# VR-Based Simulators for Training in Minimally Invasive Surgery

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**Simulation-based training using VR techniques is a promising alternative to traditional training in minimally invasive surgery (MIS). Simulators let the trainee touch, feel, and manipulate virtual tissues and organs through the same surgical tool handles used in actual MIS while viewing images of tool-tissue interactions on a monitor as in real laparoscopic procedures.**

Throughout medical history, the training paradigm for surgeons has not changed substantially. Traditionally, surgical training has followed the apprenticeship model: Novice surgeons receive their training over time in small groups of peers and superiors in the course of patient care. The operating room (OR) and the patient comprise the most common, the most readily available, and often the only setting where hands-on training takes place. Novice surgeons acquire skills by observing experienced surgeons in action and then progressively performing additional surgical procedures under varying degrees of supervision as their training advances and skill levels increase. This so-called "see one, do one, teach one" paradigm has proved reasonably effective for more than 2,500 years.

Recently, however, experts, physicians, and the public are examining this training model and questioning its efficiency. According to "To Err is Human," a 1999 report from the Institute of Medicine of the National Academy of Sciences, more people die from medical mistakes each year than from highway accidents, breast cancer, or AIDS. In addition to this devastating human cost, the financial burden is significant. Among the main reasons cited for this situation are the inexperience of beginners, as well as the inexperience of experts with new techniques and rare medical situations. One of the major shortfalls identified in the report is medical education and training.

In particular, minimally invasive surgery (MIS) is a revolutionary surgical technique that poses an immediate need for improved training methods. Physicians have used MIS in various procedures since the early 1960s. This technology involves a small video camera and a few customized surgical instruments.[1] The surgeon inserts the camera and instruments into the body through small skin incisions or natural orifices to explore internal cavities without making large openings. For patients, MIS's major advantages over conventional surgery are a shorter hospital stay, a quicker return to activities, and less pain and scarring. Some common MIS procedures are laparoscopic cholecystectomy (gallbladder removal), appendectomy, and hernia repair. Using minimally invasive techniques is a trend in other procedures as well. We can predict that as instruments get smaller and thus easier for surgeons to handle, new minimally invasive techniques will develop.

In spite of the advantages of MIS over traditional surgery, surgeons are still handicapped by the current technology's limitations, which pose four problems in the OR:

- Visualization of internal organs achieved with a wide-angle camera is monoscopic and limited by the camera's field of view.
- Hand-eye coordination is difficult because surgeons must move the tool around a pivot point, thus inverting the direction of movement inside and outside the body. Moreover, the location of the displayed image is not the actual manipulation site.
- Surgeons receive limited haptic (tactile sensing and force feedback) cues because they must interact with internal organs by means of surgical instruments attached to long, thin tubes.
- The instruments rotate about a fixed entrance point, making it impossible for the surgeon to perform direct translational movements while interacting with organs.

Although the importance of MIS training is widely acknowledged, there is no consensus on the most effective training method. OR time is an expensive and

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**1** **Components of a typical minimally invasive surgery simulator (the Simbionix LAP Mentor laparoscopic surgery simulator) include a visual display and surgical instruments fitted with haptic devices for force feedback (photo courtesy of Simbionix).**

limited resource to use for training surgeons. Many leading academic institutions in the United States and Europe have established training centers with facilities for practicing surgical techniques on both inanimate and animate models. Box trainers, for instance, are inanimate models equipped with real surgical instruments, endoscopic cameras, and plastic tissue models. They provide the trainee with an environment similar to actual surgery settings. However, simulated surgical procedures are usually poor imitations of actual ones. It is not easy to customize these training systems to the trainee's needs. Moreover, it is not easy to measure the trainee's performance with these systems.

Currently, the most realistic training model available is animals. This model is dynamic and approaches real operative conditions. Animal tissues, although not always of the same consistency as human tissues, respond similarly to applied forces. Using animals for training, however, is expensive and controversial. It requires expensive, dedicated facilities, including care and housing of the animals. Only a few trainees (often only one) can practice on the same animal and for only a limited number of times. (The expensive training session generally ends with euthanizing the animal.) Additionally, animal anatomies are different from human anatomies, and ethical issues surround the use of animals for training. Finally, with animal models, quantitative measurement of a trainee's performance is not straightforward, and evaluation (performed by the instructor) is often subjective.

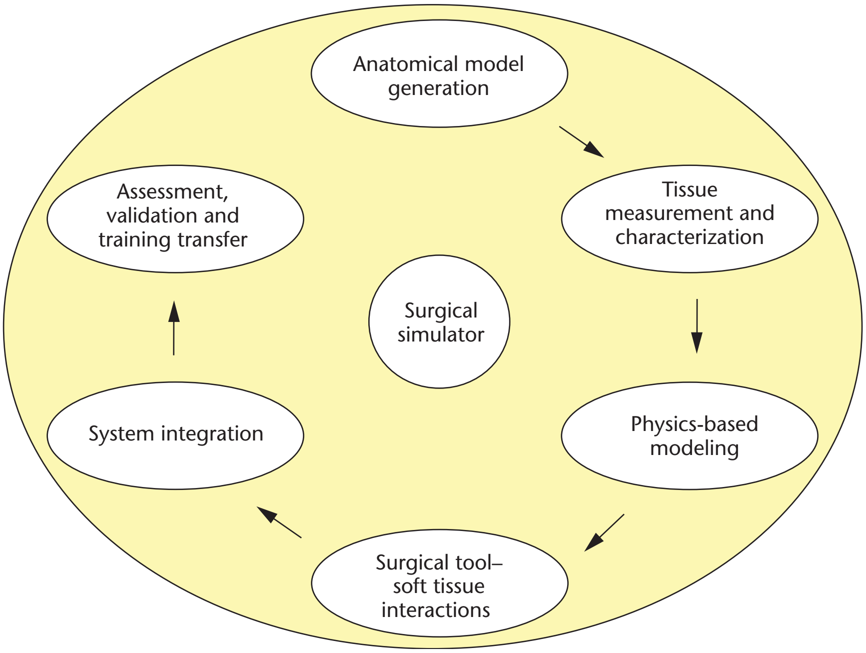
With either inanimate or animate models, conventional MIS training methodologies suffer from the same main drawbacks: the need for an instructor or supervisor, nonstandard feedback methods, and subjective performance evaluation methods. Hence, new training approaches and devices to reduce the risks and constraints of surgical procedures are necessary. To meet this need, VR-based surgical simulators that give the surgeon visual and haptic cues promise to be powerful aids for training medical personnel and monitoring their performance.[1] Computer-based simulation can revolutionize medical education and augment training by quantifying performance and progress, standardizing training regimens independent of patient population, and exposing trainees to unusual cases.[2-4] Integrating VR-based simulators in medical training would result in better-trained physicians, reducing the likelihood of error and improving patient outcome. Figure 1 shows a typical VR-based surgical simulator.

## MIS simulator development

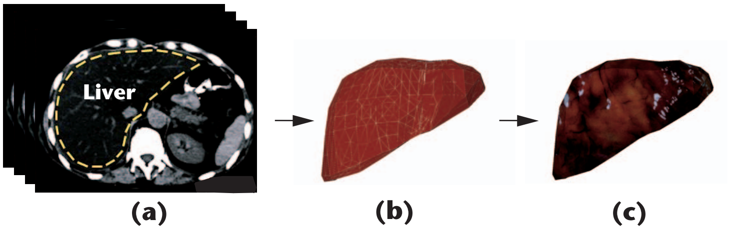
Developing a VR-based MIS simulator requires expertise in systems engineering, materials engineering, robotics engineering, computer science, biomedical engineering, and medicine. As Figure 2 shows, simulator development involves six steps. First, the developers use segmentation and reconstruction techniques of computer vision and computer graphics to generate 3D anatomical models of organs from medical images. Second, they measure and characterize the material properties of soft tissues and integrate these properties in organ-force models. Next, they develop collision detection and response techniques to simulate the real-time interactions of simulated surgical instruments and manipulated organs. Then, they integrate the simulator's hardware and software components to form a complete system. Finally, they validate the system and measure training transfer through user studies.

### *Anatomical model and training-scene generation*

Medical applications use various imaging modalities. Anatomical imaging techniques include computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound. Functional techniques include single



**2** **Simulator development steps for minimally invasive surgery.**



**3** **A set of 2D medical images of the abdomen is segmented via filtering techniques for identifying different tissue regions, lesions, and pathologies (a). Segmented contours in each image are combined to create a 3D surface model of the organ—the liver in this example (b). Texture mapping over the surface gives the model a more realistic appearance (c).**

photon emission computed tomography (Spect), positron emission tomography (PET), and functional MRI. For generating anatomical models, anatomical techniques play the key role—mainly CT and MRI, which provide sufficient resolution. Today's CT scanners, which integrate 64 detector rows, provide nearly isotropic voxels of approximately 0.4 mm. MRI devices provide a spatial resolution of about 1 mm in each direction. Besides different spatial resolutions, the main difference between CT and MRI is their ability to distinguish different tissue types. CT makes it easy to see bone structures, whereas MRI provides superior soft tissue contrast. In recent years, the use of CT for virtual colonoscopy and bronchoscopy has gained importance. These techniques supplement or even replace endoscopic procedures by employing a patient model derived from CT data and displayed with the help of volume-rendering techniques without any preprocessing. Ultrasound, although widely available and inexpensive, suffers from a lower imaging quality than CT and MRI and is therefore not appropriate for anatomical modeling.

The National Library of Medicine's Visible Human (Man and Woman) data sets have become standard sources of medical image scans of the human body. Because of their high resolution and good image quality, several projects have used them for highly accurate anatomical models.

To build 3D models of organs from image data, developers of surgical simulators use either surface or volumetric elements. Surface models represent the external border of the organs. Generating surface models requires extraction of the structure's outer surface, using segmentation algorithms that provide the outer contour. Figure 3 shows an example of the segmentation and generation of a 3D surface model.

The segmentation approaches often used for anatomical modeling are simple classification schemes such as thresholding and region growing. These techniques extract isocontours that serve as input to the marching cubes algorithm, which creates a polygonal representation of the structure's surface. Another way to extract organ surfaces is to use active contour models, also known as snakes. This technique obtains a contour by adjusting splines that fit the structure's outer surface, using a physical description of the image data's external and internal forces. Applying the contour found in one 2D slice to the next neighboring slice starts a contour that is gradually refined. This process, called boundary tracking, delivers the organ's 3D contour and thus its surface representation.

An advantage of generating surface models from CT and MRI scans is the reduction in data size. Also, we can display the triangulated meshes created by this method using the hardware acceleration available from modern graphics boards.

An alternative to surface modeling and surface data visualization is direct volume rendering. Ray casting, a classical volume-rendering technique, provides high-resolution visualization but is rather slow.

Several commercial and free software packages are available for 3D reconstruction from medical images, but most are semiautomated and often require labor- and time-intensive segmentation. Amira (http://www.amiravis.com), Analyze (http://www.mayo.edu/bir/Software/Analyze/Analyze.html), IDL (http://www.ittvis.com/idl/), Image-Pro (http://www.mediacy.com/), and MEDx (http://medx.sensor.com/products/medx/index.html) are commercial packages for medical and other scientific image data visualization and manipulation, anatomical structure extraction, and surface and tetrahedral model generation. The Visualization Toolkit (http://www.vtk.org) is a free, open-source image data visualization package with contour extraction and mesh generation algorithms. Another free volume visualization system is VolVis (http://www.cs.sunysb.edu/~vislab/volvis_home.html). Mesh generation and manipulation packages developed at academic institutions include TetGen (http://tetgen.berlios.de/) and SUMAA3d (http://www-unix.mcs.anl.gov/sumaa3d).

For a realistic visualization of reconstructed organ models, system developers map textures to the models' surfaces. This process involves generating realistic textures and obtaining appropriate texture coordinates. The most basic method of creating organ textures is direct texture painting, which usually requires a medical illustrator to manually draw the texture with appropriate tools. Another way to obtain textures for medical images is to map real volumetric data to surfaces. K.D. Reinig et al. use the Visible Human data set to obtain organ textures.[5] Recently, Paget, Harders, and Szekely introduced a fully automatic framework for generating variable textures.[6] The first step in their approach is acquiring in vivo images to form a database. Next, a texture synthesis step creates tileable variable textures from the in vivo images. The final step is mapping the texture to the 3D mesh geometry.

### *Soft tissue measurement and characterization*

A core component of a VR-based surgical simulation and training system is realistic organ-force models. Realistic organ-force models are virtual representations of soft tissues that display accurate displacement and force response. To develop these models, we must measure and characterize the material properties of organs in living condition and in their native locations. Models with incorrect material properties will result in adverse training effects. Measuring the material properties of soft organ tissues is highly challenging. Soft tissues exhibit complex, nonlinear, anisotropic, nonhomogeneous behavior. Moreover, the tissues are layered, and each layer consists of different materials in varying combinations. Because of this nonhomogeneity, soft tissues have both coordinate- and direction-dependent properties. Time- and rate-dependent behavior caused by viscoelasticity is also common.

Various methods of measuring material properties of organ tissues have appeared in the literature. We categorize these methods in terms of the measurement site and the degree of tissue damage that occurs during measurement. The two types of measurement sites are ex vivo and in vivo. In the past, most tissue experiments were ex vivo studies.[7-9] For ex vivo measurements, the tissue's biological functioning has ceased; in other words, the tissue to be measured is dead. Ex vivo measurements can take place within the body (in situ) or outside the body (in vitro). For in vitro measurements, researchers use standard materials-testing methods (tension or compression tests) under well-defined boundary conditions. Typically, they transfer tissue samples in a chemical solution to a laboratory for measurements. Because they carefully decide on sample geometry and experimental conditions in advance, they can easily obtain stress and strain values from the measurement data. However, dead organ and muscle tissues typically stiffen with time, leading to changes in mechanical properties, so the results of in vitro measurements can be misleading. Therefore, recent research has focused on in vivo, in situ measurement of soft tissues' mechanical properties.

**Most mesh-based methods consider the deformable object a continuum and are generally more accurate than mesh-free techniques.**

Soft-tissue measurement methods incur three levels of tissue damage: invasive, noninvasive, and minimally invasive. In invasive methods, measurement instruments enter the body through a puncture or an incision. Because large openings allow easy insertion of test apparatus into the body, scientists have performed many measurements invasively. However, the experimental devices and procedures used for invasive measurements typically don't match the actual surgical devices and procedures used during MIS. In addition, the invasive approach is unacceptable for conducting human experiments.

In contrast, noninvasive tissue measurements require no incisions. Noninvasive approaches include CT, MRI, and ultrasound. Most of these approaches can measure only linear material properties, but soft organ tissues exhibit nonlinear material characteristics as well.

Minimally invasive methods require small incisions, causing much less tissue damage than the invasive method does. A few research groups have recently conducted minimally invasive animal and human experiments to characterize nonlinear and time-dependent material properties of soft tissues. A challenge of this approach is characterizing the measured properties. Determining unknown material properties from the measured system response requires formulating an inverse solution. For this purpose, scientists typically construct a finite-element model of the soft tissue and use it with an optimization method to iteratively match the experimental data to the numerical solution.[7,9]

### *Physics-based modeling*

Developing realistic organ-force models for simulating soft-tissue behavior requires a system that reflects stable forces to the user, displays realistic smooth deformations in real time, and handles various boundary conditions and constraints.[1] The material properties and structure of organ tissues mentioned earlier make developing real-time, realistic organ-force models challenging. In addition, surgical-tool and soft-tissue interactions cause dynamic effects and contact between organs, which are difficult to simulate in real time. Furthermore, simulating surgical operations such as cutting and coagulation requires updating the organ's geometric database frequently and can cause force singularities in the physics-based model at the boundaries.

We classify current physics-based approaches for developing organ-force models as mesh free and mesh based. Mesh-free methods use point clouds (vertices) only for deformation and force computations and make no assumptions about the underlying geometry. Most mesh-based methods consider the deformable object a continuum and are generally more accurate than mesh-free techniques. However, mesh-free techniques provide a better solution to topological changes encountered in simulating surgical cutting and tearing. In addition, they are computationally less expensive and easier to implement than mesh-based methods.

**Mesh-based methods.** One of the most widely used mesh-based methods is the finite-element method.[10-14] FEM solves the deformation problem by considering the organ a continuous body that is trying to minimize its potential energy under the influence of external forces. To implement this method, we divide the geometric model of an organ into surface or volumetric elements, formulate each element's properties, and combine the elements to compute the organ's deformation states under the forces applied by the surgical instruments.[1] A major advantage of FEM is that it uses continuum mechanics and has a solid mathematical foundation. On the basis of the partial differential equations and the constitutive relation used, FEM can accurately approximate static and dynamic deformations of an object with linear and nonlinear material properties.[13] Another advantage is that FEM requires only a few material parameters to describe a physical system's response.

However, FEM also has some drawbacks. It has a heavy computational load, and its computational complexity usually increases quadratically with the underlying mesh's quality. Moreover, while simulating a procedure such as cutting, in which the object's topology is modified, we must recalculate and reassemble element mass and stiffness matrices, which is computationally intensive. Precomputation and condensation have been suggested as remedies to these problems.[11]

Another mesh-based method based on continuum mechanics is the boundary element method. BEM discretizes an object's surface or boundary into elements and patches and relies on surface integral equations to calculate displacements at the boundary.[15] On the assumption of linear elasticity, BEM computes small deformations accurately. Extending this approach to large deformation analysis is not straightforward. Another drawback is that direct solution of BEM is computationally too expensive to execute in real time. Yet, precomputation and superposition make it possible to execute a linear deformable model at haptic update rates.[15] BEM can model changes in topology resulting from procedures such as cutting by using iterative solvers that update precomputed data to approximate the modified topology.

The long-element method is another mesh-based approach. It is based on Hooke's law, Pascal's principle, and volume conservation as the boundary condition.[16] LEM discretizes the object into a set of two-dimensional long elements filled with an incompressible fluid. During deformation computation, these elements reach equilibrium under the effect of bulk variables including pressure, density, volume, and stress. One advantage of LEM is that the parameters such as pressure, density, and volume are easy to identify. The elements filled with an incompressible fluid can represent nonhomogeneous material properties. Because the method intrinsically preserves volume, it supports topological changes such as cutting. On the other hand, LEM produces accurate results for small deformations only. It yields inconsistent results for large deformations. The element deformations must be reevaluated when the object undergoes large deformations, a bottleneck for real-time performance.

Mesh-free techniques provide a better solution to topological changes encountered in simulating surgical cutting and tearing.

The tensor-mass model is also a mesh-based approach. Its methodology lies between the continuum mechanics and particle-based approaches. Cotin, Delingette, and Ayache developed TMM as a continuum model based on linear elasticity.[17] The model discretizes the object into tetrahedrons, and the tensors are stored at the edges of the tetrahedrons. Like particle-based approaches, the object's mass is stored in the nodes of the tetrahedrons as lumped mass points. However, unlike particle-based approaches, TMM computes deformation and force through energy-based continuum mechanics, and the computations are independent of mesh topology. One of TMM's main advantages is that the model can handle topological modifications; hence, we can use it to simulate tissue cutting and tearing. In addition, TMM's time complexity is linear and lower than that of the standard FEM approach. The initially proposed TMM approach could simulate small deformations only. Later, Picinbono, Delingette, and Ayache extended TMM to simulate large deformations as well.[18]

**Mesh-free methods.** The mass-spring model, also called the particle system approach, is a widely used mesh-free method in surgical simulation.[10,19] MSM models the object as point masses connected to each other with springs and dampers.[1] Each point mass is represented by its own position, velocity, and acceleration and moves under the influence of inertial and damping forces and the forces applied by the surgical instrument. This technique is relatively easy to implement because the motion equations need not be constructed explicitly. Hence, the technique's computational complexity allows real-time simulation. However, the integration of realistic tissue properties into particle models is not trivial. In addition, the resulting physical behavior depends on the point masses' connectivity. The construction of an optimal spring network in 3D is a complicated process, and MSM can become oscillatory or unstable under certain conditions.

The point-associated finite-field (PAFF) approach, also called the finite-spheres method, is a newer meshless FEM approach applied to surgical simulation.[20] This method, like TMM, resides between the continuum mechanics and particle-based approaches. Like MSM, it is a point-based approach, using only the nodes of a 3D object for the displacement and force calculations. PAFF approximates the displacement field by using nonzero functions over small spherical neighborhoods of nodes. Like FEM, this technique uses a Galerkin formulation to generate the discretized versions of the partial differential equations governing the deformable medium's behavior. PAFF supports simulation of large deformations as well as topology modifications such as cutting. PAFF can also be used to simulate other procedures involving particles, such as smoke generation during cauterization. Although the technique's brute-force implementation is computationally intensive, users can generate localized solutions in real time.[20]

### *Simulating tool-tissue interactions*

Simulating interactions between surgical tools and soft tissues involves graphical rendering of computer-generated models of surgical instruments, detecting collisions between instruments and deformable organ models, and haptic rendering of the collision response in the procedure to be simulated.[1]

We classify MIS tools on the basis of their functionality:

- long, thin, straight tools for palpation, puncture, and injection (for example, palpation probes and puncture and injection needles) and
- articulated tools for grasping, pulling, clamping, cutting, and coagulating (biopsy and punch forceps, grasping forceps, hook scissors, and coagulation hooks).

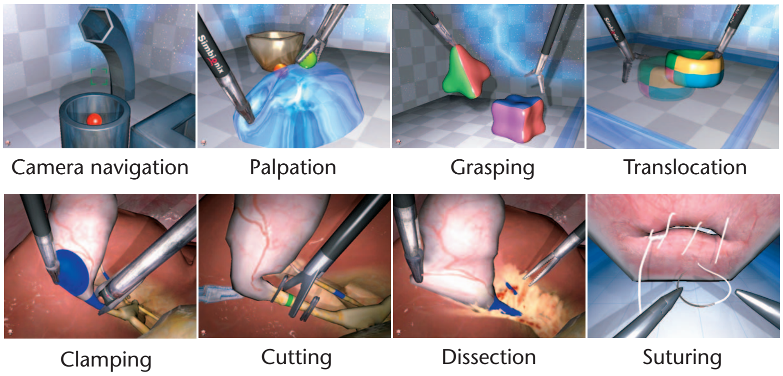
For realistic visual display during simulations, we render 3D graphical models of surgical tools in exact dimensions and shape using several polygons. But we typically assume that the models consist of a set of geometric primitives such as points or connected line segments for fast detection of collisions between instruments and organs in real time. Collision detection algorithms developed in computer graphics cannot be used directly in rendering force interactions between instruments and organs. Nevertheless, to achieve real-time update rates, haptic rendering algorithms can take advantage of computer graphics rendering techniques:

- space partitioning (partitioning the space that encloses an object into smaller subspaces for faster detection of the first contact),
- local search (searching only the neighboring primitives for possible new contacts), and
- hierarchical data structures (constructing hierarchical links between primitives constituting the object for faster access to the contacted primitive).

In point-based haptic interactions of surgical instruments with organs, only the instrument's end point interacts with virtual organs. Each time the user moves the surgical instrument fitted with haptic devices in physical space, the collision detection algorithm checks whether the end point is inside the virtual organ. This approach provides users with similar force feedback as they would feel when exploring organs in real surgery settings with the tip of an instrument only. However, actual MIS instruments have long, slender bodies, so point-based rendering methods are not sufficient to render realistic tool-tissue interactions.

In ray-based haptic interaction models, the probe is a finite line segment whose orientation the detection algorithm takes into account while checking for collisions between the line segment and the objects. This technique has several advantages over point-based rendering. In addition to displaying forces, users can feel torques if they are using an appropriate haptic device, which is not possible with point-based approaches. For example, they can feel the coupling moments generated by contact forces at the instrument tip and the forces at a trocar's pivot point. Second, users can detect side collisions between the simulated tool and 3D organ models. Third, users can render multiple tissue layers by virtually extending the ray representing the simulated surgical probe to detect collisions with an organ's internal layers. Finally, they can touch and feel multiple objects simultaneously.

Once the algorithm detects contact between an instrument and tissue, the tool-tissue interaction problem centers on collision response. This involves a realistic graphical and haptic display of tissue behavior according to instrument type and the surgical task the user chooses to perform. Tissue deformation is the most generic collision response. Simulation of basic surgery skills such as palpating, grasping, stretching, translocating, and clip applying mainly involves tissue deformation. Simulation of surgical cutting such as transsection, dissection, and coagulation fall into a different category, in which tool-tissue interactions modify the geometry and the underlying model. Figure 4 shows several of these simulated interactions.



**4 Typical simulations of MIS tasks: (a) basic and (b) advanced skills (courtesy of Simbionix).**

Realistic graphical and haptic simulation of cutting is a requirement in any surgical simulator. Research in this area has focused mainly on the graphical display of cut and tissue separation, but some recent studies report the development of mechanistic models for displaying forces during cutting. Cutting approaches for graphical simulation include straightforward element deletion, mesh subdivision, and topology adaptation.

Cotin, Delingette, and Ayache have applied straightforward deletion of mesh entities to remove the elements contacted by a cutting tool.[17] Unfortunately, this method leads to visual artifacts because it cannot approximate the cutting path accurately. Achieving acceptable visual quality would require very high resolution meshes. Moreover, the method violates the physical principle of mass conservation.

Mesh subdivision methods have produced better visual representations of incisions. Bielser et al. discuss the use of a state machine to keep track of incisions in tetrahedral meshes.[21] All the described mesh subdivision approaches considerably increase the element count. Moreover, introducing new mesh elements often necessitates extensive model recalculations—for instance, in using implicit FEM. Another negative factor is reduction in element size. Researchers have also reported deformation stability problems in the simulation of tissue cutting. This required a significant reduction of the time step, thus rendering real-time simulation intractable. Finally, Molino, Bao, and Fedkiw report on work in which they decoupled the simulation and visualization domains.[22] Their virtual node algorithm copies nodes and elements so that no new elements are created. Elements are decomposed only in the visualization domain. A tetrahedron cannot be cut more than three times, however, and the surface resolution depends on the resolution of the underlying tetrahedral mesh.

Topology adaptation approaches can ameliorate some of the problems.[23,24] Their central idea is to approximate a cutting path with existing vertices, edges, and polygons of the geometric model. This enables mesh incisions without large increases in element count and also without reductions in element size. Unfortunately, problems arise from degenerated elements, which can appear with unconditional node displacement in the mesh. Also, the initial mesh resolution limits incision approximation quality. In addition, topology adaptation approaches require an update of the undeformed mechanical model's mesh parameters, which can be difficult if the displacements are large. Steinemann et al. recently proposed a hybrid cutting approach for tetrahedral meshes.[25] It combines topological update via subdivision with adjustments of the existing topology. In addition, after the initial cut, local mesh regularization improves element quality. Moreover, the mechanical and the visual models are decoupled, allowing different resolutions for the underlying mesh representations. This method can closely approximate an arbitrary, user-defined cut surface, while avoiding the creation of small or badly shaped elements, thus preventing stability problems in the subsequent deformation computation.

In addition to graphical rendering, cutting simulation research involves the development of a mechanistic model of the cut for realistic force feedback to the user. Most of these models are based on experimental data collected from tissue samples, Chanthasopeephan, Desai, and Lau developed an instrumented hardware–software system for characterization of soft tissue's mechanical response during cutting.[26] They performed ex vivo cutting experiments with porcine liver using various cutting speeds and angles. They showed that although force displacement behavior for different combinations of cutting speed and angle has a characteristic pattern (loading, then a sudden puncture, then unloading), deformation resistance changes with the instrument's speed and angle. Mahvash and Hayward developed a cutting model based on a fracture mechanics approach.[27] They model cutting in three steps: deformation, tearing, and cutting. Their model assumes that energy is recoverable during deformation, it is zero during tearing, and it is not recoverable during fracture generation.

**A VR-based surgical simulator is actually a human-computer interface consisting of a network of high-end hardware and software components.**

In tissue cutting during MIS, smoke and bleeding can occur—for example, when a coagulation hook tears apart the membrane tissue around organs. A coagulation simulation requires realistic smoke generation in real time. Kuhnapfel, Cakmak, and Maab use animation techniques to simulate smoke generation and fading away of the generated smoke after coagulation.[10] They integrate this approach in their MIS training environment Kismet. De et al. simulate smoke generation using the PAFF method, which they developed for simulating deformable objects.[20] They use the Lagrangian form of the Navier-Stokes formulation as the governing equation to simulate smoke formation. Like smoke simulation, real-time simulation of bleeding is a recent surgical simulation research area. Basdogan, Ho, and Srinivasan developed a surface flow algorithm based on Navier-Stokes equations for bleeding simulation.[23] They generate an auxiliary mesh for the blood flow and project it to the incision area. Kuhnapfel, Cakmak, and Maab developed a mass-spring model for simulation of arterial bleeding, irrigation, and suction.[10] Zatonyi et al. introduce a real-time approach based on computational fluid dynamics for simulating blood flow in the fluid-filled uterine cavity during hysteroscopy.[28]

Advanced surgical skills such as suturing, thread handling, and knot tying show similarities to cutting in many ways. Brown et al. implemented a suturing simulation environment for training in microsurgical skills.[19] The user manipulates virtual blood vessels, sutures them together, and then ties the knot. MSM is the underlying deformation model for the vessels. Berkley et al. simulate suturing and knot tying in real time on a 3D model of a hand.[14] They use the banded-matrix approach, a fast finite-element modeling technique developed for real-time deformation simulation, as the underlying deformation model. During simulation, they visually display the highly stressed areas on the hand model to prevent the user from damaging the tissue during needle interactions.

### System integration

A VR-based surgical simulator is actually a human-computer interface consisting of a network of high-end hardware and software components. Providing a realistic training environment in which trainees act as if they are operating on an actual patient is the simulator's essential goal. Selection and design of simulator components depend on the type of training the simulator will serve.

A part-task trainer is a simulator system that is designed to train a particular surgical task. A part-task trainer's hardware components typically include a computer with a 3D graphics accelerator for visualization of virtual organs, force feedback devices to simulate haptic sensations, and auditory interfaces to guide the trainee. Force-reflecting devices and actuators fitted with surgical tool handles are embedded in a mannequin in a manner similar to standard MIS settings where surgical tools are inserted to the body through small incisions. During simulations, the user manipulates actual surgical instruments attached to the force feedback devices in the mannequin to interact with computer-generated anatomical organs. The computer monitor displays the organ manipulations (as the video monitor would do in MIS), and the haptic interfaces feed the reaction forces back to the user. Using this set-up, a trainee can learn to execute a specific procedure. The part-task trainer can monitor and record the trainee's performance during the session for further analysis.

A full-task (team) trainer is designed to train one or more trainees at the same time on a full range of surgical operations in a simulated OR. Compared with part-task trainers, full-task trainers require a larger space and enriched sensory feedback to simulate the OR environment. Sensors and mechanical actuators (such as mechanical lungs, voice output, and drug delivery systems) sensitive to the trainee's actions are placed in the mannequin and around the table to create a realistic OR environment for team training. We can envision a more sophisticated team trainer in which multiple trainees equipped with stereo glasses, head trackers, and exoskeleton haptic devices enter an immersive room such as CAVE, a projection-based VR system, which provides a large-scale virtual environment. Visual images seamlessly projected on the walls would display a 3D anatomical model, information charts, and a floating virtual patient's vital signs.

Integrating a part-task trainer's software components typically requires the construction of hierarchical data structures for storing objects' geometric and material properties, a client-server model, and multithreading and multiprocessing programming techniques to separate visual and haptic servo loops. Each sensory loop has its own requirements and demands a CPU time accordingly. Although a graphics update rate of 30 Hz is sufficient for the human sensory system to perceive a flawless display of visual images, the human sensory system is far more sensitive to the haptic update rate. For a realistic sense of touch and stable force interactions, the haptic update rate should be as high as 1 kHz. Moreover, displaying surface textures and vibrations requires even more demanding rates: 5 to 10 kHz.

**To achieve real-time update rates, adaptive subdivision techniques can progressively increase the model's resolution.**

In a multithreading structure, a separate thread can be assigned to each sensory modality, and a priority level for each thread can be set in advance or dynamically during simulations. Threads can share the same database, but their proper synchronization in accessing the shared database is important for achieving real-time graphical- and haptic-rendering update rates. However, there is always a trade-off between realism and real-time performance. For example, as tissue models get more sophisticated, update rates can easily drop below acceptable levels. To achieve real-time update rates, adaptive subdivision techniques can progressively increase the model's resolution.

To simulate procedures that require topological modifications (such as cutting), we can decouple visual and haptic models or implement hybrid approaches. For example, we can use more accurate but computationally more demanding deformation models such as FEM for areas where topology is preserved. At the same time, to model cutting, we can use less accurate approaches such as MSM, TMM, or PAFF, which allow easier topology changes.[17,25] In addition to being efficient, the simulator should provide realistic visual images. Instead of standard, static texture-mapping techniques, we can use view-dependent texture-mapping techniques to simulate the complex glistening effect of the movements of the endoscopic-camera light.

Another issue in system integration is standardization of software architectures and languages that bind the various simulator components efficiently. Although many languages and formats exist for geometric representation of 3D objects, there are no standards for representation of physics-based deformable objects. Because there are different approaches to modeling the behavior of deformable organs, and material properties must be integrated uniformly in these models, the need for a generic modeling architecture is obvious. Recently, Chabanas and Promayon have presented the idea of developing a standard language called Physical Model Language (PML), based on Extensive Markup Language (XML), for unified representation of continuous and discrete deformable models for surgical simulation.[29] Cavusoglu, Goktekin, and Tendick have developed the General Interactive Physical Simulation Interface (GiPSi), an open-source and open-architecture software development framework for surgical simulation.[30] GiPSi provides a shared development environment and a standard API to ensure modularity. With GiPSi, users can generate scenarios in which they can simulate different organs with different deformation models. A related endeavor is the Simulation Open Framework Architecture (SOFA) project, a concerted activity of several groups involved in surgical simulation. It targets an extendible, open-source framework for easy exchange of algorithmic blocks between research groups.

Currently, many research institutions are developing simulators, and several medical simulation companies are offering integrated commercial systems. Leskovsky, Harders, and Szekely provide an overview of existing simulator systems developed in academia.[31] Table 1 (next page) lists current commercial MIS part-task simulators. Whereas some companies offer a complete system consisting of customized software and hardware modules, others develop only software solutions, often in partnership with companies that provide the supplementary hardware interface. Basic-skills simulators aim at training in fundamental skills such as navigation, hand-eye coordination, and basic tool-tissue interactions. Procedure simulators, on the other hand, provide an environment for training in more complex surgical skills. The training scenarios provided by procedure systems vary from teaching complex tool-tissue interactions such as cutting and suturing to teaching a complete surgical procedure such as a laparoscopic cholecystectomy.

### *Assessment, validation, and training transfer*

Medical education focuses on knowledge-based and skill-based training. In knowledge-based training, trainees become familiar with surgical instruments and their functionality. They learn to find anatomical landmarks, to differentiate healthy and pathological organs through visual cues such as color and texture, and to track physiological changes such as heart rate and blood pressure. Training sessions guide them through the steps of surgical procedures such as cutting, suturing, and coagulation. Skill-based training involves enhancement of the trainee's visio-spatial, perceptual, and motor skills such as hand-eye coordination including depth perception, navigation, aiming, and manipulation. Hand-eye coordination is especially difficult in MIS because the laparoscopic camera reflects 2D mirror images of hand movements and locations of anatomical landmarks.[1]

**Table 1. Procedure and skill classification of commercial MIS part-task simulators. Blue: procedural simulator; red: basic-skills simulator; green: hardware interface with haptic feedback; purple: hardware interface without haptic feedback.**

| **Procedure** | **Simulators with custom hardware** | **Simulators with commercial hardware** |
|---|---|---|
| General laparoendoscopic surgery | 6, 8 | 1 (28-29), 12 (29), 19 (28), 21 (28), 24 (27) |
| Laparoscopic cholecystectomy | 9 | 1 (28-29), 20 (28), 22 (28), 25 (29-30) |
| Laparoscopic colectomy | 8 | |
| Laparoscopic anastomosis | | 1 (28-29), 7 (27-28) |
| Cardiovascular, endovascular intervention | 2, 11, 14, 17 | |
| Arthroscopy | | 13 (29) |
| Gynecology, hysteroscopy | 10, 15 | 23 (28) |
| Bronchoscopy | 16 | |
| Upper, lower GI | 3, 16 | |
| Endourology | 4 | 26 (31) |
| Percutaneous access | 5 | |
| Endoscopic sinus surgery | 18 | |
| Laparoscopic gastric bypass, ventral hernia | | 1 (28-29) |
| **Basic MIS skills** | **Simulator** | |
| Camera navigation, exploration | 1, 6, 8, 9, 10, 18, 19, 20, 21, 24, 25 | |
| Palpation | 6, 19, 20, 24, 25 | |
| Grasping | 1, 9, 10, 19, 20, 21, 24, 25 | |
| Stretching | 12, 19, 20, 25 | |
| Translocation | 12, 19, 20, 24 | |
| Irrigation, suction | 9, 10 | |
| **Advanced MIS skills** | **Simulator** | |
| Incision (cutting) | 1, 9, 10, 12, 19, 20, 21, 25 | |
| Dissection | 1, 6, 8, 9, 10, 18, 19, 20, 22, 25, 26 | |
| Coagulation | 1, 6, 8, 9, 10, 12, 19, 20, 22, 25, 26 | |
| Clamping (clip applying) | 1, 8, 9, 10, 12, 19, 20, 21, 25 | |
| Suturing | 1, 6, 7, 8, 9, 10, 12, 21 | |
| Thread manipulation, knot tying | 1, 6, 7, 8, 9, 10, 12, 22 | |

**Simulator key**

| | |
|---|---|
| 1 | Simbionix LAP Mentor |
| 2 | Simbionix ANGIO Mentor |
| 3 | Simbionix GI Mentor |
| 4 | Simbionix URO Mentor |
| 5 | Simbionix PERC Mentor |
| 6 | SimSurgery SEP |
| 7 | SimSurgery VR Anastamosis Trainer, SimLap, SimCor |
| 8 | Haptica ProMIS |
| 9 | Select-IT VEST VSOne Cho |
| 10 | Select-IT VEST VSOne Gyn |
| 11 | Mentice Procedicus VIST |
| 12 | Mentice Procedicus MIST |
| 13 | Mentice Procedicus VA |
| 14 | Immersion Endovascular AccuTouch |
| 15 | Immersion Hysteroscopy AccuTouch |
| 16 | Immersion Endoscopy AccuTouch |
| 17 | CATHI GmbH Cathi-Simulator |
| 18 | Locheed Martin ESSS |
| 19 | Reaching RLT B |
| 20 | Reaching RLT BC |
| 21 | Surgical Science LapSim Basic Skills |
| 22 | Surgical Science LapSim Dissection |
| 23 | Surgical Science LapSim Gyn |
| 24 | Verefi EndoTower, RapidFire/SmartTutor, Head2Head |
| 25 | Xitact LapChol |
| 26 | Melerit PelvicVision |
| 27 | Immersion VLI |
| 28 | Immersion LSW |
| 29 | Xitact ITP |
| 30 | Xitact IHP |
| 31 | SensAble Technologies Phantom 1.5 |

For good coordination, surgeons must use cues such as the sense of touch and the reflection of camera light from organs. Using the virtual counterparts of these cues in simulators, trainees can practice as much as necessary to develop good hand-eye coordination. For example, during a laparoscopic training session, trainees learn to aim the laparoscopic forceps at a target and move the forceps in the abdominal cavity to learn the allowable range of applied movements and manipulate organs to examine the allowable range of forces and torques applied by the forceps. In addition, an expert surgeon's movements in a procedure can be recorded in advance and played back to the trainee through haptic devices.[1] If the trainee moves out of the expert surgeon's trajectory, force feedback can return the trainee to that path. Additional guidance from visual cues and auditory feedback strengthens the learning effect.

Concerns that simulators lack validity have adversely affected the adoption of this technology in medical training. Medical boards and councils' growing interest in VR-based training has recently given rise to validation studies.[3,32] Validation is the verification of training effectiveness. We can investigate a VR-based simulator's validity, or training effectiveness, at several levels.[4]

*Face validity* is the level of resemblance between the simulated and real procedures. The factor contributing most to face validity is the fidelity of the organ-force models, as discussed earlier.

*Content validity* verifies that methods and metrics used for skill assessment are appropriate.

*Construct validity* examines whether the assessment methods can differentiate expert surgeons from novices. To compare novice and expert performance, we must define performance metrics. Unlike traditional medical training approaches, VR-based simulators can provide objective measurement and assessment of technical competence. In conventional methods, performance measurement and assessment depend on a supervisor's qualitative, subjective evaluation. VR-based simulators, on the other hand, use quantitative, concrete metrics.[3] During a training session, the system can record movements and applied forces and then evaluate the trainee immediately using the performance metrics. Quantitative performance measures include

**VR simulators can serve as an R&D environment in which expert surgeons develop, try, and test new surgery techniques and devices.**

- task completion time,
- operational accuracy,
- hand motion economy,
- path length,
- work done by trainee (force times displacement),
- number of tasks completed successfully,
- amount of unnecessary tissue damage, and
- excessive use of surgery material (for example, clamps during clip applying).

Stylopoulos et al. developed a standard assessment methodology that uses several of these measures.[33] This methodology merges the recorded values to quantify overall performance by a single number after the training session. In addition, VR simulators can support proficiency evaluation by generating learning curves based on multiple training sessions.

*Concurrent validity* is the correlation between a trainee's simulator performance and his or her OR performance. Finally, *predictive validity* is a prediction of the correlation between a trainee's present simulator performance and his or her future OR performance. The concurrent and predictive validations are related to *training transfer*, also called *VR-to-OR proof*, which refers to the success of simulator training in actual performance, or how well simulator training transfers to the real world.[4]

## Future directions

Medical boards and accreditation councils in the US and Europe have recognized the importance of VR-based training. The American Board of Medical Specialties and the Accreditation Council on Graduate Medical Education identified the mastery of technical skills under the supervision of specialized instructors as a major component of medical competence and approved residency training programs. They suggest that such training take place outside the OR to support hands-on experience with real patients in the OR. Similarly, the UK's Royal College of Obstetricians and Gynaecologists, in its 2002 report *Discussion Document on Further Training for Doctors in Difficulty*, recommends the inclusion of VR trainers in surgery training programs.

For more than 50 years, the aviation, aerospace, maritime, military, nuclear energy, and other high-risk industries have been using simulators to train novices in difficult and demanding tasks. The success of flight simulators is a convincing example of the importance of simulation technology for teaching skills that have an impact on human lives. It also shows the long-term potential of simulation techniques. Just as flight simulators train pilots, VR-based systems can select, train, credential, and retrain physicians in the art and science of their profession. Recent technology advances, reported inefficiency of traditional training approaches, and increasing support from medical professionals seem to direct next-generation medical training toward VR simulators.

A difference between MIS simulators and conventional training approaches is that VR-based systems can provide trainees with unusual training scenarios—an artery mistakenly severed during a procedure, perception difficulty under limited visual or haptic cues, or device malfunction—to improve their problem-solving and decision-making skills. Users who complete the training program can regularly practice with the simulators to maintain their competency. In addition, surgeons can use simulators as a preoperative planning environment. After entering patient-specific data into the simulator, the surgeon can plan and rehearse procedures before performing the actual surgery. Finally, simulators can serve as a research and development environment in which expert surgeons develop, try, and test new surgery techniques and devices.

Academia and industry have made significant progress in surgical simulation, but many questions still remain. Some are outside this article's scope, but here we highlight research directions that require further attention.

**Variations in anatomical models.** A key aspect of an effective surgical training simulator is its ability to provide a wide range of anatomies and pathologies. Only by doing so can it present the trainee with a realistic situation, because organs and pathologies in any two patients are never alike. So far, this aspect has received little academic attention. Most projects use only one static organ model. They usually derive the model's geometry from an exemplary data set, acquired through medical-imaging technology from a patient or volunteer. Researchers have paid even less attention to providing problem cases—that is, pathological alterations of the models. To that end, Sierra et al. recently proposed a method of automatic generation and addition of various typical pathologies to healthy anatomies in hysteroscopy simulation.[34]

**Material properties of organs.** We know little about the material properties of organs in their living state and native location. Moreover, there is great variation in tissue properties of the same organ as measured by different research groups. Although part of this variation is due to differences in measurement devices, techniques, and sites, we know that tissue properties vary within the same species depending on age, weight, and gender. How to include these variations in organ-force models is an open question. This is an important issue because soft-tissue models with incorrect material properties can lead to negative training transfer.

Establishing visual, auditory, and haptic design guidelines can aid the developers of VR-based surgical systems.

**Integrating material properties into deformable models.** Another open question is how to set a deformation model's parameters based on acquired in vivo data. Integrating the material properties of soft tissues into FEM models requires only a few parameters extracted from the experimental data. For example, Sedef, Samur, and Basdogan introduced a numerical method for real-time, linear, viscoelastic simulation of soft-tissue behavior using experimental data.[13] In contrast, mass-spring models need a considerable number of parameters, such as spring constants and mesh topology, which must be adapted to match real tissue's behavior. Several systems using mass-spring models rely on tedious manual parameter tuning with the help of a medical expert. Bianchi et al. suggest an alternative approach: using genetic algorithms to optimize the model's parameters to approximate a known reference system.[35]

**Physics-based tissue models.** Another controversial issue is the fidelity, or realism, of organ-force models. The main question is how simple a simulation we can get away with while preserving a level of fidelity between virtual and real organ behavior that leads to positive training transfer. Thus, we must find out what is needed for effective VR training before investing time and effort in developing complicated models of human organs and tool-tissue interactions. Another neglected issue is modeling physiological organ responses. Many organs' primary function is to maintain a stable internal environment despite external fluctuations. Hence, physiologic variables such as blood pressure, heart rate, and body temperature change in response to surgical interventions, and should be included in organ-force models.

**Graphical rendering and visual realism.** The cost of rendering polygonal objects grows drastically with the scene's geometric complexity. Depending on this complexity, we can switch back and forth between low- and high-fidelity 3D geometric representations of organs for efficient graphical rendering (the level-of-detail approach). An unexplored alternative solution is image-based rendering. In image-based rendering, we use a set of input images to create an intermediate data structure from which we can create new images of the scene later. Recent progress in this area suggests that new, efficient image-based rendering algorithms might have many advantages over traditional polygon rendering. For example, it is worthwhile to explore the efficient implementation of image-based approaches in simulating organ textures as an endoscopic camera applies light to them during an MIS. The reflected light generates complex visual effects and textures. Simulating these effects is challenging and requires advanced light interaction models and texture-mapping methods. Another emerging area is point-based rendering. The lack of topology information in point sets makes geometric modifications and adaptive refinements possible. For example, simulating tissue cutting with polygonal models requires polygon remeshing and subdivision, which can be eliminated with point-based approaches.

**Human factors studies.** There is great interest in validation of commercial surgical simulators. A missing component of these investigations is the lack of detailed human factors studies. Even if we assume that surgical simulators' hardware and software components will improve one day to provide richer sensory stimulation, the trainee will still have to perceive the information. Hence, better understanding and measurement of human perceptual and cognitive abilities is important for more effective training and training transfer. Establishing visual, auditory, and haptic design guidelines can aid the developers of VR-based surgical systems. For example, visual perception dominates human haptic perception, and if the visual display is not coherent with the haptic display, the human sensory system can estimate the virtual object's softness incorrectly. We can program a virtual organ to be perceived as softer simply by altering the visual displacement of its nodes rather than its force response. Similarly, we can perhaps model an organ's nonlinear force response as a series of approximated linear responses if the error in force response is below the just noticeable difference of human haptic perception.

**Integrating VR-based simulators into the medical curriculum.** Another critical issue is the integration of a simulator system into the medical education program. Simulation system development should be needs driven, not technology driven. First, the educators must identify the requirements of a trainer in the context of the education program. This usually requires a task decomposition of the surgical procedures to be taught. Then, they must identify the skills to be taught, which can be basic manipulative or higher-level cognitive skills. On the basis of this analysis, the educators can select the appropriate simulation setup. The open question of the level of realism needed to train in specific skills is related to this selection. Many surgeons believe that successful training must use highly realistic simulation trainers, even though low-fidelity training simulators have been effective in many domains.

Although technical efforts are going into surgical simulator development, we still do not know all the requirements of effective VR-based medical training. Is a complex but accurate tissue model needed for effective training? What is the role of force feedback in learning a particular procedure? How can we customize the training environment to the needs and skills of trainees? How much time should a trainee spend with a simulator? How well does the simulator training transfer to the real world? ■

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