score) than the surgeons, this difference was not significant ($P > 0.05$).

Fig. 7 shows pooled data from both groups (n = 10 subjects, surgeons and nonsurgeons) on the subjective rating of sample compliance. The force-feedback Babcock grasper yielded improved force feedback when compared with the standard nondisposable Babcock grasper ($P \leq 0.05$) with a tool tip of identical mechanics and surface area. The human hand was significantly better ($P \leq 0.05$) than the other two in determining the correct order of sample compliance.

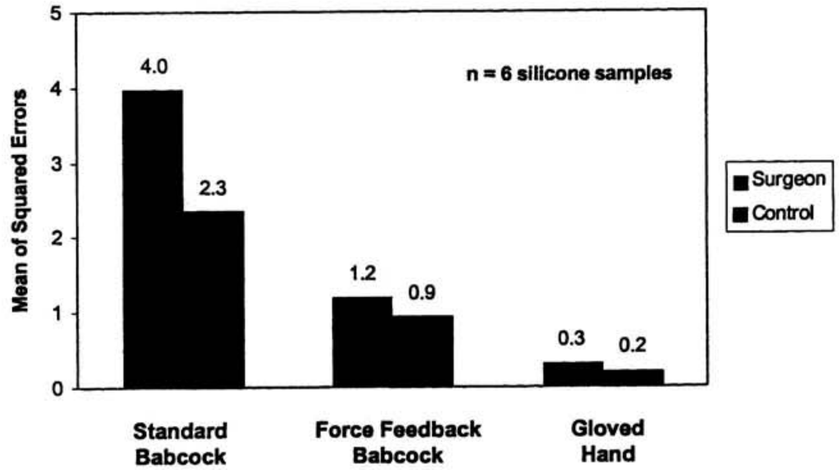

Fig. 7. Palpation experiments of six silicone phantoms by surgeons and nonsurgeons *(control)*. Three different tools (standard laparoscopic Babcock grasper, force-feedback Babcock grasper, and gloved hand) were used. No significant difference is observed between the two (surgeon and nonsurgeon) groups.

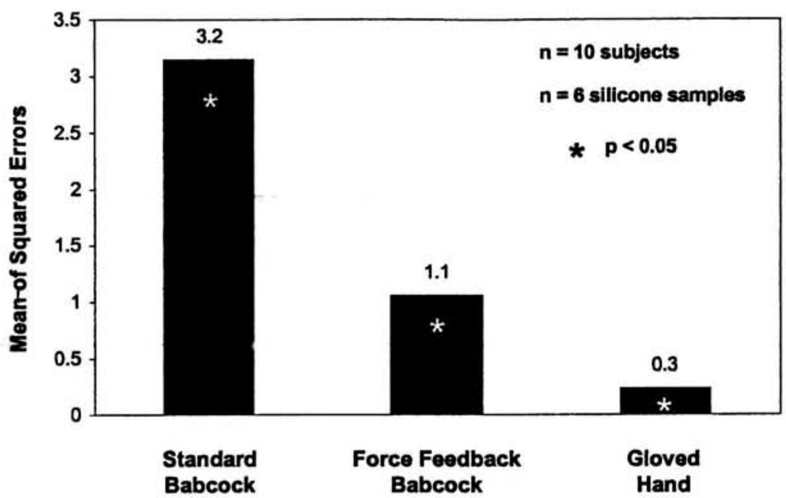

Fig. 8. Silicone phantom palpation error scores. Pooled data (surgeon and nonsurgeon) from palpation experiments on the six silicone phantoms. Significant differences are observed based on the palpation tool used.

DISCUSSION

Endoscopic-based operations continue to expand into new areas of surgery. Operations that were once thought possible to complete only by means of an open approach are now being performed commonly via an endoscopic approach.[18] In order for an endoscopic approach to surgery to be beneficial, it must also be safe. Although most endoscopic surgery proceeds without incident, there are reports of injury to organs resulting in significant complications.[13] Surgeons need to rely on visual cues to compensate for lack of depth perception and poor haptic feedback secondary to reliance on long instruments to perform the operation.

To potentially improve the force feedback during endoscopic surgery, we have designed and tested a prototype surgical endoscopic instrument that has the advantage of easy tool tip interchangeability with existing marketed tool tips. Although the prototype design is bulky, the intracavitary portion of the tool is identical to that of conventional endoscopic instruments.

As depicted in Fig. 8, the human hand is superior to both the force-feedback Babcock instrument and the standard Babcock endoscopic grasper at determining the correct order of silicone phantom compliance. This is not surprising given the fact that the human hand is a highly complex diagnostic tool and has multiple haptic properties (sense of position, proprioception, temperature, texture sensation). What is surprising is the degree of haptic sensation improvement of the force-feedback Babcock vs. the standard Babcock grasper. Although the time to complete each rating of the six samples was not measured, there was a noticeable time difference to complete each subjective rating by all subjects (human hand, force feedback grasper, standard grasper with increasing time requirements, respectively). This further underscores the differences in difficulty in determining the correct order of phantom compliance for each tool type.

The premise that improved force feedback will result in less tissue injury during endoscopic operations is difficult to assess since improved force feedback is not yet available to the endoscopic surgeon. A similar premise is that three-dimensional imagery may produce increased efficiency in endoscopic operations.[15,16] It seems apparent that visual cues are very powerful in filling in the gaps of visual and haptic deficits in endoscopic surgery, but these "compensations" may not be necessarily accurate or safe.[14-16] Until improved force-feedback capabilities can be made available for testing, we will not know if improved haptic feedback will result in fewer injuries to soft tissues. In addition, it is not known how much force and torque applied to a given tissue by laparoscopic operations will result in tissue injury, either reversible or irreversible injury. This aspect is currently undergoing study in our laboratory.

The inability to palpate tissues accurately during endoscopic surgery because of inadequate force feedback undoubtedly results in loss of diagnostic information. As surgeons of the open surgery era, we have been spoiled by the luxury of the human hand to supply this diagnostic information. Common examples would include hand palpation of common bile duct stones, lung and liver nodules, and intestinal masses. As endoscopic surgery further displaces open surgery as the standard of care, we will be additionally handicapped in our diagnostic intraoperative capabilities. Although endoscopic ultrasound imaging has excellent potential for bridging some of this gap of intraoperative diagnostic limitations,[19,20] it does not work well on hollow organs because of artifacts of shadowing from air/tissue interfaces. Future generations of force-feedback devices will surely improve in their compactness and fidelity of information. Furthermore, we have previously reported with a computerized grasper that normal biologic organs have characteristic force profiles[17] based on their intrinsic tissue properties. If the force profile is not "normal" for a given biologic tissue, then this could represent tissue inflammation, fibrosis, foreign body, or cancer, thus improving diagnostic yield.

Another potential application of this technology is in the area of tissue protection. If the degree of forces and torques that result in tissue injury can be determined (work in progress), then "smart endoscopic force-feedback instruments" can be developed that will apply force/torque limitations resulting in tissue protection from iatrogenic operative tissue injury.

CONCLUSION

Although minimally invasive surgery techniques have brought forth astounding changes in surgical care, with benefit to all participants who provide and receive health care, we need to continue to strive to make operations safer, more efficient, and with fewer complications. We have demonstrated that haptic feedback can be potentially improved during minimally invasive surgery. Whether this will translate into fewer episodes of tissue injury and improved diagnostic capabilities remains unclear. However, the first step is to be able to make this technology available for testing. The ultimate goal is to perform operations which are performed more efficiently, less invasively, and with fewer complications to patients.

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Discussion

Dr. L. W. Traverso (Seattle, Wash.). Of the three common laparoscopic procedures we do—cholecystectomy, Nissen fundoplication, or appendectomy—which do you think will be helped the most by this technology?

Dr. M. MacFarlane. We certainly perform many laparoscopic Nissen fundoplications and I can say that we see a fair number of serosal tears, although perforations are very rare in our hands. So I think the more advanced cases are going to be the best application for this technology.

Dr. B. Schirmer (Charlottesville, Va.). This is a very interesting concept, but I am a little concerned about whether it is going to be generally applicable. Do you see this as being something that every grasper will be equipped with eventually and at what cost? Will equipping these graspers be cost-effective? Second, if you were to design just one type of instrument, in which specific situations would you use it? Ultrasound imaging does very well for solid organs—would you, for example, want to use it in the colon to palpate lesions? What else do you envision for this application?

Dr. MacFarlane. Laparoscopic ultrasound is a wonderful modality. It is very sensitive, especially on solid organs, so I think the grasper would be most applicable, in terms of diagnostic information, on hollow organs. Second, if the cost of new technology were the sole determining factor, we would not have any new technology. Until this technology is developed further, I do not think we will know the answers to your questions. In its current prototype form, our instrument is very bulky. It needs to have stronger actuator forces to carry out the steps in the operation that are performed.

Dr. N. Soper (St. Louis, Mo.). You are at the low end of the development of this instrument and I think there is a long way to go. In terms of the bulkiness of the instrument as currently designed, it looks like there will need to be something at the actuator end, which will bulk up the end that is going through these little incisions we are going to make. Is there any possibility of placing that actuator back out, near the handpiece for instance, rather than down at the tip?

Dr. MacFarlane. The actuator itself does not limit our capabilities inside the abdomen because the length of the intra-abdominal portion is identical to what is currently used in laparoscopic surgery. As with all prototypes, future models will become more compact and more efficient. I cannot currently estimate what the final product will look like.