A Virtual Environment Testbed for Training Laparoscopic Surgical Skills

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Abstract

With the introduction of minimally invasive techniques, surgeons must learn skills and procedures that are radically different from traditional open surgery. Traditional methods of surgical training that were adequate when techniques and instrumentation changed relatively slowly may not be as efficient or effective in training substantially new procedures. Virtual environments are a promising new medium for training.

This paper describes a testbed developed at the San Francisco, Berkeley, and Santa Barbara campuses of the University of California for research in understanding, assessing, and training surgical skills. The testbed includes virtual environments for training perceptual motor skills, spatial skills, and critical steps of surgical procedures. Novel technical elements of the testbed include a four-DOF haptic interface, a fast collision detection algorithm for detecting contact between rigid and deformable objects, and parallel processing of physical modeling and rendering. The major technical challenge in surgical simulation to be investigated using the testbed is the development of accurate, real-time methods for modeling deformable tissue behavior. Several simulations have been implemented in the testbed, including environments for assessing performance of basic perceptual motor skills, training the use of an angled laparoscope, and teaching critical steps of the cholecystectomy, a common laparoscopic procedure. The major challenges of extending and integrating these tools for training are discussed.

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. This model has survived in part because of the limitations of the training media available outside the operating room for teaching surgical skills, and in part because the techniques of traditional open surgery mostly rely on familiar eye-hand coordination, allowing most residents to achieve competence by repeated practice.

Two events are occurring that may lead to a significant change in the nature of surgical training. First, increasing numbers of surgical procedures are performed using minimally invasive techniques, in which trauma to external tissue is minimized. The skills of minimally invasive surgery (MIS) present unique perceptual-motor relationships that make these skills difficult to master. Second, virtual environments with the capability to teach surgical skills are becoming available.

Virtual environments are a promising medium for surgical training, just as they have been effective in pilot training. If virtual environments are to achieve their potential in surgical training, however, research is necessary in two major areas. First, the technical elements of simulation, especially the dynamical modeling of the mechanical behavior of tissue, limit the realism of interaction with virtual anatomy in comparison to the complexity of real tissue. The second need is the development of a better understanding of the basis of procedural skills in surgery. There has been very little research effort toward understanding the perceptual-motor and cognitive processes that contribute to surgical performance. Virtual environments are a versatile medium for performing experiments to elucidate the basis of skill in surgery. This paper describes a testbed and research program, a cooperative effort between the San Francisco, Berkeley, and Santa Barbara campuses of the University of California, for training laparoscopic surgical skills in which both aspects of simulation can be advanced.

1.1 The State of Surgical Training

Although learning by apprenticeship in the operating room (OR) has benefits, it has major disadvantages as well. Although residents are supervised by experienced mentors, there is nevertheless potential risk to the patient. Operations proceed slowly, resulting in greater costs. Teaching effectiveness in the OR environment may be suboptimal. A stressful environment can reduce learning, and students are not free to experiment with different techniques to see which might be best for them. Because every mentor teaches his or her own technique, it is difficult to develop standards for training or assessment.

Despite the limitations of teaching in the OR, media for learning outside the OR have had little impact because of their own limitations. Although journal articles, textbooks, videos, and CD-ROMs can demonstrate steps of procedures, they are poor media for training skills because they are two-dimensional and the user cannot physically interact with them. 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 is 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.”

Training in the OR has endured because of these limitations of alternative media and because the techniques of traditional open surgery mostly rely on familiar eye-hand coordination. Consequently, most residents can achieve competence by repeated practice. Although procedures change, experienced surgeons can learn them relatively quickly because the fundamental techniques change little. With the introduction of new minimally invasive and image-guided techniques, perceptual-motor relationships are unfamiliar. The introduction and successful adoption of these techniques is often impeded by the inability to effectively train residents and practicing surgeons in their use.

Increasing numbers of surgical procedures are performed using minimally invasive techniques, in which trauma to external tissue is minimized. Laparoscopic surgery, or minimally invasive surgery of the abdomen, has undergone rapid growth in the last decade. In these procedures, a laparoscope is inserted with a cannula through a 10 mm dia. incision in the abdominal wall (Way, Bhoyrul, & Mori, 1995). 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, can be inserted through separate 5–10 mm cannulas. Typically, the primary surgeon works with two assistants to hold the laparoscope and retract tissue.

With the introduction of minimally invasive techniques, perceptual-motor relationships are unfamiliar (Tendick et al., 1993). The operative site is viewed as a 2-D image on a video screen. The relationship between visual and motor coordinates changes as the laparoscope moves. Dexterity is reduced to four degrees of freedom of movement by the fulcrum in the body wall. Tactile sensation (the perception of surface shape, compliance, texture, and temperature by the receptors in the fingertip) is lost. Kinesthetic feedback of forces exerted on tissue is significantly reduced. Consequently, surgeons must learn radically new skills to perform minimally invasive procedures.

With the benefits of minimally invasive surgery, new procedures are becoming popular. The reduced pain, scarring, and recovery times associated with minimally invasive methods have made such surgery the treatment of choice for diseases that were most often treated medically, such as gastroesophageal reflux disease. The skills necessary to perform these operations cannot be acquired in one- or two-day courses in the animal laboratory (See, Cooper, & Fisher, 1993). Additional methods of training, education, and assessment are necessary.

1.2 Virtual Environments for Surgical Training

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

Many research groups have recognized the potential of virtual environments and developed surgical applications. Most have emphasized minimally invasive procedures, both because of the need for better training media in MIS and because the impoverished MIS interface—which eliminates cutaneous tactile feedback, reduces kinesthetic force feedback, and limits visual information—also makes it easier to reproduce the actual feedback the surgeon receives in a virtual environment. Applications include laparoscopic surgery (Kuhnapfel et al., 1997; Szekely et al., 1999), endoscopy of the colon (Baillie et al., 1991; Ikuta, Takeichi, & Namiki, 1998) and sinus (Wiet et al., 1997), arthroscopy (Gibson et al., 1997; Muller & Bockholt, 1998; McCarthy, Harley, & Smallwood, 1999; Smith et al., 1999), bronchoscopy (Bro-Nielsen et al., 1999), endoscopic retrograde cholangio-pancreatography (Peifer, Curtis, & Sinclair, 1996), retinal laser photocoagulation (Dubois et al., 1998), phacoemulsification of cataracts (Sinclair et al., 1995), and spinal biopsy and nerve blocks (Blezek et al., 1998; Cleary, Lathan, & Carignan, 1998). Most of these efforts have focused on a single application, but one notable exception is the Teleos toolkit (Higgins et al., 1997a) which permitted the development of a variety of simulations based on deformable tubes, such as coronary artery catheterization, ureteroscopy, and neuroendoscopy of the ventricles.

Many research efforts have focused on the development of real-time methods for simulating the physical behavior of deformable tissue and the integration of these methods into simulators. Although finite-element methods are the most accurate, they are computationally intensive. When linear elastic models are used, much of the costly computation can be performed offline during development of the simulation, rather than in real time (Berkley et al., 1999; Bro-Nielsen, 1998; Cotin et al., 1996). Other means of implementing finite elements in real time include using parallel computing (Sagar et al., 1994; Szekely et al., 1999) and using local and global models of differing complexity (Hansen & Larsen, 1998). Other research groups have developed innovative approximate methods for real-time modeling of tissue (Gibson et al., 1997; Suzuki et al., 1998; Basdogan, Ho, & Srinivasan, 1999; De & Srinivasan, 1999). The most common method is to model a surface or volume as a mesh of mass, spring, and damping elements (Henry et al., 1998; Kuhnapfel et al., 1997; Neumann, Sadler, & Gieser, 1998). Another popular approximate method is to use deformable contours (Cover et al., 1993) or splines (Higgins et al., 1997a). The major limitation of schemes that do not rely on finite elements is that there is no way to incorporate accurate material properties into these methods through constitutive models.

Another major research emphasis in surgical simulation has been the development of haptic interfaces and methods. Haptic (that is, kinesthetic or force) sensation is important in the performance of many surgical skills, yet research in haptic interfaces is relatively young. Novel interfaces have been designed and incorporated into simulations for teaching epidural anesthesia (Stredney et al., 1996), flexible endoscopy (Ikuta et al., 1998), laparoscopic surgery (Asana, Yano, & Iwata, 1997), and catheter navigation (Wang et al., 1998). Suzuki et al. (1998) developed a 16 degree of freedom (DOF) device to provide force feedback to the hand, thumb, forefinger and middle finger to simulate open surgery. Stredney et al. (1998) compared haptic feedback with volumetric and surface models using a three-DOF interface in simulations of endoscopic sinus surgery. They found that the slow computation of the volumetric model induced oscillation.

The majority of research efforts have focused on the development of virtual environments, and there have been relatively few assessments of the effectiveness of environments for training. Some studies have compared the performance of simulated skills by subject groups with different skill levels, such as attending surgeons, residents, and medical students (Johnston et al., 1996; McCarthy et al., 1999; O'Toole et al., 1998; Smith et al., 1999; Taffinder et al., 1998; Weghorst et al., 1998). Better performance by the experienced subjects as compared to the other groups in these studies suggest that performance in the simulations is a measure of achieved skill in the associated specialty. These studies did not measure training effectiveness, however. Tuggy (1998) did measure the effectiveness of simulator training for flexible sigmoidoscopy by residents. He demonstrated the benefit of five hours of simulator training prior to the first performance of the procedure in a live patient, especially in component measures that were strongly dependent on eye-hand skills. Experiments by Peugnet, Dubois, and Rouland (1998) suggest that resident training in their retinal photocoagulation simulation may actually be more effective than training with patients. This is possible because a large library of anatomical variations can be represented in simulation, whereas the number of patients available to residents is limited (five to eighteen patients over a period of 39 to 53 days of training). Consequently, the ready availability of simulation could permit residents to achieve more-varied practice. This study was limited by a very small subject population, however, and results may have been influenced by possibly different abilities of the experimental and control groups.

The goal of the testbed described in this paper is to integrate research on the technical aspects of virtual environments, including deformable tissue modeling and haptic and visual interfaces, with research to elucidate the cognitive processes of surgical skill and to evaluate the effectiveness of virtual environments for training skills. We believe that it is essential to study the technical and training aspects simultaneously. The technical elements contribute to realism of the simulations, which will affect training transfer to the real environment. Conversely, understanding how surgeons perform complex tasks can guide the development of the virtual environments and suggest which elements of the simulation are necessary for effective training.

1.3 Components of Surgical Skill

An important goal of our research effort is to better understand what contributes to skill in surgery and the cognitive processes that underlie performance. Because there are few standardized training methods in surgery, there is little information concerning the essential skills that must be trained and assessed. Most research has relied largely on the intuition of experienced surgeons as to the component skills in surgery and has not been informed by cognitive models (Winckel et al., 1994; Bhoyrul et al., 1994; Hanna et al., 1998; Derossis et al., 1998; Rosser Jr., Rosser, & Savalgi, 1998). Methods of identifying component skills in a complex domain include consultation with content-matter experts (Higgins et al., 1997b) and task, skills, or error analyses (Patrick, 1992; Seymour, 1966; Gantert et al., 1998). The perceptual motor consequences of degraded visual information, reduced dexterity, and limited haptic sensation in laparoscopic surgery have been identified (Tendick et al., 1993; Breedveld, 1998), and detailed time and motion studies have also been performed (Cao, MacKenzie, & Payandeh, 1996; Sjoerdsma, 1998). Nevertheless, these studies have done little to elucidate the underlying cognitive demands in surgery. While experts can provide declarative information (which can be described verbally) on strategies, key skills, critical steps, and common errors, much surgical experience consists of procedural knowledge in the form of perceptual-motor or spatial skills that cannot be expressed verbally.

Consequently, unlike training in the domains of aviation, military, and even professional sports, there is poor understanding of the basis of skill in surgery. Because the OR environment is not conducive to carrying out experiments, it would be difficult to perform research or develop methods of assessment that could lead to better training unless an alternative medium is available. Virtual environments permit controlled conditions under which we can elucidate the elements of skill and test models of the underlying representations and processes. Of course, the virtual environments must have sufficient similarity to the real environment to create transfer between the artificial and real situations. We will introduce some of the ways we plan to use virtual environments to study perceptual motor skills, spatial skills, and critical steps of procedures. Simultaneously, we will discuss the parallel issues of how to train these skills and validate training effectiveness.

1.3.1 Perceptual Motor Skills. It is still poorly understood how surgeons learn and adapt to the unusual perceptual motor relationships in minimally invasive surgery. Virtual environments may be a valuable tool in understanding the development of perceptual motor skills and their relationship to higher cognitive abilities and skills in surgery. On the other hand, the perceptual cues that surgeons use, both visual and haptic, are complex. Some of these cues, such as subtle lighting changes or differences in tissue consistency, may be difficult to reproduce in a virtual environment. Their role in performance and training must be understood if we are to determine which skills can be taught in simulation and which require practice in vivo. To study visual and haptic cues, we are initially exploring point-to-point movements in a relatively simple environment described in section 4.1.

1.3.2 Spatial Skills. Some skills, most notably laparoscopic suturing and knot tying, are complex tasks that must be explicitly trained. Other important skills are harder to define, and appear to depend on spatial cognitive ability. An example is obtaining proper exposure, which 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. Spatial skills or abilities involve the representation, storage, and processing of knowledge of the spatial properties of objects (such as location, movement, extent, shape, and connectivity). There are large individual differences in spatial abilities (Eliot, 1987). Several studies have shown high correlations between standardized tests of spatial ability and performance ratings on a variety of tasks in open surgery (Gibbons, Gudas, & Gibbons, 1983; Gibbons, Baker, & Skinner, 1986; Schueneman et al., 1984; Steele, Walder, & Herbert, 1992). It is likely that laparoscopic surgery is more dependent on spatial ability, because there is less perceptual information available (for example, through vision and touch) so that planning of action is more dependent on internal representations of spatial information.

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. This will be discussed more fully in section 4.2, which describes the development of a virtual environment to train this skill.

1.3.3 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 that comprise 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, a few key steps 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 (Grundfest, 1993; Higgins et al., 1997b).

Cholecystectomy, or removal of the gallbladder, is commonly performed laparoscopically. One of the most significant errors that can occur during the laparoscopic cholecystectomy is bile duct injury. The development of a virtual environment to train surgeons how to avoid bile duct injuries is described in section 4.3.

1.4 An Integrated Approach

This paper describes an integrated effort of the Virtual Environments for Surgical Training and Augmentation (VESTA) project between the San Francisco, Berkeley, and Santa Barbara campuses of the University of California to develop a testbed for research in understanding, assessing, and training surgical skills. The testbed includes virtual environments for training perceptual motor skills, spatial skills, and critical steps of surgical procedures. It supports research in both the technical aspects of simulation and the application of virtual environments to surgical training. The current implementation of the testbed is described in section 2. Technical challenges, especially realistic modeling of tissue mechanical behavior, are described in section 3. Our current foci of research in understanding, assessing, and training surgical skills are described in section 4, while challenges in training are discussed in section 5.

2 Implementation

The simulations run on a dual-processor Silicon Graphics Octane workstation with MXE graphics. They are implemented in C and OpenGL. Novel technical elements of the testbed include a four-DOF haptic interface, a fast collision detection algorithm for contact between rigid and deformable objects, and parallel processing of physical modeling and rendering.

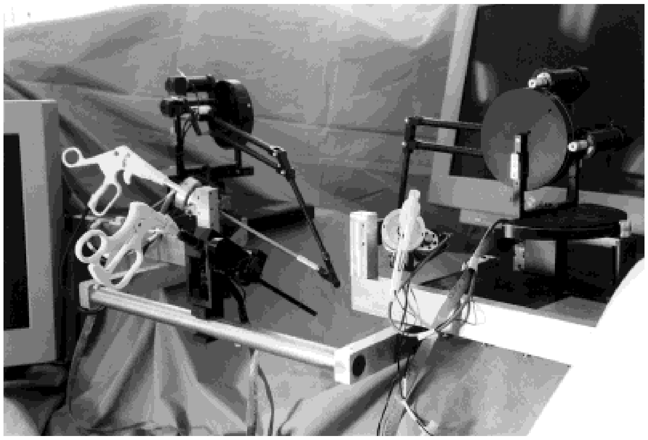


Figure 1. *Laparoscopic haptic interface. Force-feedback devices with four degrees of freedom are provided for the user's left and right hands to control simulated instruments in the virtual environment. A third device in the center has four degrees of freedom without force feedback. It is intended to control simulated laparoscope motion, although it is shown here with a trigger instrument handle.*

2.1 Interface

Motion of a laparoscopic instrument is constrained to four degrees of freedom by the fulcrum at the incision through the abdominal wall. To produce a four-DOF interface with proper kinematics and force feedback, we modified a PHANToM three-DOF haptic interface from Sensable Technologies. The fulcrum was added with a gimbal arrangement (figure 1). For torque about the instrument axis, we achieved high torque, stiffness, minimal friction, and smooth power transmission from a DC motor through a wire-rope capstan drive and a linear ball spline. The spline made it possible to smoothly transfer torque to the tool shaft while allowing it to translate. Low inertia was guaranteed by concentrating the mass of the system near the pivot.

The entire laparoscopic workstation comprises a pair of four-DOF interfaces to control two simulated instruments, a four-DOF interface with encoders but no force feedback to command motion of the simulated laparoscope (modified from a Virtual Laparoscopic Interface from Immersion Corp.), and a supporting adjustable frame to allow different laparoscope and instrument configurations (figure 1). Communication with the computer is through parallel and serial ports and the PHANToM PCI interfaces.

For the visual display, the environments use a single monoscopic display rather than a head-mounted display or stereographic monitor. This is because monoscopic displays are still the standard in surgery because of the expense and limitations of stereo displays (Tendick, Bhoyrul, & Way, 1997). To simulate open surgery, or as better displays become available in minimally invasive surgery, it would be simple to incorporate stereo interfaces into the system.

2.2 Tissue Modeling

To provide a meaningful educational experience, a surgical training simulation must depict the relevant anatomy as accurately as possible. In addition, the physical model is closely tied to the geometric models of objects in the environment, so accurate geometric models enable 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 data set. Such manual segmentation produces high-fidelity models but at the cost of large amounts of time spent identifying structures in 2-D slices of the overall data set. To the anatomical models we have added flexible sheets to represent fat and connective tissue. These sheets are joined to the underlying anatomy and must be dissected to reveal the organs. We are also experimenting with fast automatic segmentation techniques (Malladi & Sethian, 1996) to incorporate real patient data into the simulation.

To imbue the anatomical models with the characteristics of deformable objects, simple lumped parameter models are used, composed of mass-spring-damper meshes. As in much of the work in physically based modeling in computer graphics, a triangulated model is interpreted 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 that coincide with the edges of the triangles and have equilibrium lengths equal to the initial lengths of their equivalent edges.

We experimented with several different integration schemes, model natural frequencies, and integration step sizes to optimize display frame rates (Downes et al., 1998). Because qualitatively reasonable behavior—rather than quantitative accuracy—is satisfactory for simulation, a fast integration scheme like Euler's method can be used. To minimize unnecessary calculation, the force exerted on each node was compared to a "deadband" value at each simulation time step. Integration was skipped at that node if the force was less than this value.

A major goal of the testbed is to experiment with different deformable modeling methods. The modularity of the simulation will allow us to easily exchange the current simple scheme for new methods. The challenges of accurate real-time modeling will be discussed in section 3.

2.3 Collision Detection

Instruments must interact realistically with deformable organ models in the simulation. This requirement necessitates the development of an accurate method for detecting collisions between tools and organs. This amounts to detecting collisions between rigid and deformable objects.

A large body of literature addresses the problem of rigid body with rigid-body collision detection (for example, Canny, 1986; Lin, 1993; Cohen et al., 1995). However, many of these methods presuppose an unchanging polygon mesh representation for the objects and are thus inappropriate for our purposes. A variety of approaches in recent years have begun to address the problem of deformable object collision detection. Our method bears some similarities to volumetric approaches discussed in Gibson (1995), He and Kaufman (1997), and Kitamura et al. (1998).

Our approach takes advantage of the fact that we have a known, finite workspace in the simulation. We begin by subdividing this hexahedral workspace into a 3-D grid of voxels, all of which have the same dimensions. In a preprocessing step, we assign the vertices of all the deformable meshes in the environment to the voxels that contain them. To perform collision detection, we define "hot points" at locations on the surgical tool models that may come into contact with tissue. At each time step of the simulation, for each hot point we use the coordinates of the hot point as indices into a 3-D array representing the voxel grid to identify the deformable vertices that are in the same voxel as the hot point. If there are vertices in the same cell as a hot point, we calculate the distance between the hot point and each of these vertices. Each vertex closer than some predefined threshold is considered to be colliding with the hot point if the normal at the vertex and the motion vector for the hot point are in opposite directions. This last condition prevents tools from getting trapped inside models. Any vertex that moves as a result of a collision with a rigid object has its position in the voxel array updated.

2.4 Integration

The simulation runs on a Silicon Graphics Octane workstation with dual 250 MHz R10000 processors. It comprises two C programs, called simply *main* and *physics,* that run concurrently on the two processors. The programs are synchronized through two buffers, a control buffer and a display buffer. The control buffer contains the current simulation state, including the physical models, collision detection grid, and instrument locations. The display buffer holds a copy of 3-D geometry data of the deformable objects. The *main* program is divided into processes responsible for polling the input devices, performing collision detection, and rendering the image. The *physics* program calculates the new geometry of the deformable objects based on the current state contained in the control buffer, then dumps the new geometry into the display buffer. Synchronization between the processes maximizes the operations performed in parallel and minimizes the idle time spent waiting for other processes to finish.

The laparoscopic cholecystectomy simulation described in section 4.3 and shown in figure 5 uses a physical model with 2,800 deformable nodes. Because the liver model does not deform, many more triangles are displayed (12,371). This simulation runs at an interactive speed, roughly thirteen updates per second.

The haptic interface must run at much higher rates. The controller is called 1,000 times per second by the Unix scheduler. Currently, we use a simple time interpolation scheme to generate the displayed force for the samples between the forces calculated by the physics routine. We are experimenting with local linear reduction of the physical model to permit fast estimates of changes in forces due to local stiffness and damping (Cavusoglu & Tendick, 2000).

3 Technical Challenges

The lumped parameter models used in the current simulation (constructed as meshes of mass, spring, and damper elements) are a form of finite difference approximation. They are computationally simple and can be computed at interactive speeds. A problem with lumped parameter models, however, is the selection of component parameters. There is no physically based or systematic method for determining the element types or parameters from physical data or known constitutive behavior. Joukhadar, Garat, & Laugier (1997) use a predefined mesh topology and then determine the element parameters with a search using genetic algorithms. In other cases, the parameters are hand-tuned to get reasonable behavior. The difficulty of incorporating accurate material properties is shared by many other methods that have been proposed in the computer graphics literature for real-time modeling of deformable bodies (Metaxas, 1997; Platt & Barr, 1988; Terzopoulos & Fleischer, 1988; Gibson, 1997).

Linear finite-element methods are used by some researchers to obtain models with physically based parameters (Cotin et al., 1996; Martin, Pentland, & Kikinis, 1994). Linear models are computationally attractive as it is possible to perform extensive offline calculations to significantly reduce the real-time computational burden. However, linear models are based on the assumption of small deformation, which is not valid for much of the manipulation of soft tissue during surgery. They also cannot permit cutting of the tissue.

Unfortunately, nonlinear finite-element methods that could accurately model the behavior of tissue are computationally forbidding. However, several properties of surgical simulation may allow the modification of nonlinear methods into real-time algorithms while maintaining reasonable behavior. The important abdominal structures are often in the form of tubes or sheets, so 2-D models will often suffice. Also, accuracy is usually important only in small regions where instruments are in contact with tissue. Qualitatively plausible deformation would often be adequate outside these regions.

We are exploring several approaches to achieve real-time modeling of tissue deformation. Remeshing of a local region where an instrument grasps or cuts tissue will permit local accuracy while a coarse mesh will be adequate elsewhere. Implicit integration methods can be faster and more stable than explicit algorithms, but require significant recomputation when the mesh changes (as when tissue is cut). Consequently, we are investigating hybrid methods that maximize stability and reusable computation. Local linear approximations to nonlinear behavior will also be useful, especially for updating stable haptic interfaces at much higher rates than the visual model. Parallel algorithms, especially for remeshing, will become practical as multiprocessor computers become popular.

Of course, it will be necessary to obtain tissue properties to insert into the models. Although the viscoelastic properties of tissue can be extremely complex, reasonable training likely can be achieved with simple models using data obtained from tools mounted with position and force sensors (Hannaford et al., 1998; Morimoto et al., 1997). The necessary resolution of models is limited by the perceptual capabilities of users. We are now conducting psychophysics experiments to determine human capability to detect changes in compliance of deformable surfaces through a haptic interface (Tendick et al., 2000). Finally, the necessary accuracy of models should be experimentally determined by comparing transfer between simulations and performance in vivo using different models. The modularity of our simulation allows easy substitution of models.

4 Current Simulations

In this section, the currently implemented simulations for studying and training perceptual motor skills, spatial skills, and critical procedural steps are described. Challenges in extending these simulations and creating integrated training of the skills are discussed in section 5.

4.1 Perceptual Motor Skills

To study the significance of the altered perceptual motor relationships in minimally invasive surgery, we are exploring the performance of simple skills both in vitro and within virtual environments. Conceptually, the simplest perceptual motor skill is visually guided movement from one point to another point. Nevertheless, performance of this skill depends on the accuracy of the surgeon's mental model of the 3-D geometry of the environment and the use of visual depth cues that may be complex. Performance also depends on haptic factors. The speed and stiffness of the movement's final phase leading to contact with a surface will depend on the compliance of the surface. In addition, when movements are repeated, the surgeon can develop a haptic memory of points and surfaces. We are exploring some of these issues using simplified environments.

Freehand 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 (Jeannerod, 1988). It is likely that the initial phase is largely preprogrammed and uses minimal visual feedback. Consequently, the viewer's internal model of the 3-D 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. Our experiments with reaching using laparoscopic instruments (Tendick & Cavusoglu, 1997) and in virtual environments (Blackmon et al., 1997) show similar patterns to the free hand under direct vision, but are less accurate and have longer slow phases because of the poor geometric information provided by video and computer graphic viewing conditions.

Nevertheless, with experience, surgeons become skilled at targeted movements. Haptic cues and visual surface cues such as texture and lighting variations are probably strong aids. Haptic cues have the advantage of being invariant even when the laparoscope viewpoint changes. Surfaces have been hypothesized to be represented at a low level of visual processing (Nakayama, He, & Shimojo, 1995) and may strongly contribute to the mental reconstruction of scene geometry. Virtual environments permit experimental variation of these cues to determine their role in performance and learning. In fact, physically impossible conditions, such as a visually solid surface that is haptically penetrable, can be produced.

We are currently using several relatively simple virtual environments to explore the role of perceptual factors in point-to-point movements. We expect that the same factors will be important in more-complex skills. An example environment is shown in figure 2 in which the effect of visual surfaces is being examined. The subject must touch targets that are either not coplanar, or coplanar with or without a surface drawn to emphasize the plane. Haptically, the targets feel solid in all conditions, but the surface offers no resistance.

After describing environments for training spatial and procedural skills in the next two sections, we will return in section 5 to discuss some of the relationships between perceptual motor skills and the higher cognitive skills.

4.2 Spatial Skills: Angled Laparoscope Simulation

An example of a skill that requires the use of spatial cognition is guiding an angled laparoscope. We have

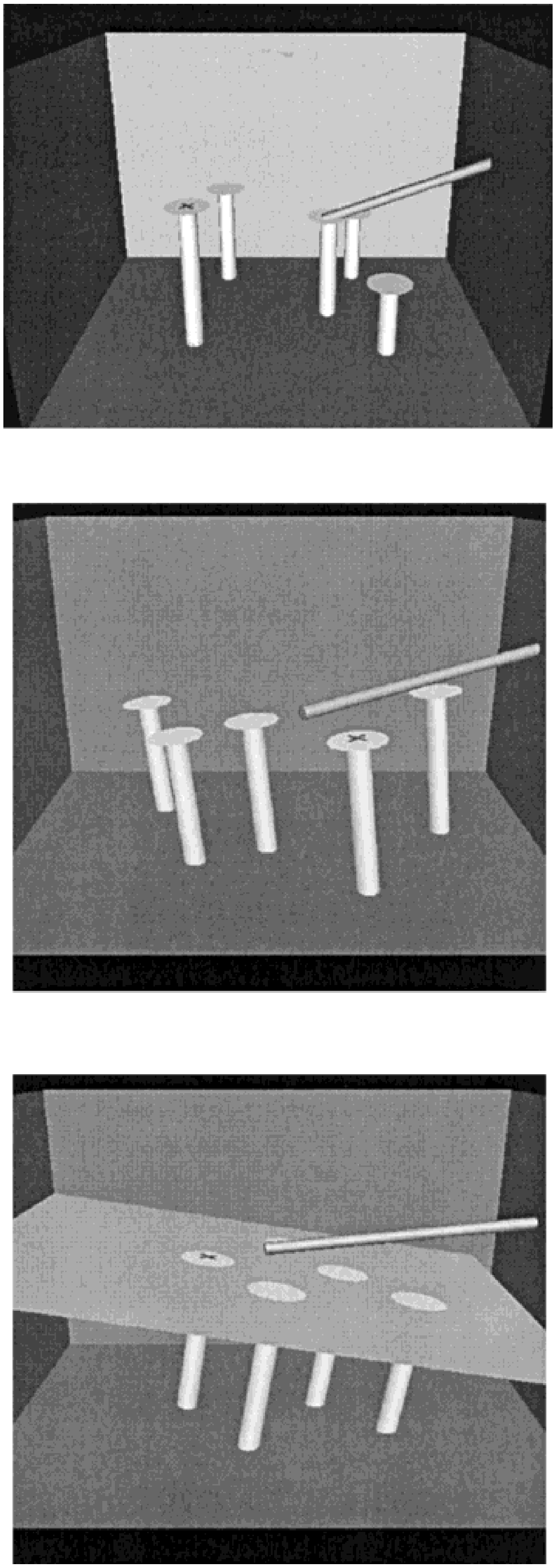


Figure 2. *An example perceptual motor task. Point-to-point movements with (a) targets not coplanar, (b) targets coplanar, and (c) targets coplanar with surface drawn to emphasize plane.*

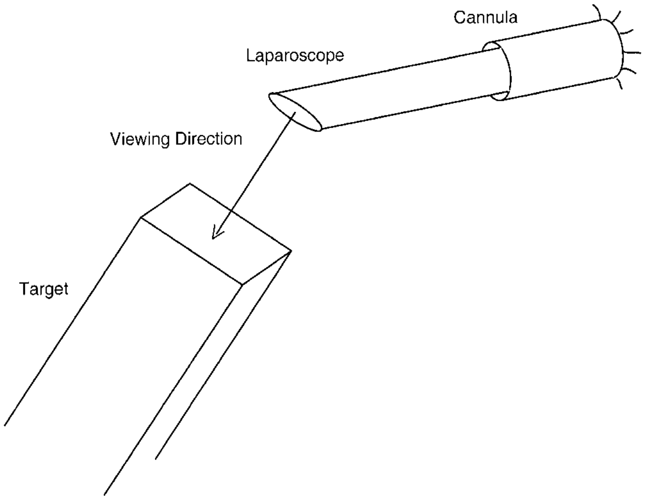


Figure 3. *Angled laparoscope concept. The laparoscope passes through a cannula, which is constrained by the fulcrum at the abdominal wall. The objective lens is angled with respect to the laparoscope axis.*

developed a virtual environment to aid in training this skill. 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 possible to view only 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 lens 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 3).

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 3), the laparoscope objective must point along a line into the cavity. Because of the constrained motion of the laparoscope, only one position and orientation of the laparoscope 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 and the field of view of the laparoscope). The viewer can see only 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 performance 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.

Input to the simulation is through the Virtual Laparoscopic Interface (Immersion Corp.). The device has optical encoders to measure motion of a handle in four degrees of freedom, with kinematics identical to a laparoscopic 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 deg. laparoscope.

The environment comprises six targets, each a tall box suspended in space at a different position and orientation (figure 4). 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 a one-day course for first-year surgical residents and in advanced courses for practicing surgeons. The former group had little prior experience in handling the laparoscope in the operating room (mean of 6.5 cases, range 0 to 30, $n = 13$). Each had experience operating an angled laparoscope in one procedure performed in a pig during the day. The median time to complete the test was 94 sec., with a range of 35 sec. (for the subject with 30 procedures experience) to 305 sec. (for a subject with no prior experience). We have seen an even wider range of performance among the experienced surgeons than in the basic course. One participant needed over 26 min. to complete the task, even with substantial coaching from the experimenter, and despite having used angled lapa-

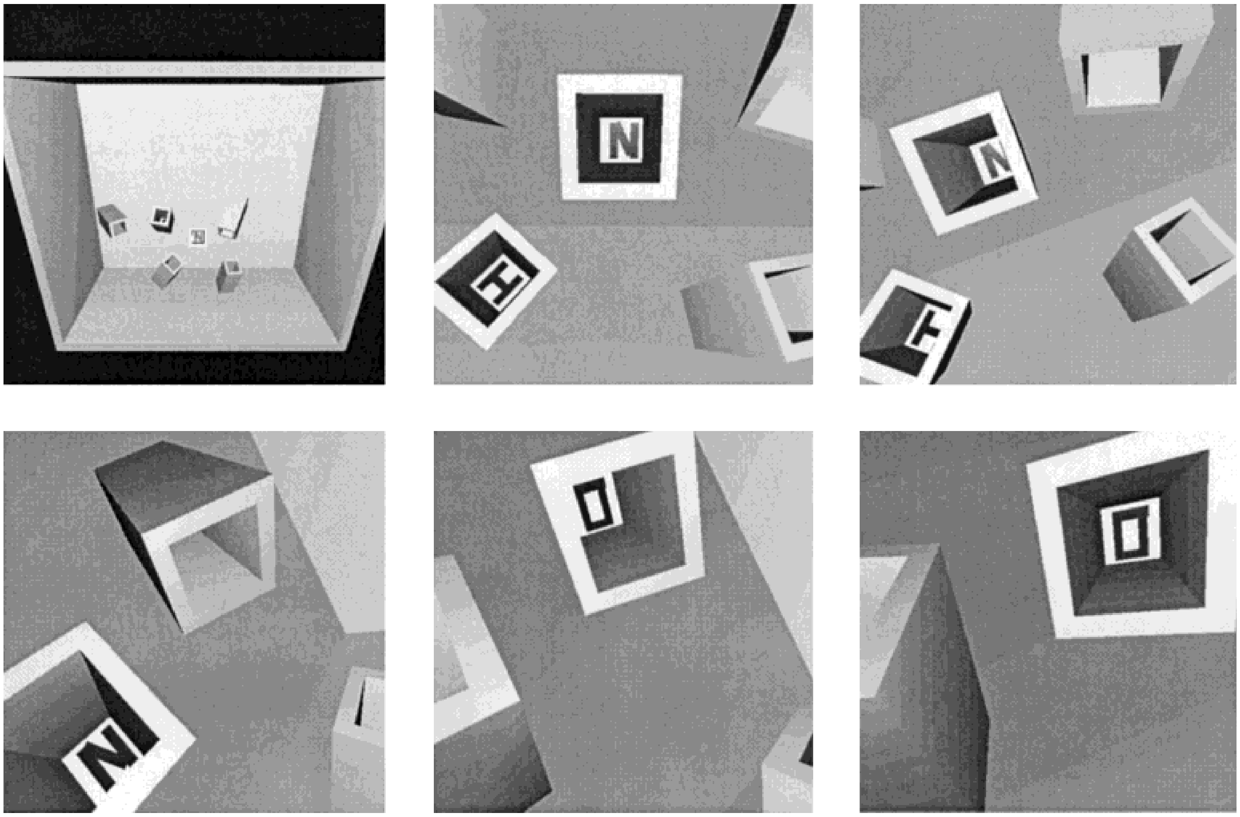


Figure 4. *Angled laparoscope simulation. Upper left shows distant view of targets suspended at different positions and orientations. Remaining images show a sequence as the user smoothly changes the laparoscope position and orientation from view of target N to target O.*

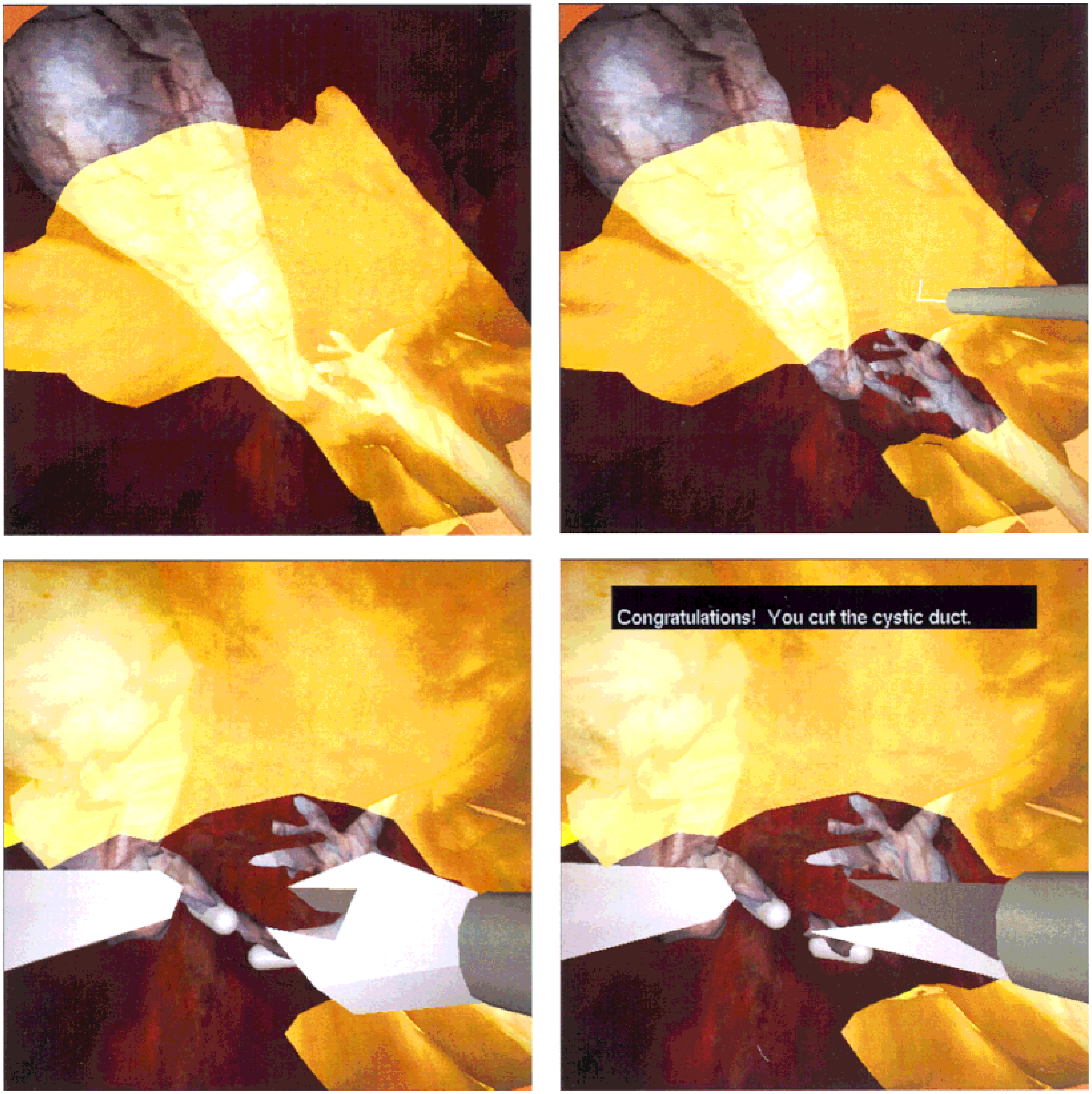
roscopes in his practice. It is clear that some surgeons do not achieve competence in this skill even with experience in the operating room.

Use of the angled laparoscope is one example of a challenging spatial skill in laparoscopic surgery. Unfortunately, there is little research in the psychology literature on training spatial skills. Virtual environments could allow us to study the development of spatial skills and experiment with training methods. These will be discussed in section 5.2.

4.3 Training Critical Procedures: Laparoscopic Cholecystectomy Simulation

An example of the importance of training critical steps of procedures is the laparoscopic cholecystectomy (gallbladder removal). Laparoscopic surgery became practical with the mid-1980s introduction of the compact CCD camera, which could be conveniently mounted on a laparoscope. The first laparoscopic cholecystectomy was performed in 1985 (Muhe, 1986). 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 (Graves, 1995). 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 5) carry bile created in the liver to the gallbladder, where it is stored and concentrated



Congratulations! You cut the cystic duct.

Figure 5. *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.*

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 5, the cystic duct is easily identified, clipped (closed with a staple which encircles the duct), 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, because 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 (Southern Surgeons Club, 1991). Experienced surgeons also caused 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 (with layperson's explanations in parentheses):

- Use lateral traction (pull to the side) on the infundibulum (bottom) 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 (between the cystic duct, liver, and bile ducts leading from the liver) enough to show the hepatic (liver) side of the infundibulum of the gallbladder. This allows the cystic duct to be identified with greater certainty, as 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 9 mm clip (which should close around the duct to seal it), assume it is the common duct (because the common duct has a larger diameter than the cystic duct).
- Any duct that can be traced to disappear behind the duodenum (intestine) has to be the common duct.

The virtual environment shown in figure 5 is being developed to teach proper techniques that should avoid bile duct injuries. In the current simulation, the user must dissect through a single layer of overlying fat to see the biliary structures. 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.

5 Training Challenges

5.1 Perceptual Motor Skills

While the limited dexterity and perception of videoscopic surgery create a challenge for the surgeon, they also constrain the new perceptual motor skills the surgeon must learn. Within the domain of motor skills (Fleishman & Quaintance, 1984), laparoscopic surgery requires a relatively narrow range when classified by kinematics, limb and muscle involvement, range of motion and force, or the modes of sensory feedback available. Consequently, much of an expert's skill in laparoscopic surgery may depend on the use of higher cognitive skills, such as spatial reasoning, to plan strategies to overcome the limited dexterity and reduced sensory feedback.

It is important to distinguish the relative importance of perceptual-motor and higher cognitive skills so that training priorities can be established. Unfortunately, this is difficult using traditional methods of task or skills analysis because the difficulty in performing motor components of skill can be strongly dependent on cognitive and external factors. Controlled conditions using tasks performed in training boxes or virtual environments could permit the experimental assessment and training of perceptual motor skills without the presence of complicating factors. Several groups have developed in vitro tasks (Bhoyrul et al., 1994; Hanna et al., 1998; Derossis et al., 1998; Rosser Jr. et al., 1998). Instrument motions can be measured, allowing the analysis of movement components (Hanna et al., 1998; Tendick & Cavusoglu, 1997). However, virtual environments could make possible a wider range of experimental conditions, including physically impossible situations. For example, we plan to examine the relative importance of visual and haptic cues using the simulations described in section 4.1.

Virtual environments are not ideal tools, however. A difficulty we have encountered in pilot experiments with these tasks is the reduced depth cues in environments implemented with common, real-time, computer graphics algorithms. Despite the 2-D video image in laparoscopic surgery, there are rich monoscopic depth cues including lighting variations and surface textures (Tendick et al., 1997). Use of specular reflections in the virtual environment improved the subjective perception of depth, but did not produce a performance benefit. These differences could reduce transfer between performance in the virtual and real environments. Taffinder et al. (1998) were successful, however, in achieving skill transfer in basic perceptual motor tasks performed by novices. Transfer might be less in tasks of greater complexity performed by subjects at intermediate skill levels where learning involves subtler cues that are difficult to duplicate in virtual environments.

Because training time is limited, it will be important to determine which skills are in greatest need of explicit training outside the operating room. Some basic skills may be adequately learned by rote practice or by relatively short training using in vitro trainers. For example, we have developed a series of tasks in a custom training box to assess perceptual motor ability (Bhoyrul et al., 1994). Performance curves of fifty trials by novice subjects showed a wide range of ability in the tasks, although they all improved substantially during the experiment. For example, most novices can quickly learn to perform 3-D point-to-point movements with laparoscopic instruments, despite the confounding nature of videoscopic imaging and the fulcrum effect of instruments through the cannula (figure 6).

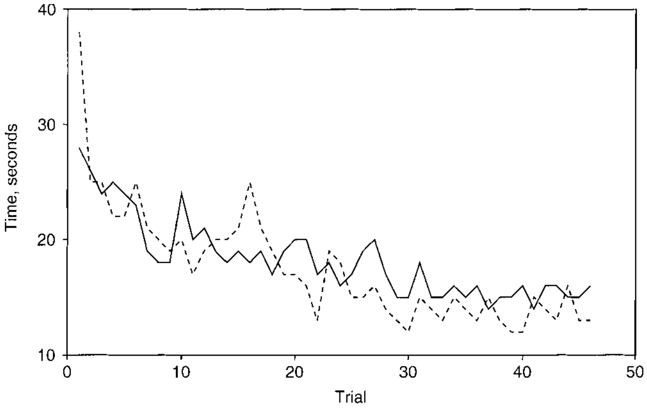


Figure 6. *Performance of point-to-point movements under laparoscopic conditions by an experienced laparoscopic surgeon (solid) and a medical student with no previous experience (dashed). Many novices can quickly gain skill comparable to an expert in this task.*

5.2 Spatial Skills

The difficulty that some experienced surgeons have in using angled laparoscopes suggests that this is a skill that cannot be learned by everyone through experience and repetitive practice alone. Instead, explicit training may be necessary using progressively more difficult examples and demonstrations of successful strategies. 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. Unfortunately, there is little research in the psychology literature on training spatial skills. Virtual environments allow us to study the development of spatial skills by, for example, showing physically impossible views, creating simulated mechanisms with which the user can interact, graphically portraying information otherwise not perceptible (such as internal forces in tissue), and varying the degree of visual and kinesthetic information presented to the user. By changing conditions, we can elucidate the processes underlying performance in complex tasks.

The performance of surgical tasks requires a broad range of spatial processes in order to plan, navigate, and reason using complex representations of space. The complexity of surgery permits the use of different strategies calling on different mental processes. We have observed that experts use different strategies from novices, and those with high spatial ability use different strategies from those with lower ability. It appears that the strategies used by high-spatial surgeons rely to a greater degree on, for example, visualization ability that may be limited in low-spatial surgeons. Consequently, teaching the same strategies to all would not be optimal. By measuring performance in simulations, we can elucidate different strategies used in a set of representative surgical tasks and the mental processes and abilities on which they depend.

A major surgical skill that we will study by measuring users' performance in virtual environments is that of obtaining exposure. This involves achieving an optimal view of the relevant tissue (thus minimizing the need to maintain a spatial representation in working memory), creating a space in which the surgical instruments can be easily manipulated, and applying traction on tissues to facilitate dissection. Besides the positioning of the laparoscope, exposure tasks involve reasoning with a dynamic mental model of the anatomy. In order to plan his or her actions, the surgeon must represent the dynamic interactions between the instruments and tissues to plan how to achieve a desired result. Because haptic feedback is limited to that which can be sensed through surgical instruments, planning actions in laparoscopic surgery is heavily dependent on the surgeon's ability to reason about the mechanical interactions between the instruments and tissues.

Mechanical reasoning has been studied in the context of solving practical problems such as machine assembly and troubleshooting. Reasoning has been characterized as mentally simulating or "running a mental model" of the machine (DeKleer & Brown, 1984; Forbus, Nielson, & Faltings, 1991; Gentner & Stevens, 1983). These accounts suggest that people mentally represent both the spatial configuration of components of the machine (in a static mental model) and the kinematic and dynamic relations between these components, allowing them to mentally animate the behavior of the systems (producing a dynamic mental model). Evidence suggests that ability to run a mental model of a machine depends strongly on spatial ability (Hegarty & Sims, 1994; Sims & Hegarty, 1997).

Mental animation in the context of surgery is further complicated because the components to be animated are deformable rather than rigid, and the mechanical interactions among components occur in multiple dimensions so that they cannot be perceived in a single 2-D view of the system. Therefore, it requires a high level of spatial skill. Virtual environments offer an opportunity to study and to train these complex mental animation skills in the context of surgery.

5.3 Critical Steps of a Procedure

A key question in any complex simulation is the level of detail necessary for training. Interaction with the cholecystectomy simulation is still relatively primitive because it is easy to dissect through the single layer of fat and identify the cystic duct. To improve realism and create a better training tool, adhesions and anatomical variations of the biliary tree should be modeled. We are analyzing the events that lead to errors in laparoscopic surgery to better understand the critical steps that must be trained (Gantert et al., 1998). A measure of fidelity of the simulation will be whether surgeons perform the same steps and errors in the virtual environment as those that have been observed in vivo.

While it is relatively easy to evaluate training of basic motor or spatial skills by measuring transfer to in vivo performance, 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. However, the medical field has no equivalent of the Federal Aviation Administration 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.

6 Conclusion

We have described the testbed developed for our research in training fundamental skills in laparoscopic surgery. The emphasis so far has been on creating flexible software and interfaces to allow a wide range of training experiments. Much work remains to be done on the training side, but the integrated testbed allows us to study a range of skills in parallel under similar conditions. Although we have focused on laparoscopic skills, the environments and knowledge gained will be largely applicable to other minimally invasive techniques as well. We also plan to extend the research on spatial skills to understanding how 2-D and 3-D information from multiple modalities—including ultrasound, CT, MRI, and video—is interpreted by surgeons and radiologists.

In our application of the angled laparoscope simulation, we have seen an extremely wide range of skill in this essential task. This range exists despite the experience surgeons have in using the laparoscope in the operating room, demonstrating that fundamental skills are not necessarily perfected by repeated practice. Other research groups have shown promising preliminary evidence of the effectiveness of virtual environments for surgical training (for example, Peugnet et al., 1998; Taffinder et al., 1998; Tuggy, 1998). With our testbed, we hope to elucidate the nature of the performance of perceptual-motor, spatial, and procedural skills, study the role of technical elements of virtual environments in producing adequate realism for transfer, and finally demonstrate the effectiveness of simulation for teaching a broad range of surgical skills.

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