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Human-Machine Interfaces for Minimally Invasive Surgery

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Abstract—

Increasing numbers of surgical procedures are performed using minimally invasive techniques, in which trauma to external tissue is minimized. Unfortunately, reduced access reduces dexterity, limits perception, increases strain and the likelihood of error, and lengthens procedure time. Surgical technology must improve the interface between task requirements and human abilities. This paper describes three projects to evaluate and improve the human interface in laparoscopic surgery, or minimally invasive surgery of the abdomen: (a) measurement of movement trajectories under different visual conditions to determine the effect of viewing geometry, (b) the development of virtual environments for training, and (c) the development of haptic interfaces and control algorithms for teleoperative surgery.

Keywords— **laparoscopic surgery, video displays, virtual environments, teleoperation**

I. INTRODUCTION

Traditional surgery requires an incision large enough for the surgeon to see directly and place his or her fingers and instruments directly into the target operating site. Most often, the damage done to skin, muscle, connective tissue, and bone to reach the region of interest causes much greater injury than the curative procedure itself. This results in more pain to the patient, longer recovery time, and complications due to surgical trauma. The accelerating trend is toward minimally invasive surgery (MIS), in which unnecessary trauma is limited by reducing the size of incisions to less than about 1 cm or using catheters or endoscopes threaded through vessels, the gastrointestinal tract, or other tubular structures. The other side of MIS, unfortunately, is that from the surgeon's point of view it is minimal access surgery. Reduced access reduces dexterity, limits perception, increases strain and the likelihood of error, and lengthens procedure time.

Laparoscopic surgery, or MIS of the abdomen, has undergone particulary rapid growth in the last decade. In these procedures, a laparoscope is inserted with a cannula through a 10 mm incision in the abdominal wall [1]. A CCD camera mounted on the laparoscope transmits the image to a CRT monitor viewed by the surgical team. Several long instruments, including graspers, scissors, needle drivers, staplers, and electrosurgical devices, are inserted through separate cannulas. Typically, the primary surgeon works with 1–2 assistants to hold the laparoscope and retract tissue (a commercial voice-actuated manipulator is also available to control the laparoscope [2]). The major difficulties with videoscopic imaging in laparoscopic surgery include the lack of a stereoscopic image, geometric viewing distortions, and the limitations of resolution, contrast, and color inherent in video imaging [3], [4]. The instruments reduce dexterity, eliminate tactile sensation, and reduce kinesthetic force feedback [3]. Laparoscopic techniques are also more difficult to learn than conventional surgical techniques.

All of these issues are human interface problems, and their potential solution lies in the design of interface technology to match human abilities to the surgical task. This paper describes three projects underway in joint efforts between the Department of Surgery at the University of California, San Francisco and the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley to evaluate and improve the human interface in minimally invasive surgery: (a) measurement of movement trajectories under different visual conditions to determine the effect of viewing geometry, (b) the development of virtual environments for training, and (c) the development of haptic interfaces and control algorithms for teleoperative surgery.

II. IMAGING

An obvious limitation of videoscopic imaging in surgery is the monoscopic display. Commercial stereoscopic laparoscopes and display systems have been developed to provide binocular disparity from laterally displaced views, within the limit of the diameter of the laparoscope or its aperture. Several research groups have performed experiments to attempt to measure the benefit of stereo imaging. Although slightly faster performance has been shown, primarily in tasks requiring precise alignment [5] or in less experienced subjects [6], stereo systems do not provide measurable benefit for experienced subjects in complex tasks like knot tying [4], [7].

There are many significant monoscopic depth cues in videoscopic imaging, including occlusion, lighting, and texture [4], so it is not surprising that most tasks can be performed reasonably well without stereo imaging. Nevertheless, point-to-point movements and complex tasks such as knot tying are significantly slower with substantially more

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errors under videoscopic conditions than with direct viewing [3], [4]. It is likely that geometric factors in viewing contribute substantially to these problems. These factors include the improper eyepoint of the viewer watching a wide angle image from afar, the optical distortion of wide angle images, and misalignment between camera, display, viewing, and instrument axes.

It is well known that free hand movements to a target in space consist of a coarse phase of a fast movement to the region of the target followed by a slower fine phase to intercept the goal, made up of visually guided adjustments [8]. It is likely that the initial phase is largely pre-programmed and uses minimal visual feedback. Consequently, the viewer's internal model of the three-dimensional workspace would be especially critical in determining the accuracy of this phase, affecting both the duration and accuracy of the total movement. Geometric factors would be critical in the development of the internal model. To provide preliminary evidence for this hypothesis, pilot experiments were performed comparing point-to-point movement trajectories under direct and videoscopic conditions.

A. Methods

Trajectories of subjects' movements were measured using a specially modified Virtual Laparoscopic Interface (Immersion Corp., Santa Clara, CA). This device measures the motion of a laparoscopic tool in four degrees of freedom about a fulcrum, with kinematics similar to an instrument in a cannula, using a gimbal arrangement with optical encoders on each axis. The advertised resolution of the device is .0005 in. Target boards comprising 5 black nails driven into a white block were mounted interchangably on the device. Two boards were used in this experiment; one had nails driven to varying heights, the other had all heights the same. The nail heads were 3 mm in diameter; they were spaced from 30–50 mm apart for a Fitt's index ($\log_2 2width/diameter$) of 4–5 bits.

Two viewing conditions were used, direct and videoscopic. In the direct condition, subjects viewed the targets directly from a distance of about 60 cm. In the videoscopic condition, a laparoscope was mounted with the lens 10 cm from the center of the targets. The imaging system, from Karl Storz Imaging (Goleta, CA), consisted of a 0° (forward viewing) telescope with a 70° field of view, model 202100 camera and processing unit, and Sony monitor. Subjects viewed the monitor from a distance of about 2 m at eye level.

Two subjects touched the front center target followed by one of the other four targets, then returned to the original target. A trial consisted of repeating this action for a total of 8 movements forward and back. Subjects performed 10 trials, the second and tenth of which were recorded. Only data from the tenth trials are presented in this paper; although there was some learning evident, the data were qualitatively similar between trials. Direct vision trials were performed first, followed by videoscopic trials.

The system recorded the instrument position at the rate of 100 samples per second. The data were analyzed by viewing position and speed curves in custom analysis software. All records showed an initial fast phase followed by a slower interception of the target. The duration of the initial phase was measured from initiation to the first minimum in the speed curve. The accuracy of this phase was the distance between the position at the end of the phase and the calibrated target position. The total movement duration extended until the subject lifted the instrument after touching the goal.

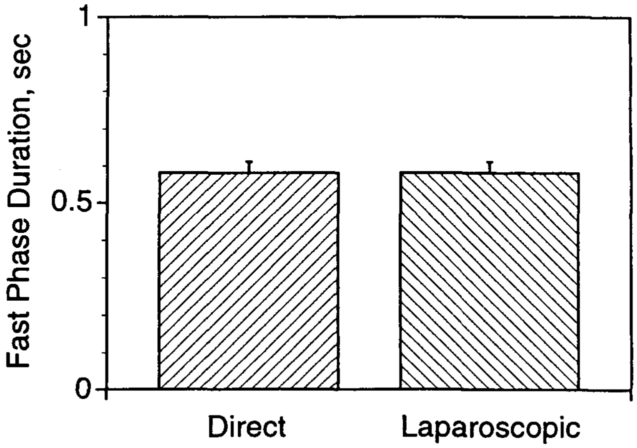

Fig. 1. The duration of the initial phase of point-to-point movements is equal under direct and laparoscopic viewing conditions.

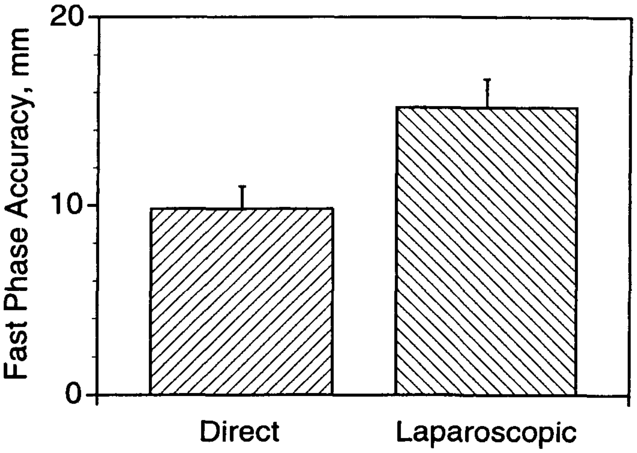

Fig. 2. The initial phase of movements is significantly more accurate under direct viewing.

B. Results and Discussion

The duration of the initial phase of movements was the same (580 ms) under direct and videoscopic conditions (Figure 1). The accuracy of the initial phase was better in direct viewing, however (Figure 2). This resulted in shorter total movement duration (Figure 3).

These data are consistent with the hypothesis that the initial phase of movement is largely pre-programmed, with little adjustment from visual feedback. Under direct vision, subjects have good (and consistent) depth cues and view-

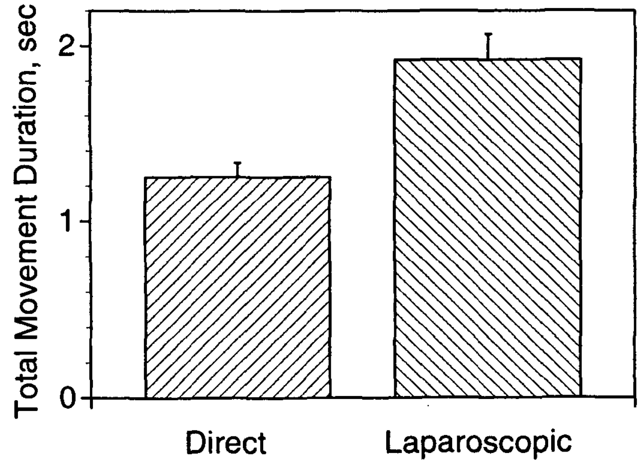

Fig. 3. Movements have significantly shorter durations under direct viewing.

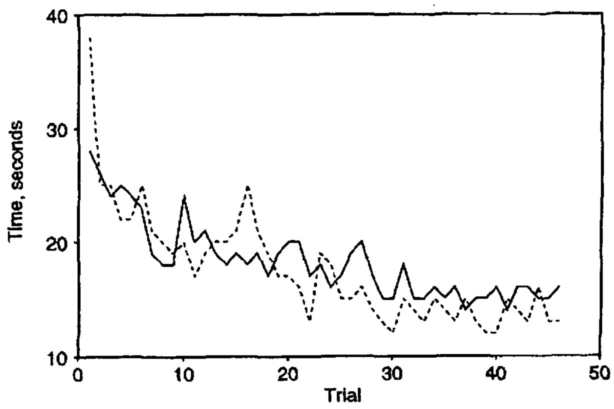

Fig. 4. Performance of point-to-point movements under laparoscopic conditions by an experienced laparoscopic surgeon (solid) and a novice medical student with no previous experience (dashed). The novice can quickly gain skill comparable to the expert in this simple task.

ing geometry, allowing an accurate estimate of the target position and an accurate initial phase. A poorer estimate under videoscopic conditions leads to decreased accuracy, a longer corrective phase to reach the target, and longer total movement duration.

The implication of these results is that poor viewing geometry and distortions of the workspace image lead to a poor mental model of the locations of the targets and instrument. Geometric factors include the viewing of a wide angle (70°) image subtending a much narrower (13°) visual angle [9]; the lack of correspondence between camera, display, viewer, and instrument axes [10]; wide angle optical distortion, and competition between depth cues in the environment and the display image. These factors are not likely to be substantially improved with a stereoscopic display.

These pilot experiments identify the need for better understanding of the role of geometric factors in visually-guided movements. Further experiments will evaluate the effect of the angle between the camera, instrument, and display axes, and the importance of the viewer's eyepoint relative to the display. Potential solutions may include head mounted displays or lightweight flat panel displays suspended in optimal viewing arrangements.

III. TRAINING

Training in surgery is traditionally based on an apprenticeship model. Students learn by watching and participating in cases, taking greater roles with each procedure. Although this can be an effective method of teaching, it has great drawbacks in an era when techniques and technology change rapidly, yet economy in health care is of increasing importance.

Training in the operating room can increase risk to the patient and slows the operation, resulting in greater costs. It also has drawbacks in teaching effectiveness. A stressful environment can reduce learning, and students are not free to experiment with different techniques to see which one might be best for them. Because every mentor teaches his or her own technique, it is impossible to develop standards for training or assessment.

Other methods of training have limitations. Books are not interactive and cannot portray anatomy in three dimensions. Cadavers and live animals are expensive and usually cannot demonstrate pathologies. Animal anatomy is not the same as human anatomy. In vitro training models made of synthetic materials can be useful, but it would be difficult to maintain a library of models with all important pathologies and anatomical variations, especially if the models are of little use after being "dissected."

Computer-based training has many potential advantages. It is interactive, yet an instructor's presence is not necessary, so students may practice in their free moments. Any pathology or anatomical variation could be created. Simulated positions and forces can be recorded to compare with established performance metrics for assessment and credentialing. Students could also try different techniques and look at anatomy from perspectives that would be impossible during surgery.

Some have suggested training basic skills in virtual environments, but these are usually learned adequately with conventional training or in unstructured practice. For example, novices can quickly learn simple skills such as three dimensional point-to-point movements, despite the confounding nature of videoscopic imaging and the fulcrum effect of instruments through the cannula (Figure 4). On the other hand, complex skills like knot tying could be tutored and assessed in a consistent fashion in a virtual environment. Usually, these skills are taught during brief courses, and even after practice and experience surgeons do not achieve facility. Because kinesthetic sense is as important as vision in performing complex skills, good force display is necessary. This is described in section IV.

Inadequate training can lead to consistent patterns of errors. Bile duct injuries, a major complication in laparoscopic cholecystectomy (removal of the gall bladder), are

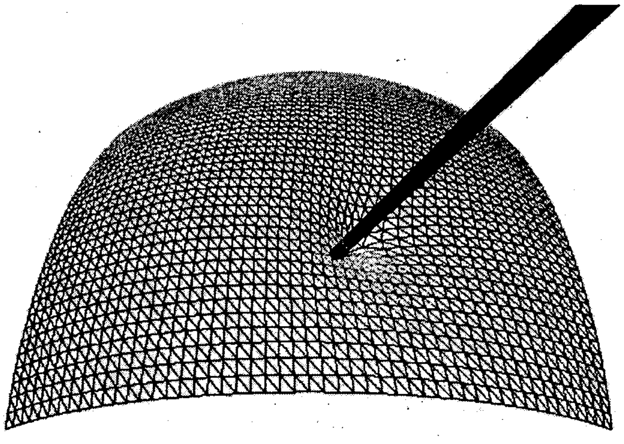

Fig. 5. Deformation of a dynamically modeled 2,500 node mesh.

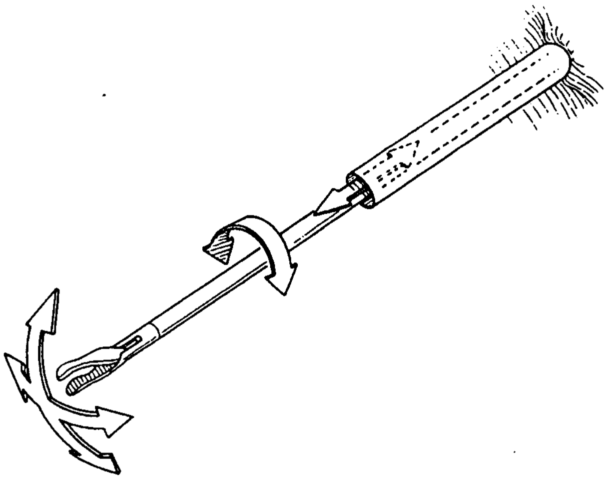

Fig. 6. Because of the fulcrum at the cannula entry through the abdominal wall, the motion of laparoscopic instruments is constrained to 4 DOF.

the direct result of inappropriate technique in exposing the anatomy surrounding the gall bladder. It is likely that proper technique could be trained in a variety of anatomical variations using a virtual environment. Modeling tissue behavior requires physical models of its compliant properties. Fortunately, although three-dimensional modeling of thick organs is computationally formidable, most tissues of interest in modeling the exposure and dissection steps where errors occur in surgery are thin layers or tubes. Two-dimensional models are within the capabilities of current systems. For example, even the dynamic behavior of the 2,500 node mesh shown in Figure 5 can be simulated and rendered in real time on a Silicon Graphics O2 workstation. The authors are currently developing algorithms for multi-scale modeling and tissue interactions, and integrating anatomical data into demonstration systems.

IV. DEXTERITY ENHANCEMENT

The fulcrum at the incision through the abdomen constrains the motion of laparoscopic instruments to four degrees of freedom (DOF), as shown in Figure 6. This does not produce significant difficulties in simple tasks like point-to-point movements [3], and even novices can quickly learn to perform such basic tasks (Figure 4). Complex tasks like suturing and knot tying, however, that require dexterity and the ability to orient the instrument tip, are performed much slower than with hand instruments and require lengthy training and practice to master [3]. Because of friction in the cannula and stiffness in the inflated abdominal wall, much of the sensation of forces exerted on compliant tissues is lost. Tactile sensation, which is especially useful to feel hidden lesions or vessels embedded in fat, is not available [11], [12].

Teleoperation technology can restore some of the lost dexterity and sensation [13], [14], [15], [16]. Millimeter scale manipulators that fit through the cannula provide additional degrees of freedom in orientation, while external limbs control position (Figure 7). The surgeon uses master controllers to command the slave manipulator position, while interaction forces between the slave and tissue are reflected to the master. Similar technology could be used in remote surgery for experts to perform or assist surgery in remote rural areas, or for emergency care in urban trauma or the battlefield.

Such a system has been developed at Berkeley [1], with a 2 DOF internal manipulator [16] (Figure 8) and a parallel platform externally (not shown). The master is a force feedback joystick (Impulse Engine 3000, Immersion Corp., Santa Clara, CA) with 2 DOF customized in addition to the original 4 DOF (Figure 9). The positioning DOF and orientation about the instrument axis are actuated; moments about the other 2 DOF at the tip were assumed to be insignificant. A pair of tactile displays will also be incorporated into the master [11].

The authors are currently developing control algorithms to maximize sensation in force-reflecting teleoperation. Theory and analysis in teleoperation have emphasized stability and fidelity in hard contact situations (e.g., [17], [18]). With conventional force-reflecting schemes, the impedance of the master mechanism and controller dominates the compliance of soft tissue. Force-torque sensing on both the slave and master will permit better compensation for the mechanical characteristics, especially when a miniature slave has significant friction (or viscosity in hydraulic systems) and effective mass. A better understanding of how compliance is perceived, and better models and data of tissue behavior, are necessary to allow amplification of the local changes in tissue hardness near a lesion or embedded vessel. Similar algorithms will be necessary for accurate force display in virtual environments as well.

V. CONCLUSION

This paper has given an overview of efforts to evaluate and improve the human interface in laparoscopic surgery. Pilot experiments measuring movement trajectories showed

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[1] This is joint work with S. Sastry, M. Cohn, and R. Fearing.

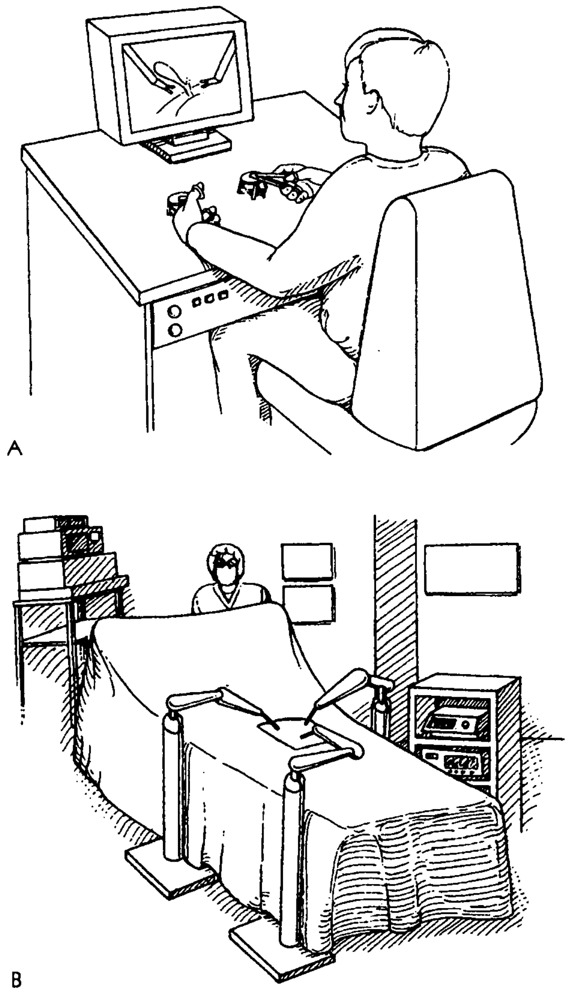

Fig. 7. Teleoperative surgery concept. Motions of the master controller handles operated by the surgeon (A) are transmitted to slave manipulators inside the patient (B), and forces are reflected to the master.

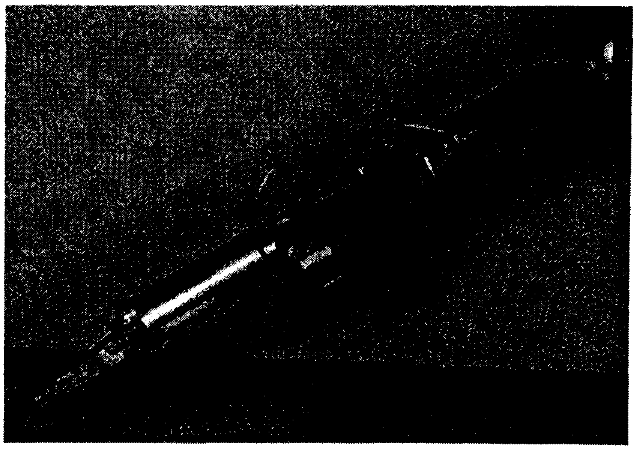

Fig. 8. A prototype 2 DOF (plus grasper) hydraulic wrist for teleoperative surgery. Actuators are not shown.

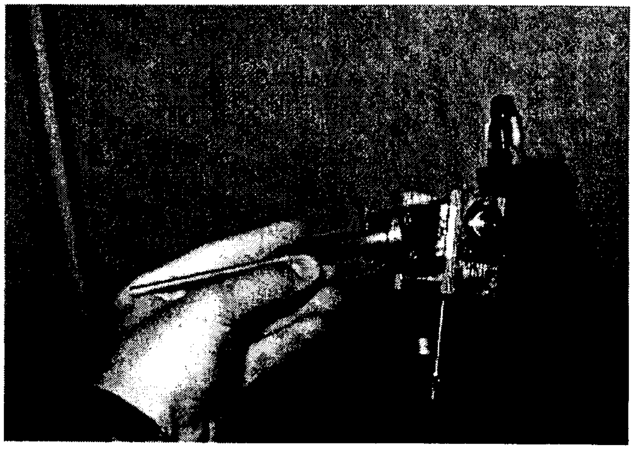

Fig. 9. A sample master manipulandum with force feedback and 6 DOF.

the importance of geometric factors in videoscopic imaging. Further experiments will quantify the importance of individual factors, with the goal of identifying an optimal range for display location and orientation. Training methods in surgery clearly need to be improved, and virtual environments have many desirable qualities for training the complex motor and spatial skills necessary. Current workstations have the capability to model and render tissue deformation with sufficient fidelity to teach fundamental anatomical relationships and the steps necessary to expose them in surgical procedures. Modeling algorithms should be optimized, and training transfer of integrated simulations measured. The quality of haptic interaction with deformable models remains to be investigated. Teleoperative surgery has the potential to improve dexterity and haptic sensation in minimally invasive surgery. The hardware telesurgery testbed at Berkeley is ready to be used to develop and compare force reflecting control schemes to optimize the perception of compliance in tissue.

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