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Development of Virtual Environments for Training Skills and Reducing Errors in Laparoscopic Surgery

Frank Tendick[a], Michael Downes[b], M. Cenk Cavusoglu[b],
Walter Gantert[a], and Lawrence W. Way[a]

[a]Department of Surgery, University of California, San Francisco, CA 94143-0475

[b]Dept. of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720

ABSTRACT

In every surgical procedure there are key steps and skills that, if performed incorrectly, can lead to complications. In conjunction with efforts, based on task and error analysis, in the Videoscopic Training Center at UCSF to identify these key elements in laparoscopic surgical procedures, the authors are developing virtual environments and modeling methods to train the elements. Laparoscopic surgery is particularly demanding of the surgeon's spatial skills, requiring the ability to create three-dimensional mental models and plans while viewing a two-dimensional image. For example, operating a laparoscope with the objective lens angled from the scope axis is a skill that some surgeons have difficulty mastering, even after using the instrument in many procedures. Virtual environments are a promising medium for teaching spatial skills. A kinematically accurate model of an angled laparoscope in an environment of simple targets is being tested in courses for novice and experienced surgeons. Errors in surgery are often due to a misinterpretation of local anatomy compounded with inadequate procedural knowledge. Methods to avoid bile duct injuries in cholecystectomy (gallbladder removal) are being integrated into a deformable environment consisting of the liver, gallbladder, and biliary tree. Novel deformable tissue modeling algorithms based on finite element methods will be used to improve the response of the anatomical models.

Keywords: virtual reality, virtual environment, laparoscopic surgery, minimally invasive surgery, cholecystectomy, spatial cognition, error analysis

1. INTRODUCTION

Training in surgery is principally based on an apprenticeship model. Residents learn by watching and participating, taking more active roles in the operation as their experience increases. There are few textbooks or established methods for teaching fundamental technical skills, so techniques and teaching methods vary among instructors. The apprenticeship training model has probably survived in part because the techniques of traditional open surgery mostly rely on familiar eye-hand coordination. Consequently, most residents can achieve competence by repeated practice.

With the introduction of minimally invasive techniques, perceptual-motor relationships are unfamiliar. Direct vision is replaced by a video image. Because endoscope and instrument positions are continuously changing, the relationship between visual and instrument coordinates also changes continuously. Dexterity is diminished, and kinesthetic feedback of the interaction forces between instruments and tissue is also reduced. Tactile sensation, which is especially useful to feel hidden lesions or vessels embedded in fat, is unavailable. Consequently, there are fundamental changes in the required perceptual motor skills.

Surgical advances often result from laboratory work and prospective clinical trials. The results are disseminated through journals, textbooks, and postgraduate courses. Historically, changes in technical knowledge (e.g., technique or instrumentation) have occurred much more slowly than changes in verbal knowledge. The latter can be taught effectively in short courses or picked up ad hoc. The former is taught in surgical residencies, but the profession has never developed standardized systems for teaching technical knowledge to surgeons who have completed residency training and are in practice.

(Send correspondence to F. Tendick. E-mail: frank@robotics.eecs.berkeley.edu)

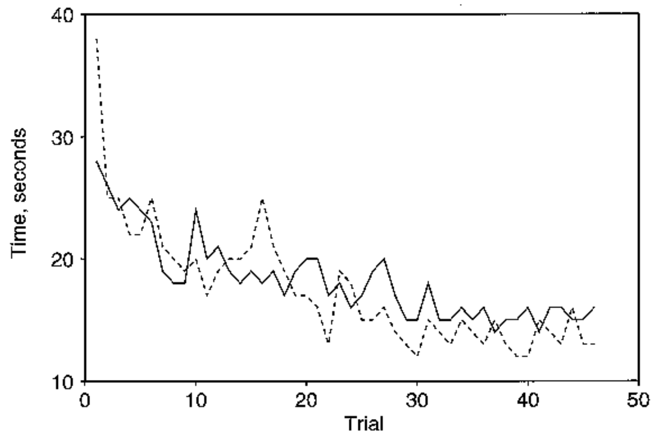

Figure 1. Performance of point-to-point movements under laparoscopic conditions by an experienced laparoscopic surgeon (solid) and a medical student with no previous experience (dashed). Many novices can quickly gain skill comparable to an expert in this task.

Because new instruments are being developed at a rapid pace, techniques are also changing rapidly. Simultaneously, new procedures are becoming popular. The reduced pain, scarring, and recovery times associated with minimally invasive methods have made surgery the treatment of choice for diseases that were most often treated medically, such as gastroesophageal reflux disease (GERD). The skills necessary to perform these operations cannot be acquired in 1 or 2 day courses in the animal laboratory.[1] Additional methods of training, education, and assessment are necessary.

1.1. Advantages of Virtual Environments

Training in the operating room could increase risk to the patient and slow the operation, resulting in greater costs. Teaching effectiveness may be suboptimal. 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 difficult to develop standards for training or assessment.

Other methods of training have limitations. Books are not interactive and cannot portray anatomy in three dimensions. Live animals are expensive and cannot demonstrate the changes resulting from disease. Furthermore, 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 the important anatomical variations and changes resulting from disease, 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 can practice in their free moments. Changes can be made that demonstrate variations in anatomy or disease state. 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 the tissues from perspectives that would be impossible during a real operation.

1.2. Assessing and Training Surgical Skills

Because there are no standardized training methods in surgery, there is little information concerning the essential skills that must be trained and assessed. We have developed a series of tasks to assess perceptual motor ability.[2] Performance curves of 50 trials by novice subjects showed a wide range of ability in the tasks, although they all improved substantially during the experiment. These basic perceptual motor skills might be learned by practice, without the need for special training. For example, most novices can quickly learn to perform three dimensional point-to-point movements with laparoscopic instruments, despite the confounding nature of videoscopic imaging and the fulcrum effect of instruments through the cannula (Figure 1). The results of these experiments are now being prepared for publication.

Some skills, most notably laparoscopic intracorporeal suturing and knot tying, are complex tasks that must be explicitly trained. Other important skills are harder to define. Proper exposure is essential in any operation. The surgeon must orient the tissues for good vision and access, place the laparoscope to obtain an adequate view, and apply traction on tissues in a way that facilitates dissection. An inexperienced surgeon struggling as he performs a procedure will often find it far simpler after an expert makes only a few adjustments of the camera and instruments that provide better exposure.

Exposure skills appear to be predominantly spatial, rather than perceptual-motor. There are many approaches to understanding spatial skills, including psychometric, developmental, and experimental.[3] For present purposes, they may be defined as skills that require mental representation of relationships, and the ability to plan action, in three dimensional space. Several studies have shown strong correlations between standardized tests of spatial ability and performance ratings on a variety of tasks in open surgery.[4–7] It is likely that laparoscopic surgery would be at least as strongly dependent on spatial ability.

An example of an important spatial skill in laparoscopic surgery is the use of a laparoscope with the objective lens angled with respect to the laparoscope axis. Development of a virtual environment for training this skill is described in section 2.

1.3. Training Critical Steps of a Procedure

Many experimental and commercial prototype environments for training have tried to simulate entire operations, resulting in low fidelity in each of the component tasks comprising the operation. This is an inefficient and probably ineffective approach. It is relatively easy to learn most steps of a procedure by watching and participating. In every procedure, however, there are a few key steps that are more likely to be performed incorrectly and to result in complications. The significance of these steps might not be obvious, even to an experienced surgeon, until situations arise such as unusual anatomy or uncommon manifestations of disease. The value of a surgical simulator is analogous to the value of a flight simulator. In current practice, pilots are certified to fly by confronting simulated situations, such as wind shear or engine emergencies, that happen only once in a lifetime, if at all. A surgical simulator should train surgeons for the principal pitfalls that underlie the major technical complications. Such training and assessment could be used by medical schools, health administrations, or professional accrediting organizations to enforce standards for granting surgical privileges and for comparing patient outcomes with surgeon skill.[8,9]

One of the most significant errors than can occur during the cholecystectomy is bile duct injury. The development of a virtual environment to train surgeons how to avoid bile duct injuries is described in section 3.

2. ASSESSING AND TRAINING SPATIAL SKILLS: ANGLED LAPAROSCOPE SIMULATION

In laparoscopic surgery, the fulcrum at the abdominal wall limits the range of motion of the laparoscope. Consequently, the viewing perspective within the abdomen is also limited. If the objective lens is aligned with the laparoscope axis, it is only possible to view from directions centered at the fulcrum. Some regions may be obscured by neighboring organs, or it may be impossible to view important structures *en face*. Laparoscopes with the objective at an angle with respect to the laparoscope axis are preferred and are often essential for many procedures, as they expand the range of viewing orientations (Figure 2).

Although the concept of the angled laparoscope is simple, in practice its use can be difficult. For example, to look into a narrow cavity (shown as a box in Figure 2), the laparoscope objective must point along a line into the cavity. Because of the constrained motion of the laparoscope, there is only one position and orientation of the laparoscope that will place the lens view along this line. (Or, more strictly, there is a narrow range of position and orientation that will suffice, depending on the width of the cavity.) The viewer can only see the location of the cavity relative to the current video image, and consequently must use spatial reasoning to estimate how to achieve the necessary laparoscope location.

In teaching laparoscopic surgery, we have observed that experienced laparoscopic surgeons exhibit a wide range of skill in using the angled laparoscope. Unskilled use of the laparoscope makes it difficult to obtain adequate exposure, potentially resulting in errors. Consequently, we have developed a virtual environment designed specifically to train the use of the angled laparoscope.

The simulated environment was implemented in Performer on a Silicon Graphics O2 workstation. Input to the simulation is through the Virtual Laparoscopic Interface (Immersion Corp., Santa Clara, CA). The device has optical encoders to measure motion of a handle in four degrees of freedom, with kinematics identical to a laparoscopic

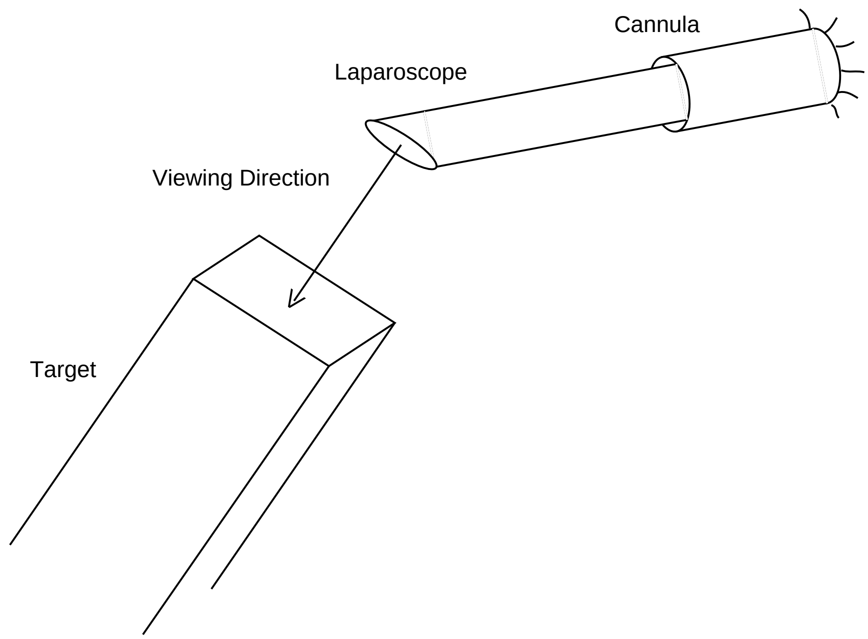

Figure 2. Angled laparoscope concept. The laparoscope passes through a cannula, which is constrained by the fulcrum at the abdominal wall. The objective lens is angled with respect to the laparoscope axis.

instrument. By turning the handle about its axis, the orientation of the simulated laparoscope is changed. Camera orientation is not currently measured. The simulation models the effect of a 45 degree laparoscope.

The environment comprises six targets, each a tall box suspended in space at a different position and orientation (Figure 3). The test begins with the laparoscope pointed at the first target. One of the other targets changes color, and the subject must position and orient the laparoscope to view all four corners at the bottom of the target box. When this view is demonstrated, the experimenter hits a key and the process is repeated for the next target in sequence. The subject's score is the total time to view all targets.

The simulation has been tested informally at UCSF in both the Advanced Videoscopic Surgery Training Course for practicing surgeons and in a basic laparoscopic surgery course for first year surgical residents. The latter group had little prior experience in handling the laparoscope in the operating room (mean of 6.5 cases, range 0 to 30, $n = 13$). Participants performed three cholecystectomies in pigs during the one day course, one each as surgeon, assistant, and camera operator. Thus each had experience operating an angled laparoscope in one procedure during the day. The median time to complete the test was 94 seconds, with a range of 35 seconds (for the subject with 30 procedures experience) to 305 seconds (for a subject with no prior experience).

In the advanced course, practicing surgeons experienced in performing laparoscopic cholecystectomies learn advanced procedures over 2-1/2 days. Approximately 12 hours are spent performing procedures on pigs, with participants taking turns as surgeon, assistant, and camera operator. Angled laparoscopes are used in all procedures. The simulation has been used in three course offerings so far, but we have not attempted to test all participants. Instead, primarily participants who appear to have difficulty operating the laparoscope in the lab are tested and coached in the simulation. Consequently, we have seen a much wider range of performance than in the basic course. One participant needed over 26 minutes to complete the task, even with substantial coaching from the experimenter, and despite having used angled laparoscopes in his practice.

The difficulty that some experienced surgeons have in using angled laparoscopes suggests that this is a skill that cannot be learned by every individual through experience and repetitive practice only. Instead, explicit training may be necessary using progressively more difficult examples and demonstrations of successful strategies. Unfortunately, there is little experience in the psychology literature on training spatial skills. The subjects who had difficulty in this task were also often observed to have general difficulty with exposure skills in vivo. This may be indicative of low spatial ability.

The next step in the development of the angled laparoscope simulation will be to obtain performance curves on a substantial number of novices by testing them in repeated trials. This will serve three objectives. First, it will determine the reliability of the test, or the variability between trials by a single subject. Second, it will provide data on individual learning rates. Based on our experience so far, we expect these will vary considerably. Finally, by running the subjects through a battery of standardized tests, we can correlate performance on the task with known measures of components of spatial ability.

After reliability is established, we must test for construct validity by showing that performance in the simulation correlates with a meaningful measure of skill in vivo. We are developing a task analysis as a foundation for in vivo skills assessment. We will also attempt to develop and validate a training system for subjects who have difficulty.

3. TRAINING CRITICAL PROCEDURES: LAPAROSCOPIC CHOLECYSTECTOMY SIMULATION

Laparoscopic surgery became practical with the introduction of the compact CCD camera, which could be conveniently mounted on a laparoscope. The first laparoscopic cholecystectomy (gallbladder removal) was performed in 1985.[10] The faster recovery and reduced pain of laparoscopic compared with open cholecystectomy led patients to demand it, and surgeons adopted it at an unprecedented pace. By 1993, 67% of cholecystectomies in the U.S. were performed laparoscopically.[11]

This rapid adoption of a radically new procedure was possible because the cholecystectomy is technically relatively easy to perform. Nevertheless, there are technical hazards and the frequency of bile duct injury increased sharply at this time.

The bile ducts (Figure 4) carry bile created in the liver to the gallbladder. There it is stored and concentrated until it is released into the intestine. Bile duct injury can be the result of poor technique or misinterpretation of the anatomy. The cystic duct, which leads directly from the gallbladder, must be cut before the gallbladder can be removed. In Figure 4, the cystic duct is easily identified, clipped, and cut. In reality, however, the biliary tree is obscured by connective tissue. The surgeon may confuse the common bile duct (the large duct leading to the intestine) for the cystic duct. If so, the common duct may be inappropriately divided. The repair of this injury is difficult, and since it usually goes unnoticed during the procedure, it requires a second operation.

One prospective study found a high rate (2.2%) of bile duct injuries in procedures performed by inexperienced laparoscopic surgeons.[12] Experienced surgeons also had injuries, although at a lower rate (0.1%). Based on our analysis of 139 bile duct injuries, a few simple rules have been developed to reduce the likelihood of injury:

- Use lateral traction on the infundibulum of the gallbladder during dissection. This draws the cystic duct to full length and maximizes the difference in lie of the cystic and common ducts.
- Dissect any potential space between gallbladder and cystic duct completely. This will help uncover a hidden cystic duct when the gallbladder is adherent to the common duct.
- Clear the triangle of Calot enough to show the hepatic side of the infundibulum of the gallbladder. This allows the cystic duct to be identified with greater certainty, since it will be found as a continuation of the gallbladder.
- Use an angled scope to gain the optimal (*en face*) view of the triangle of Calot.
- If the duct about to be clipped will not fit entirely within a 9mm clip, assume it is the common duct.
- Any duct that can be traced to disappear behind the duodenum has to be the common duct.

The virtual environment shown in Figure 4 is being developed to teach proper techniques that should avoid bile duct injuries. It is written in C and OpenGL, currently running on a Silicon Graphics Octane workstation. The anatomic data is from the Visible Human male, using liver, gallbladder, and biliary tree manually segmented by Visible Productions LLC (Fort Collins, CO). Deformation of the gallbladder, biliary tree, and fat are modeled using a dynamic mesh of mass nodes connected by spring-damper elements. Currently, the user interacts with the simulation through the Virtual Laparoscopic Interface (Immersion Corp., Santa Clara, CA). Although this device does not provide force feedback, interaction forces are calculated by the simulation's tissue deformation modeling algorithm. As soon as a force feedback device with proper kinematics and a PCI interface is developed, it can be incorporated into the environment. Details of the implementation of the environment can be found in Downes et al.[13]

In the current simulation, the user must dissect through a single layer of overlying fat to see the biliary structures (Figure 4). The dissection is achieved by removing small regions of fat with a simulated electrosurgical tool. Although the simulated fat performs the function of hiding the key structures, it is not anatomically accurate. We are developing a version in which the structures are joined by adhesions. The gallbladder must be retracted to expose the cystic duct, which is clipped in two places so that it can be cut between the clips. It is easy to identify the cystic duct in the Visible Human male. In future versions, variations in which greater difficulty is encountered can be created. Anatomic variations of the biliary tree can also be simulated.

The current simulation runs at interactive speeds on the SGI Octane. The graphics capability of this mid-range workstation is sufficient for relatively detailed models. The computationally intensive aspects of simulation are the modeling of tissue deformability and collision detection between the instruments and tissue. The mass-spring-damper deformable models used in the current simulation cannot accurately model tissue properties. Fortunately, accuracy is not likely to be necessary to train procedural strategies like avoiding bile duct injuries, as long as objects deform in a qualitatively plausible manner. Nevertheless, we are attempting to develop fast and accurate modeling algorithms, based on finite element methods, that can reproduce tissue properties in applications where accuracy is necessary. These algorithms will be integrated into a general purpose simulation tool so that virtual environments can be created easily to model any anatomy or procedure.

Establishing predictive validity of a training tool like the cholecystectomy simulation will be difficult. The validity of flight simulators can be established by tracking pilot errors and accidents over a long period and correlating errors with training methods. Unfortunately, there is no equivalent of the Federal Aviation Administration in medicine that could track surgical outcomes on a large scale. Because bile duct injuries occur rarely, data from many surgeons and patients will have to be collected to obtain statistical significance in comparing training methods. In the future, large health maintenance organizations may be able to collect sufficient data, and have the incentive to do so. Virtual environments can generate objective performance data that have not been available in traditional training methods.

4. CONCLUSION

The two virtual environments developed so far demonstrate that current workstations have enough power for training tools. The rapid decline in the cost of computing predicts that personal computers will soon have similar capabilities.

The large range of performance seen among users of the angled laparoscope simulation suggests that there is wide variability in spatial ability among experienced surgeons. We must now establish reliability and validity of the simulation, and attempt to develop training methods for those users who have difficulty. We are analyzing the role of spatial and perceptual motor skills in surgery and how to teach these skills. Task analyses will aid in identifying critical skills.

The cholecystectomy simulation will be refined with better deformable tissue modeling and collision detection. To create a better training tool, adhesions and anatomical variations of the biliary tree will be modeled. We are simultaneously analyzing the events that lead to errors in laparoscopic surgery to better understand the critical steps that must be trained.[14]

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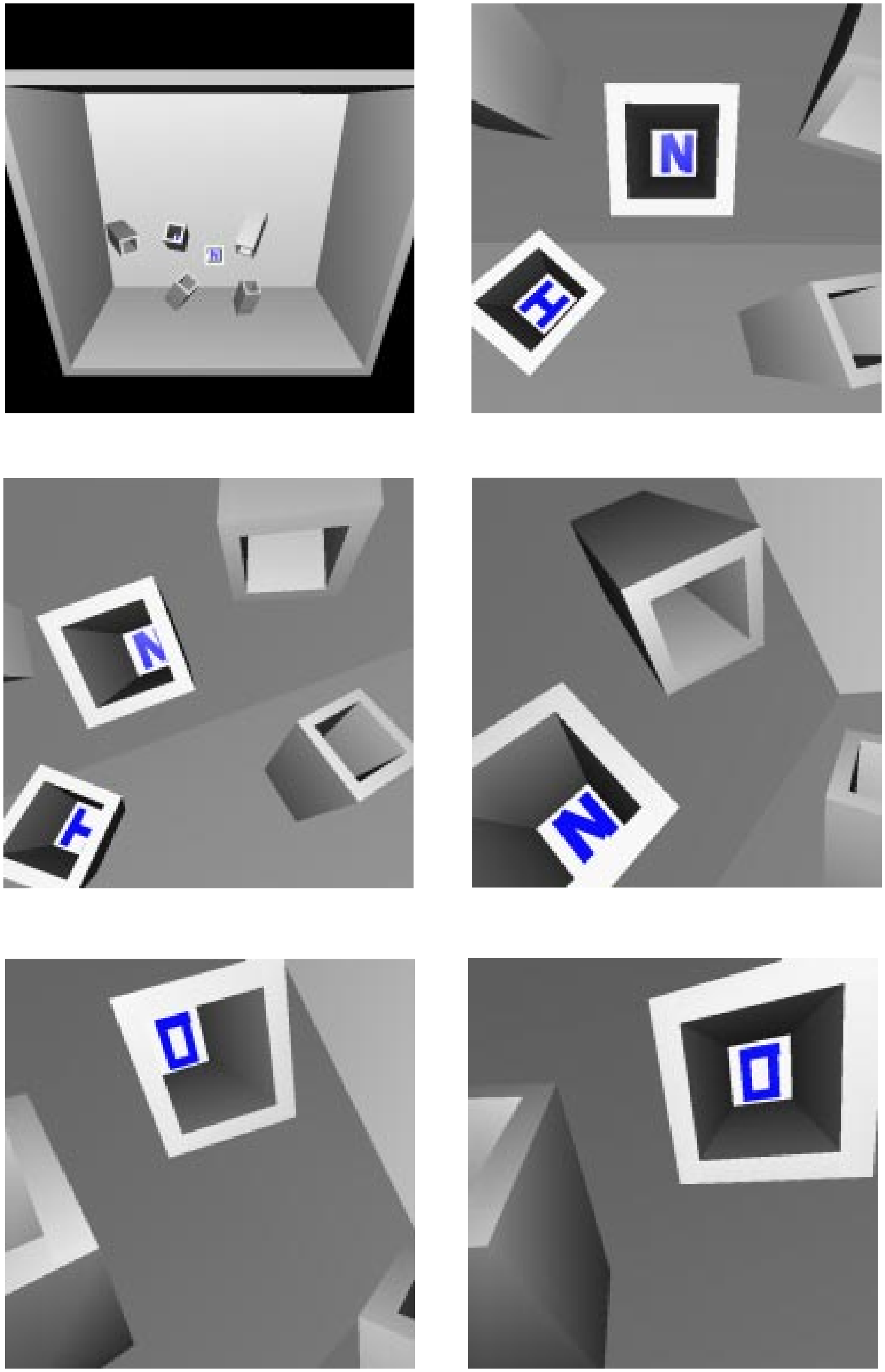

Figure 3. Angled laparoscope simulation. Upper left shows distant view of targets suspended at different positions and orientations. Remaining images show a sequence as the user smoothly changes the laparoscope position and orientation from view of target "N" to target "O".

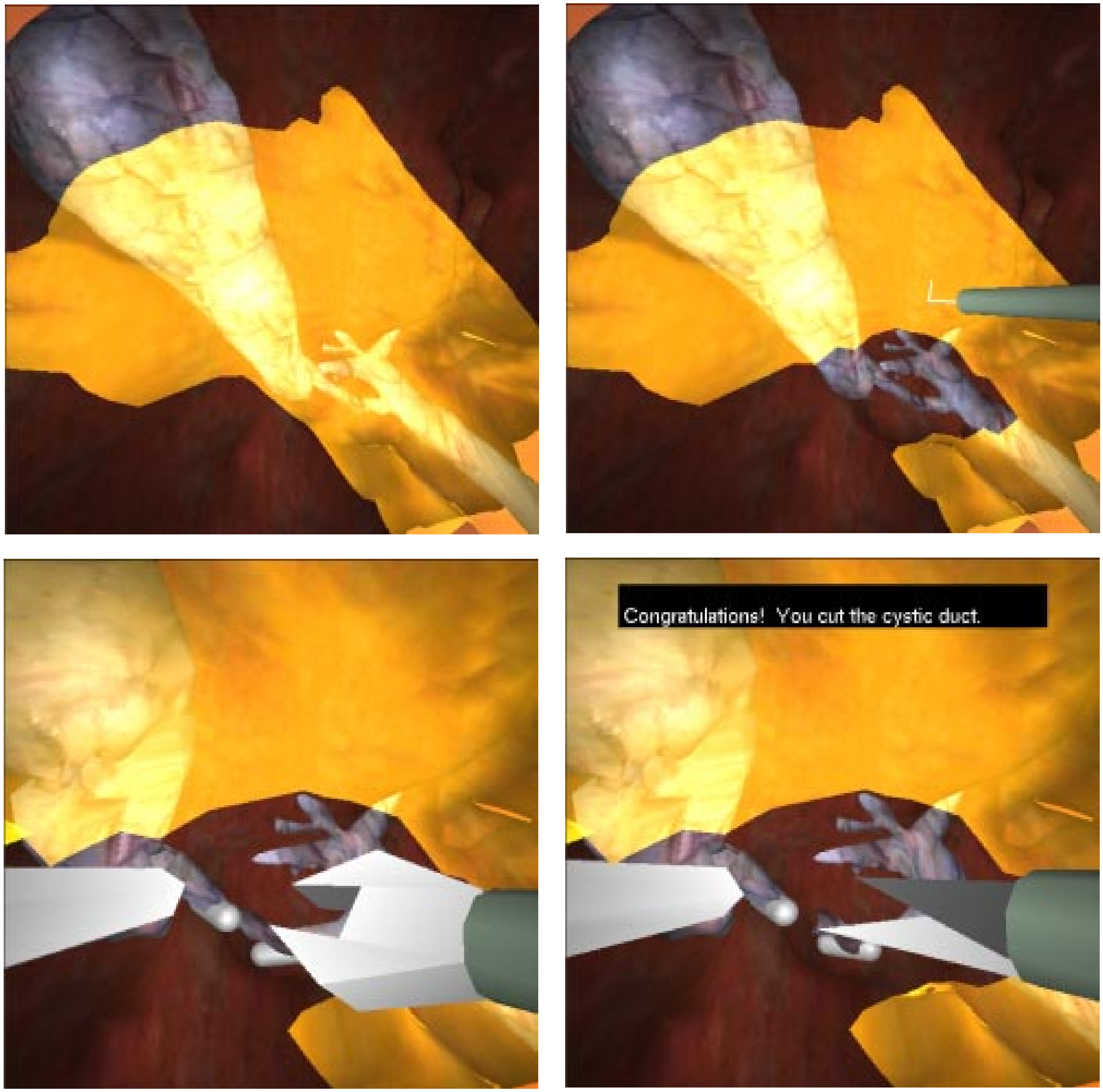

Figure 4. Laparoscopic cholecystectomy simulation showing gallbladder, biliary ducts, and liver. Occluding fat and connective tissue is currently represented by a single translucent sheet. (a) intact anatomy; (b) occluding tissue is dissected; (c) lateral traction is placed on gallbladder and cystic duct is clipped; (d) cystic duct is successfully cut.