

VIRTUAL ENVIRONMENTS FOR TRAINING CRITICAL SKILLS IN LAPAROSCOPIC SURGERY

MICHAEL DOWNES (1), M. Cenk Cavusoglu, MS (1), Walter Gantert, MD (2),
Lawrence W. Way, MD (2), Frank Tendick, PhD (2)

*(1) Department of Electrical Engineering and Computer Sciences, University of California,
Berkeley, CA 94720*

(2) Department of Surgery, University of California, San Francisco, CA 94143

Abstract : Surgical training simulations must incorporate not only advanced technical features, such as detailed geometric organ models and physically-based modeling techniques, but also a thorough understanding of the major training issues relating to a particular procedure. We have developed a prototype environment for training laparoscopic cholecystectomy, or gallbladder removal surgery, which focuses a student's attention on the critical steps performed during the procedure and provides feedback as to the common errors committed during a session. The current version of our system runs in real-time on a mid-range graphics workstation. The simulation also provides a platform for research into a variety of different areas, including tissue modeling, finite element methods, and generalized simulation authoring.

1. Introduction

While the technology used in the operating room has advanced steadily over the past century, the methods by which surgeons learn how to operate have remained virtually unchanged. Surgical residents still learn primarily through the apprenticeship model, wherein a novice assists a surgeon with greater experience in a particular procedure. Other training methods, such as textbooks, animals, and in vitro models, are occasionally used as supplements during the acquisition of technical knowledge.

This approach has a number of drawbacks. For example, training sessions in animal laboratories are expensive, and the anatomy of animals differs significantly from human anatomy. Simply watching a fully trained surgeon performing a procedure does not allow one to develop a clear understanding of the relationship between the anatomic structures encountered during the operation. The student needs hands-on experience with examining and manipulating the organs and the surgical instruments used during the procedure in order to become proficient.

Computer-based surgical simulation seeks to address these shortcomings with accurate, immersive virtual environments that simulate all the important aspects of a surgical procedure. A good surgical simulation provides the user with a 3-dimensional view of the anatomic region of interest, using either a head-mounted display or a standard monitor, and interface devices that mimic as closely as possible the surgical tools used during the procedure. A good deal of research effort has been directed toward developing such systems over the last five years.[1][2][3][4][5][6][7]

Our group has focused on creating a simulation of laparoscopic cholecystectomy that identifies and emphasizes the critical steps in performing the procedure and concentrates on developing the student's spatial skills. Although others have simulated this procedure (with varying degrees of fidelity), our system emphasizes the experience of the UCSF authors in analyzing errors that result in bile duct injuries and the other major complications of laparoscopic cholecystectomy. The current prototype also serves as a foundation for continuing research into areas such as tissue modeling and augmented reality and as a testbed for components that we are using to construct a general-purpose surgical simulation authoring system. In the remainder of the paper, a number of the more important details of the system are discussed, beginning with motivations and design goals in section 2. In section 3, we provide an in-depth analysis of the implementation of the simulation. Section 4 summarizes the current performance of the system and our findings. Directions for future work are indicated in section 5.

2. Purpose

2.1. Training

The system serves not only as a viable surgical training tool but also as a testbed for a variety of experimental algorithms and design strategies. For example, simulation improves upon the traditional training methods discussed above by allowing students to practice the procedure as frequently as they wish without requiring lengthy setup times or the presence of an instructor. This not only increases a student's exposure to the operation but also decreases the cost of training, since expensive animals and technician time are not required. In addition, the computer-based system allows instructors to present trainees with a variety of anatomic configurations and changes resulting from disease by loading new geometric models into the environment.

The simulation uses physically-based modeling to endow these models with believable dynamic properties, so the user learns the spatial orientation of the organs in the environment and how their relationships change as they are manipulated. The system can record a student's session, so the student and instructor can analyze the trainee's performance in detail. Recordings can also be used for evaluating a surgeon's competence as part of an accreditation process. By focusing attention on the most difficult aspects of the procedure and reducing the amount of time spent on the less challenging tasks, the simulation holds a user's interest and encourages him or her to practice the operation repeatedly. The system has been designed from its inception to ensure that this practice helps surgical residents develop and hone the spatial skills vital to becoming a skilled surgeon. By interacting with dynamic anatomic models, the user acquires the ability to visualize accurately the 3D organization of the region of interest. The system also provides an exploration mode that allows the trainee to view the anatomy from any point of view, including many that would be impossible in a real organism.

2.2. Research

While the laparoscopic cholecystectomy simulation we have developed represents an important advance in surgical training technology, it also serves as a robust test platform for a variety of research directions. In particular, the system has been designed using a modular approach that makes it easy to experiment with new models for the physical properties of organs in the environment. In section 3.3 we examine these models in detail. The virtual environment also serves as a prototype for a more general surgical simulation authoring tool, which we are currently developing. By following a modular design strategy,

we have been able to design components that create anatomic models from a variety of data sources, allow for the use of different interface devices (including force-feedback controllers), and model the functional properties of various laparoscopic instruments. These components serve as the groundwork for a planned general-purpose system.

3. Methods

3.1. Interface

The user interacts with the system primarily through the use of virtual laparoscopic joysticks obtained from Immersion Corp. Each joystick has five degrees of freedom and uses a real laparoscopic instrument as the control handle. During the simulation, the student uses the joysticks to control virtual surgical instruments with which he or she interacts with the anatomy being modeled. In a real operation, a laparoscope is inserted through a port positioned near the navel, and two or more instruments are inserted through other trocars located on either side of the laparoscope. Since the laparoscopic device provides only two joysticks, the surgeon can alternate between using the left-hand joystick to control the camera or an instrument.

3.2. Geometric Models

In order to provide a meaningful educational experience, a surgical training simulation must depict the relevant anatomy accurately. Unrealistic anatomic models could confuse or even misinform students as to what they might encounter in the operating room. In addition, the physical model discussed in section 3.3 is closely tied to the geometric models of objects in the environment, so accurate geometric models ensure proper physical behavior. For the simulation, we use highly detailed geometric surface models of the liver, gallbladder, and biliary ducts created by Visible Productions LLC. The company generated the models by manually segmenting the NLM's Visible Human male dataset. Such manual segmentation produces extremely high-fidelity models, but at the cost of large amounts of time spent identifying structures in 2D slices of the overall dataset. Along with the anatomical models we have added flexible sheets to represent fat and connective tissue which occlude the anatomy. These sheets are joined to the underlying anatomy and must be dissected in order to expose the organs. In future versions, we will incorporate dynamic volumetric adhesions between the ducts for a more accurate and challenging simulation.

We are also experimenting with using the simulation to practice the procedure on real patient data. For this application, we generated anatomic models by applying a fast automatic segmentation technique, developed by Malladi et al., to MRI data.[8] Although the resulting models are not as detailed as those produced by manual segmentation, they are still accurate enough to perform the procedure and to identify and to overcome many problems before entering the operating room. Both types of models can be edited to represent a variety of pathologic findings.

In order to imbue the anatomical models with the characteristics of deformable objects, we make use of simple lumped parameter models, composed of mass-spring-damper meshes. Such an approach has been used by numerous graphics researchers over the past decade. [9][10] As in much of the work in physically-based modeling in computer graphics, we interpret a triangulated model as a dynamic mesh of physical elements. Each vertex is treated as a mass, and these masses are connected to each other by spring-damper elements which coincide with the edges of the triangles and have equilibrium lengths equal to the initial lengths of their equivalent edges.

In simulating this dynamic mesh, we use multiple integration steps per graphics update, since the bandwidth of the dynamics of the deformable model is much higher than the graphics update rate. We have experimented with a variety of techniques intended to maximize the speed with which the physical model is updated in real time. Specifically, we have compared Runge-Kutta, Bulisch-Stoer and forward Euler's integration methods.[11] The first two of these methods have good accuracy, whereas Euler's method is fast but has poorer accuracy. We have also used a modified version of the forward Euler's method in which a dead-band is added to further increase integration speed.

Table 1 summarizes the results of testing the different integration schemes by simulating a deformable surface, represented by a 50x50 node mesh, in real time. Interactive frame rates with realistic dynamic bandwidths were only possible with Euler's method with dead-band, but at the expense of significantly reduced accuracy of integration. However, the accuracy of Euler's method is sufficient, as accuracy of the calculations is not critical in the simulation. The results also reveal a non-linear trade-off between the possible bandwidth and the frame rate achieved.

Table 1. Comparison of Various Integration Schemes

Integration Method	Step size	Natural Frequency	Frame Rate
4th Order	N/A	0.05 Hz	2.9 Hz
Runge-Kutta-Fehlberg			
Bulisch-Stoer	10-500 ms	0.05 Hz	4.8 Hz
Forward Euler's (no dead-band)	16 ms	0.05 Hz	5.1 Hz
Forward Euler's (no dead-band)	20 ms	0.64 Hz	5.0 Hz
Forward Euler's (with dead-band)	5 ms	0.64 Hz	10.7 Hz
Forward Euler's (with dead-band)	2 ms	2 Hz	8.38 Hz

Although the current model does not derive from a quantitative analysis of the behavior of the organs we are simulating, it does provide a qualitatively satisfying representation of the dynamic behavior of the tissues. Finite element methods for mechanical simulation can generate much more accurate models than the simple viscoelastic one, but such techniques are not yet fast enough to allow for real-time interaction with complicated models. On the other hand, by using Euler's method of numerical integration to solve the simple equations describing the motion of masses in the system, we are able to achieve interactive speeds with realistic dynamic bandwidth on mid-range graphics workstations, such as the SGI Octane. In addition, as mentioned above, the modular design allows us to experiment with different modeling techniques by simply swapping in a new component. We are currently using the system to experiment with applying the results of tissue modeling experiments to derive parameters for simple linear elastic models and with developing accelerated finite element methods.

4. Results

4.1. Interface

The simulation models four laparoscopic surgical instruments in addition to the laparoscope itself. The student can use the grasper to grab and move any of the organs modeled in the environment. Currently, the gallbladder, bile ducts, fat, and connective tissue are modeled as deformable objects, and their interconnections are taken into account, so they react as one would expect when objects are moved. The electrosurgical instrument allows the user to divide fat and occluding tissue in order to expose the underlying structures. In addition, one uses the clip applier to clip ducts and blood vessels before cutting them with scissors. Some of these instruments can be seen in action in Figure 1 which depicts the initial and final steps in a successful laparoscopic cholecystectomy.

The student uses pop-up menus and hot keys to alter various aspects of the simulation. For example, one can choose whether to use a laparoscope whose view is aligned with the shaft of the instrument or one whose view is at an angle of 45 degrees with respect to the shaft. These options reflect similar ones available to the surgeon while working with actual devices. The 45 degree laparoscope gives a surgeon the ability to look over and around anatomic structures and is a valuable, but difficult-to-master, tool. The instruments being controlled by the joysticks can be selected with hot keys or menu choices, as mentioned above. The menus also allow the user to tailor the simulation to run more efficiently on less powerful hardware by turning texture mapping off and by choosing to use simplified anatomic models.

4.2. Training Issues

To be an effective training tool, a virtual environment simulation must emphasize to students the optimal method for performing each important step of a procedure and must identify and explain common errors when they occur and provide guidance as to how to avoid them. Experience in teaching surgeons who attend courses at the Videoscopic Training Center at UCSF allows us to develop simulations that train the most critical tasks in each procedure. For instance, one of the most common errors in laparoscopic cholecystectomy is to cut the wrong bile duct. The simulator teaches students to avoid this error by requiring them to manipulate and dissect the gallbladder properly, by giving them experience in identifying the proper duct despite adhesions, and by presenting warning messages and reviews of proper procedures when errors are committed.

Figure 1 depicts the initial and final steps in a laparoscopic cholecystectomy. Table 2 summarizes the key training issues. The system provides feedback to alert students when they commit any major error and guidance as to how to avoid errors. In our more generalized system, we are developing an interface through which the instructor can define the critical errors for the procedure being simulated and specify appropriate feedback.

We have also taken into consideration the level of detail necessary to provide a beneficial educational experience. For instance, as discussed above, we use a rather simple elastic model for deformability in order to ensure that the simulation runs at interactive speeds. For the current procedure, it is more important that the simulation run smoothly and respond believably than it is to provide quantitatively accurate behavior.

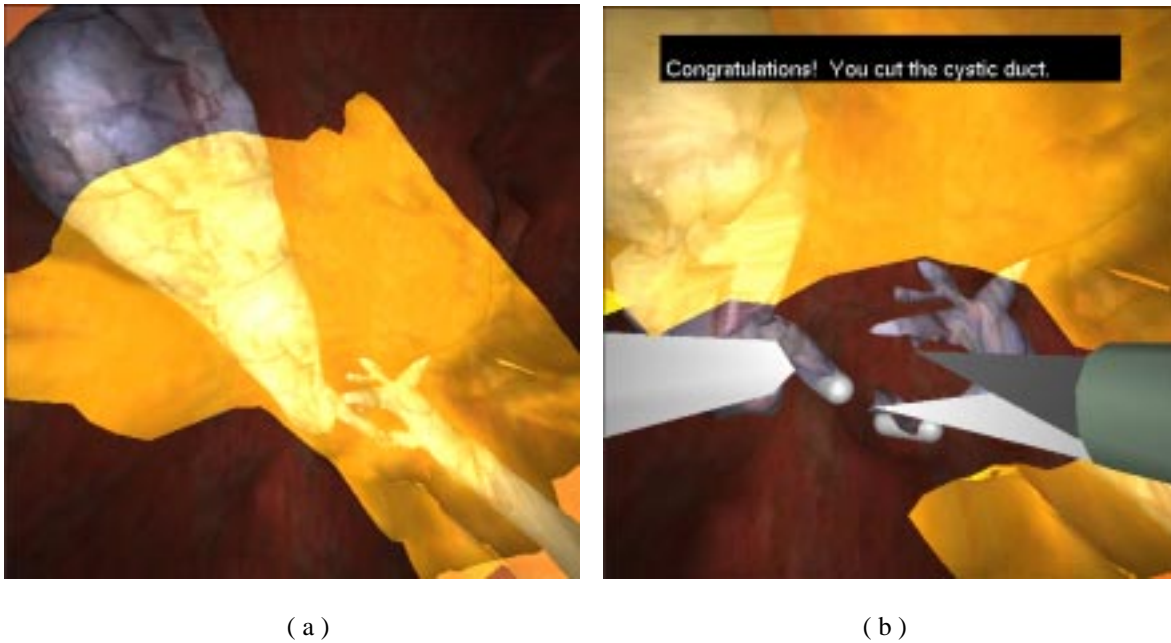


Figure 1. Laparoscopic cholecystectomy simulation showing gallbladder, biliary ducts, and liver. Obscuring fat and connective tissue are currently represented by a single translucent sheet. (a) intact anatomy; (b) obscuring tissue has been dissected, cystic duct clipped and successfully cut.

Table 2. Steps that can be trained in simulation to avoid confusion between the common bile duct and the cystic duct in laparoscopic cholecystectomy.

1. Use lateral traction on the infundibulum of the gallbladder during dissection.
2. Dissect the space between gallbladder and cystic duct completely.
3. Clear the triangle of Calot enough to show the hepatic side of the infundibulum of the gallbladder.
4. Use an angled scope to gain proper view of the triangle of Calot.
5. If the duct won't fit entirely within a 9mm clip, assume it is the common duct.
6. Any duct that looks as if it goes behind the duodenum has to be the common duct.

5. Conclusion

The laparoscopic cholecystectomy simulation represents an important integration of virtual environment simulation technology with a focused training approach. The system not only presents an accurate representation of the anatomical structures affected by the procedure, but also stimulates the development of spatial reasoning skills and a thorough knowledge of the possible missteps in performing the operation and how to avoid them. By taking into account the proper progression of the procedure, we can provide the student with context-sensitive feedback throughout the simulation, thus enhancing the overall educational experience.

The current simulation also serves as a highly modular testbed for research efforts in a number of different fields, including tissue modeling and augmented reality. We are developing techniques to incorporate models of both surface and volume elements into the simulation. In addition, the design is currently being expanded to support a general purpose authoring tool which will allow surgeons and other instructors to create simulations based on their own experience without requiring them to learn a great deal of computer programming or forcing them to use a programmer as an intermediary. We believe that such a system will lead to an increase in the quantity and the quality of available surgical simulations.

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