Application of Information Technology ■

Simulated Medical Learning Environments on the Internet

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Abstract Learning anatomy and surgical procedures requires both a conceptual understanding of three-dimensional anatomy and a hands-on manipulation of tools and tissue. Such virtual resources are not available widely, are expensive, and may be culturally disallowed. Simulation technology, using high-performance computers and graphics, permits realistic real-time display of anatomy. Haptics technology supports the ability to probe and feel this virtual anatomy through the use of virtual tools. The Internet permits world-wide access to resources. We have brought together high-performance servers and high-bandwidth communication using the Next Generation Internet and complex bimanual haptics to simulate a tool-based learning environment for wide use. This article presents the technologic basis of this environment and some evaluation of its use in the gross anatomy course at Stanford University.

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Media-rich learning experiences are widely available on the web. Medical schools and other health care organizations maintain extensive websites for learning, reference, and assessment. Continuing medical education on the Internet is one of the most commonly available and widely used services for health care practitioners. These media-based learning environments, though widely available, represent a passive medium of information retrieval by clicking a mouse.

We have been investigating the next generation of Internet-based learning technologies: simulation-oriented learning environments that support interaction, collaboration, and active learning. The topics of learning are anatomy and basic surgical manipulations. To support these topics, we have developed three-dimensional visualizations of anatomy and have enriched these anatomical models with biomechanical tissue properties of elasticity and viscosity such that the learner can use appropriate force-feedback tools to feel tissues at the same time that they visualize them. Access to and interaction with these simulation environments have required that we push the envelope of current Internet capabilities, and that we investigate the role of network bandwidth and latency in the performance of these applications. A preliminary version of this work was presented at MedInfo, 2001.[1]

Background

The learning of anatomy and surgery involves a visuo-haptic-audio experience. While books, lectures, and multimedia are important routes to this learning, the acts of touching, feeling and cutting are believed to be essential in the training of new physicians and surgeons. Simulated environments that deliver this experience are expected to form the next generation of technology-enhanced learning environments.

When this research was begun in 1998, simulators were in development for knee arthroscopy, laparoscopy, endoscopy, epidural needle insertion, and sinus endoscopy.[2–10] These were three-dimensional graphical simulations of anatomy, with haptic feedback, to support planning a surgical or clinical procedure. Some included the ability to cut and move tissue.[11] Others

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supported deformation of tissue.[12,13] The high computational demand of anatomically based simulations prevented their use over the Internet. The first such distributed systems were in non-medical fields. Faisstnauer[14] presents an analysis of the requirements of a client-server system that can support heterogeneous input and output devices. The rapid progress of this young field can be seen in the proceedings of two annual conferences, Medicine Meets Virtual Reality, and the IEEE Virtual Reality Conference.

Design Objectives

Our goal was to develop two simulation-based learning environments, one for teaching anatomy and the other for practicing basic surgical maneuvers. The anatomical learning environment, the Anatomical Workbench, would supply a diverse set of learning resources for hand anatomy, including a three-dimensional model of the hand and an interactive rotating view of the hand in stereo at different depths of dissection. The surgical environment, the Surgical Workbench, would provide a model of pelvic anatomy and surgical tools and the ability to carry out a set of basic maneuvers, including probing, cutting, and suturing.

The intended users for the Anatomy Workbench are first-year medical and other health care students, using the resources individually or collaboratively, around a single workstation or simultaneously from multiple workstations. It is a primary learning environment when used by a teacher leading a group and a supplemental or review resource for students learning alone. The Surgery Workbench is for use by novices to surgery to familiarize them with the basic maneuvers. It is also for use by residents learning about critical aspects of a procedure that is new to them.

Figure 1 The Laparoscopic Impulse Engine is a simulated surgical grasper. The realistic tool handle is used to grasp simulated tissue. The tool can be rotated around a fulcrum and can be inserted or pulled back. Force is felt in 2 rotational and one translational direction.

These learning environments are intended to be on servers that are accessed across the Internet. Therefore, network and server response time are critical for performance. Because large images and video are streamed to multiple students simultaneously, network bandwidth is another critical issue.

System Description

Simulation can represent many situations in the real medical world: physician-patient dialog, physical examination, work flow in the clinic, crisis management, and others. We focus on the simulation of three-dimensional (3D) objects that are anatomically realistic and that have both graphic (visual) and haptic (touch-and-feel) properties. This anatomy can be viewed on a computer screen, with or without stereo glasses, and can be manipulated (probed, dissected) with a haptics device (force-feedback mouse or a surgical tool with force feedback).

Simulation-Based Visuo-Haptic Environment

Hardware

User Workstation. A typical user workstation is a personal computer with the Windows NT operating system and a high-end graphics card, such as the 3D Labs Oxygen GVX210 graphics card, together with stereo viewing glasses (from StereoGraphics, NuVision or VRex) and a force feedback device, such as the PHANToM stylus (Sensable Corp.) with x, y and z force feedback[15] or the Bimanual Surgical Manipulator from Immersion, Corp.,[16] which simulates the force feedback on a simulated surgical grasping device (Figure 1). We are also exploring low-end configurations with less expensive graphics and a mouse with force feedback only in the x-y plane.

Stereo Viewing. The three-dimensional perception of objects requires providing disparate input to each of the eyes. The difference in viewing angle (5–6°) of the eyes, when looking at objects at different depths, provides the necessary sensation of three-dimensionality. This effect is achieved on computer monitors by quickly alternating the display of left and right eye images. Stereo viewing glasses have polarized lenses that are synchronized with the computer screen, such that only one eye can see the screen at any time (Figure 2). To improve viewing comfort, we use a graphics card with a high refresh rate and with support for double buffered stereo display.

Haptics. Haptics devices are electro-mechanical devices that translate digital information about computed forces into physical sensations. For example, when the user moves a haptic stylus, sensors measure the device position and a computed force vector is sent to the motors of the device. The activated motors resist the stylus movement and the device pushes back, giving a physical sensation of resistive force.

Server. Realistic simulation of tissue deformation and similar problems requires computational power that exceeds that available in a desktop workstation. In our system, the graphics of an object deformed by a surgical tool and the corresponding haptic forces, are computed on an 8-processor Sun E3500 server with 1GB of memory and transmitted over the Internet to the user's workstation.

Simulation Server with 3D Graphic and Haptic Models

Our surgical simulation software has been developed as a generalizable framework that can accept anatomy models in various standard formats, interact with devices having up to 6 degrees of freedom, with haptic feedback on some or all axes, and can output a display to devices ranging from a palm-sized device to an immersive table or wall.[17] The emphasis is on real-time interaction. The server supports collaborative interaction by multiple simultaneous users.

A typical anatomical model has many parts, such as large organs, muscles, bones, tendons, vessels, and other components. Each component is represented as a separate graphic object composed of a 3D mesh for simulation and related surface triangles for visualization. The main advantages of this representation, as opposed to a volumetric representation, are that the triangular surface representation is readily displayed by the many graphics boards available and surface connectivity information is preserved to facilitate interaction. The pelvis model has over 20 objects with between 2000 and 50000 polygons each. The model of the hand has over a million polygons for some of its components. To retain real-time interactivity, these components have been simplified through a process of polygon reduction or decimation.

Figure 2 The polarized glasses have a wireless or wired connection to the infrared emitter box, which is usually placed on top of the computer screen.

Tissue mechanical properties are needed if the graphic models are also to be perceived haptically. Again, we have chosen to use a 3D mesh representation, with masses at the nodes of triangles, linked by springs along the triangle edges. An external force can be applied to a mass at a node. The corresponding displacement of the mass is computed as the displacement necessary to generate the corresponding reactive force from the nearby compressed or stretched springs. By using a small time interval for the computation, we are able to treat this as a quasi-static problem rather than a dynamic one, solved by differential equations. A typical anatomic component of 10,000 polygons can have its haptic reactive forces updated at over 1000 times per second. Haptics research has shown that human perception of high-quality haptic feedback requires a force update rate of at least 1000/second.[18] For coherence of visual and haptic perception, the anatomy must be seen to deform at the same time as the haptic force is felt. However, the visual image can be updated at the lower rate of 30 frames/second and still provide the perception of smooth object deformation.

In the human body, anatomical components are connected to each other. Muscles attach to bone through tendons or through fascia. Vessels are attached to organ walls. Therefore, the graphic and mechanical models must include this attachment information. At present, we permit only small areas of attachment, and we restrict all movement at this location. Therefore, muscles stretch but do not detach themselves from bone when a force is applied. In the current model, the bones are static, but all other anatomic structures can move or deform. We are constructing a dynamics engine that also will compute the motion of linked rigid bodies.

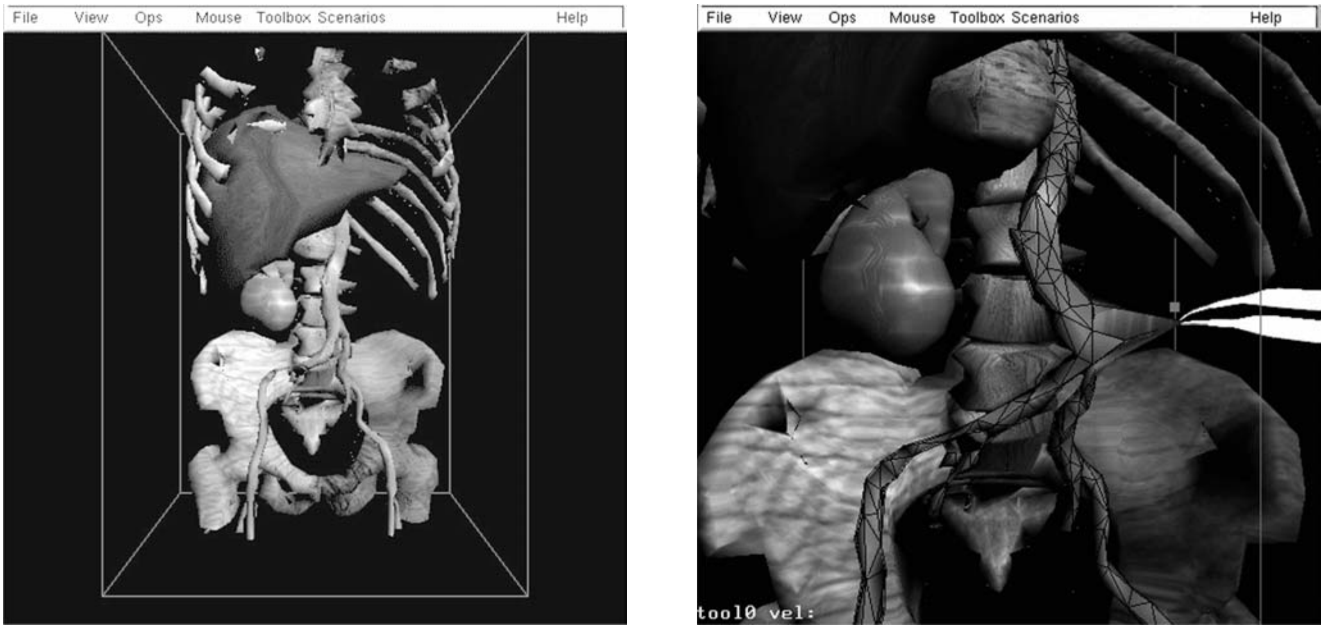


Figure 3 Interaction of a virtual tool (forceps) with a model of abdominal organs. The forceps tool pulls on and deforms the polygonal model of the aorta. *A*, The abdomen. *B*, An enlarged view of the descending aorta, with the underlying wireframe made visible.

Interactive Tools

We have chosen to focus on those anatomic and surgical manipulations that are tool-mediated rather than requiring direct interaction of the hand with the tissue. Therefore, in the surgical context, we represent those operations common in minimally invasive surgery, executed with tools inserted through small openings in the skin as opposed to the simulation of open surgery.

The student uses real tools, such as a surgical grasper, to control virtual tools, which then interact with the virtual 3D anatomical model. The virtual tool applies a force on the tissue, with the computation of a deformation and a resulting reactive force. The computed reactive force is used to activate the motors on the manipulator, thus providing resistance to the movement of the grasper in the hand of the student (Figure 3).

Each tool is represented in the virtual world with its own graphical form that approximates its real form. Each tool also has its characteristic interaction with tissue which is represented as an interaction with the polygons of the model. A grasper, for example, pinches tissue and also is able to push tissue. A probe, on the other hand, only pushes tissue. A scalpel cuts tissue on its sharp side, but pushes tissue on its blunt side. So far, we have represented the probing, grasping, and cutting actions, with the corresponding effect on the polygons of the anatomical object.[19] We have also represented the piercing action of a suturing needle.

Interactive Collaborative Software

The goal of the learning environments developed by this project is to allow students to interact with remote anatomical resources. These resources are sophisticated simulations that require computing power beyond what is available locally or are repositories of anatomical images and video that are impractical to retrieve and store on the desktop. Students interact with these resources either in an exploratory manner or according to lessons developed to integrate with the curriculum.

The software to support these learning environments consists of a client application running on the student's local computer, connected over a network to a server application running on a remote computer. In the case of a anatomical simulation, students interact with the simulation using a real local tool, connected to the client, that controls a virtual tool at the server. The server returns to the client a visual representation of the student's action, such as tissue deformation, as well as a corresponding haptic force. Applications of this kind require a tight coupling of the client and server for acceptable performance. Roundtrip latency, and its variance, introduced by the network connection must be minimized.

In addition to interacting with the model, education theory recommends that students interact with each other in order to expose different viewpoints and to encourage discussion. The software, therefore, supports interaction with the model by multiple users, together with simultaneous viewing of the model by all users.

Programs exist for multiple users to view a shared screen, and for each user to be able to control the remote application. We have embedded a similar ability in some of the applications that we have developed and have added a capability for multiple tools to manipulate the remote model simultaneously, while providing haptic feedback to each user. Collaborative manipulation takes a learning environment significantly beyond collaborative viewing. A teacher feels the forces applied to tissue by a student with a probe. A student, holding tissue with forceps, feels the stresses induced when another student pulls at the tissue from another location on the anatomy.

Content

The core content of the learning environments presented here is the simulation of the anatomy for anatomical or surgical manipulation. However, a simulation may not always be the optimal way to convey knowledge. The learning content also includes a large collection of stereo pairs of dissection images of the hand, about 2,000 cryosectioned color images of the Visible Human, a 3D haptically-enabled model of hand anatomy with millions of polygons representing bones, muscles, tendons, vessels and nerves, a 3D haptically-enabled model of pelvic anatomy with all major organs and vessels, and hypertext describing surgical manipulations and anatomical dissection using these data. In actual curricular use, the content also includes streaming video of the teacher as well as audio from all the participants.

Lessons

The technology and the content constitute the infrastructure on which a teacher builds the lessons that assist the learner to manipulate and absorb the information until it is learned. Even in an exploratory learning environment, guided paths through the content, or puzzles and games that elucidate learning points, have been found to be necessary.

We describe below two learning environments that we have constructed, in which we implement these ideas and pedagogical principles: the Anatomy Workbench and the Surgery Workbench.

The Anatomy Workbench

Since the sixteenth century, anatomy has been taught through dissection of the human cadaver[20] and study of illustrated atlases. Students probe, feel and cut tissue, exposing anatomical structures and their relationships. There are no labels in the cadaver. So they use atlases, with labeled images, to identify what they see, sometimes struggling with the natural variation of human anatomy. Dissection is a destructive process, and errors cannot be corrected. In some countries and universities, cadavers are not available for student use. They may observe an instructor dissect, or they may study from models and prepared dissections.

In the Anatomy Workbench, the students encounter a composite virtual cadaver presented through a variety of media, including photos and video of dissected material, high-quality three-dimensional models, animations, and volumetric data. While applicable to all anatomical regions, we have chosen to emphasize teaching the anatomy of the hand. The rotated views of the dissected hand, at different depths of dissection, allow the student to view the hand from different angles and study tissues at different depths. The three-dimensional model of hand anatomical structures can be rotated and flexed at each joint, and individual structures can be removed at will. An animation of finger flexion shows normal flexion and changes in flexion when a nerve is injured. We plan to continue developing these resources so that students will be able to study anatomy as they control a fully articulated hand, relate it to the dissected hand, analyze the mechanisms of different injuries and study their effect on activities of daily living. An interface is being developed so that, instead of being separate learning activities, all resources will be available from one web page, as parts of a single learning experience (Figures 4, 5, and 6).

The Anatomy Workbench is available as a collaborative, interactive learning environment for students accessing it over the Internet. Below we discuss some of the methods we have utilized to make this environment Internet-accessible.

Figure 4 Images of dissected hand in the Anatomy Workbench.

The Surgery Workbench

Learning basic surgical procedures is the learning of a set of fundamental manipulations, the application of the correct manipulations in each surgical situation, and the sequencing of these manipulations into a procedure. Circa 500 BC, eight such surgical manipulations have been characterized: probing, aspiration or injection, incision, evacuation, scarification, extraction, excision, and closure. A ninth, more modern procedure is implant or transplant.[21] A specific manipulation, such as probing, may be applied in different ways in different surgical contexts. For example, one may palpate with four fingers when feeling the skin or a large organ, probe with a blunt instrument when feeling blindly within a cavity, or separate tissue with a blunt dissector when reaching below fascia to find a vessel.

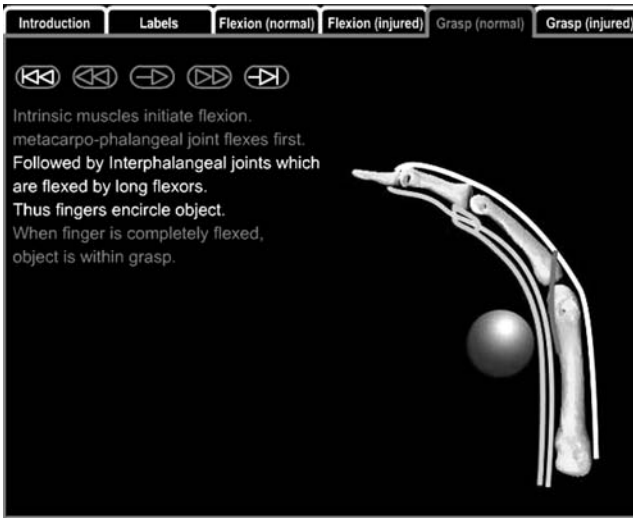
Interaction with tissue and feeling its texture and resistance are critical component of learning. Therefore, the key features of the resources in the Surgery Workbench are three-dimensional graphic models of anatomy and the corresponding biomechanical models that make the anatomy palpable through tools such as probes and dissectors. In particular, we have outlined and segmented the organs from photographs of cryogenic slices through the cadaver of a young woman to create a model of the anatomical structures in the human female pelvis.[22] These include large structures such as the bones, the bladder and the uterus, as well as fine structures such as blood vessels and nerves. The biomechanical modeling permits the tissue to be deformed and to be cut. Each structure can have unique biomechanical characteristics. At present we are collecting data about these unique properties that make tissues feel and behave differently when probed.

The Surgery Workbench is accessible over the Internet. Users from different locations can manipulate the model. As one person deforms the model, others can feel the force in the stretched tissue.

Scalability of the Application

Current simulation computers conduct all computations locally and are equipped with numerous peripherals such as stereo goggles and simulated surgical tools. Tomorrow's simulation environment will support server-based visual and haptic simulation, with data streamed to low-end displays and manipulators. At the same time, high-end desktop workstations will continue to download and manipulate data locally. Therefore, an important issue for Internet-based education is the availability of a scalable solution that makes maximal use of local computation and Internet bandwidth (Figure 7). We expect scalability of applications to be necessary along three dimensions: visualization, haptic modeling, and manipulation device.

Figure 5 Images of a 3D model of a hand (courtesy of Primal Pictures, UK).



Intrinsic muscles initiate flexion.
metacarpo-phalangeal joint flexes first.
Followed by Interphalangeal joints which
are flexed by long flexors.
Thus fingers encircle object.
When finger is completely flexed,
object is within grasp.

Figure 6 Animation depicting finger flexion where the ulnar nerve is injured.

Visualization. Available bandwidth and remote computation capability determines whether the visualization can be computed remotely, compressed, and streamed to the user's display. This mode of visualization allows all users to manipulate a single model as they interact and collaborate. If the bandwidth is low, but the local workstations have sufficient graphics computation power, each user downloads the model for local manipulation. Model state information to is transmitted to synchronize the model for all users.

Haptic modeling. Haptic feedback about interaction with a remote model requires the transmission of a change in tool position to the remote model, and the return of the resulting computed force. The time taken to accomplish this is the haptic loop time. It has been determined experimentally[18] that a loop time of 1 ms or less is required for accurate haptic perception during sudden changes in movement or in tissue mechanical properties. Loop time requirements are most stringent for haptic interactions, such as tapping on a hard surface (e.g., bone). If the latency of the network is high (that is the loop time is too high), the user will have retracted the tool well before he or she receives the sensation of tapping the surface. Therefore, a scalable solution supports a downloadable haptics model for situations of high latency.

Manipulation device. A high fidelity surgical simulation requires an authentic surgical tool as the manipulator. We have developed a bimanual, 5 degree-of-freedom, 5 axes of force feedback, manipulator set (Figure 8). This represents most of the tools and positions needed to learn minimally invasive surgery in the abdomen, and is the interaction device for the Surgery Workbench. At the other end, we are experimenting with a mouse that provides force feedback along two axes. We expect that this device will allow sensing of tissue elasticity and will support many of the learning activities necessary for the Anatomy Workbench.

Delivering Simulations Over the Internet

Visuo-haptic medical simulations usually have been implemented on single high-performance computers. Our implementation assumes that the computational aspects of the simulation are run on a high-end server while the user and the visuo-haptic interface are on a client computer which accesses the server over the Internet. We also assume that multiple clients will

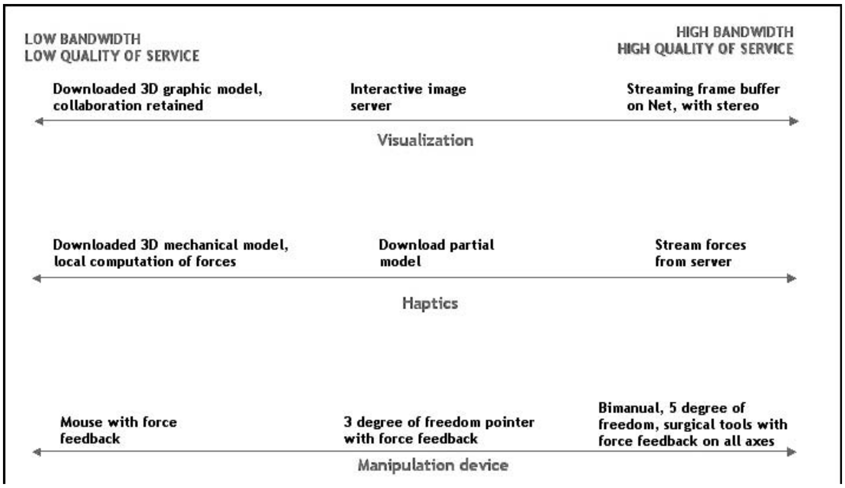


Figure 7 A schematic of three dimensions on which scalability can be achieved: Visualization, Haptics, and the Manipulation Device. (Reprinted courtesy of IMIA.)

Figure 8 Bimanual surgical manipulators that control virtual tools in the simulation. Each manipulator can translate in and out of the trochar, and has pitch, yaw and twist movement, with haptic feedback on each of these axes. Pinch forces are felt when the grip is closed. An additional twist freedom is provided to allow the tool handle to rotate with respect to the rest of the tool.

access the simulation and that they will collaborate in a learning exercise. Furthermore, the presence of the Internet in the simulation system introduces issues of bandwidth, latency, and jitter that are not encountered in the single-system implementation.

Figure 9 shows the partitioning of the application into its client and server components. In its simplest form, the client detects and reports tool position, and receives force information that is used to drive the tool motors and produce resistive forces. The client also receives the streaming images from the server with updated viewpoint, anatomical deformation and tool location.

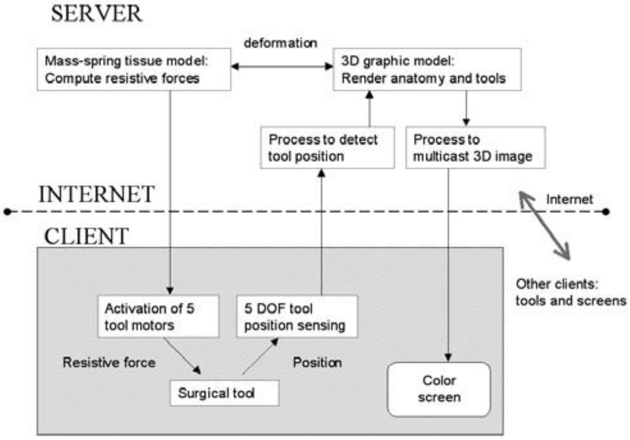


Figure 9 The simulation server supports multiple collaborative clients. Computation of the graphic rendering and the tissue forces is executed in the server.

To support collaboration between multiple clients on the Internet, a tier of middleware is introduced in the server. One process is a display server, which captures changes of the screen image and streams the changes to any client that registers to receive it. Thus numerous clients may observe the anatomy model as it is being used. The display server is able to recognize the network bandwidth and the display capabilities of the client and streams the image changes in the correct format and at the correct rate. Another process listens for tool position changes from registered clients and updates the position of the corresponding virtual tool relative to the anatomical model. The same process streams corresponding force changes back to the appropriate tool. Again, the process is sensitive to a variety of force feedback tools with different degrees of freedom.

The haptic forces need to be updated at 1000 times per second for a crisp and accurate sensation of the feel of a surface. The presence of the Internet between the server and the haptic client can introduce significant delay. A solution is to download to the client a portion of the haptic model adjacent to the tool tip. A computational process at the client then computes force changes as the tool is moved. The tool movement information is also sent to the server, which computes changes in model geometry and updates the local model as needed. It is noteworthy that the user in the loop also adapts to increased network latency, automatically slowing down when the system becomes slow to respond!

Status Report

The first learning environment, the Anatomy Workbench, is essentially complete and has been used as a teaching tool. The technology infrastructure for the Surgery Workbench is complete, and the simulator has been demonstrated successfully. The pedagogic content or lessons are being developed. Both environments have been evaluated using a range of measures.

Use and Evaluation of the Anatomy Workbench

The learning resources in the Anatomy Workbench include:

- A 3D dynamic model of finger anatomy, controllable by applying forces to the tendons
- An immersive visuo-haptic environment for interactive segmentation of Visible Human data
- A collection of 504 images of hand dissection collected at 5-degree intervals for stereo viewing. The user can rotate the views and move through seven different depths of dissection.
- Animations that depict normal and pathological finger function
- A 3D surface model of hand anatomy that can be palpated using a PHANTOM pencil-like device. (This does not operate yet over the Internet.)

All of these resources have been tested for usability and reviewed for accuracy of content.

Collaborative Learning Using the Anatomy Workench. The collection of interactive dissection images has been used for collaborative learning within the Human Anatomy course for medical students. As a teaching tool, it constituted a significant innovation in pedagogy for anatomy.

Each dissection image is approximately 1000 × 1300 pixels and is approximately 200KB in JPEG format. Typically a user views only a fraction of the images within a set. Consequently it is more effective to provide images on demand as the user navigates the image set rather than to download the entire image set before viewing. All images were accessible on servers, one at Stanford (local) and the other in Wisconsin (remote). Network latency was about 10 ms for the local server and ranged from 65 to 350 ms for the remote server, based on time of day. For the classroom experiment, the local server was used. The material was taught to students in groups of 8 to 10. The teacher was on one computer, and the students were in small groups of 2 or 3, around three other computers. All used shutter glasses for viewing stereo. No haptic device was used. All had independent interactive control through a mouse. The teacher had a 3D mouse. When the teacher used his mouse, he controlled the image seen on all the student computers and thus was able to conduct brief didactic sessions. Control returned to the students at other times. Web cameras at each computer allowed the teacher to see all student groups. All groups could hear the teacher and be heard by him.

The learning experience was quite successful, with students requesting access to more interactive stereo content and more classes taught in this manner. All groups had good, highly responsive, interactive control of hand rotation and dissection. Network data rates were computed to be 30–40 Mbytes per second when all stations were active, but the network performance tools did not permit actual traffic measurements with sufficient time granularity. The movement of the 3D cursor was smooth at the teacher station but was jerky at the student stations. We assume that this is because of programming issues and not network load since the amount of data transferred for cursor movement is small.

Measurement of Perceived Performance as a Function of Network Delay. We interposed a simulated network between the server and a single client workstation and then modified parameters to simulate a congested network. Users were asked to rate their perception of the quality of the interactive experience as the simulated congestion was varied. A 5-point scale was used, with 5 representing a high quality of interactivity and 1 representing an unusable system. Perception of the dissection viewing task underwent a graceful degradation with increasing network delay. Delay times had to exceed 100–200 ms before users indicated a significant perceptible loss in performance.

Evaluation of the Surgery Workbench

Technically, the development of the Surgery Workbench is a far more difficult task than development of the Anatomy Workbench. At present, we have developed most components of the system. The software engine for representing and manipulating the anatomy is operational and can accept a large variety of haptic input and output devices and can stream to visual displays ranging from large immersive desk-size stereo displays to miniature displays mounted in eyeglasses.[17] A large range of cutting and probing tools have also been simulated.[19] Multiple users can interact with and view the simulation simultaneously and in real time. A new compact bimanual surgical tool interface has been developed, with 5 degrees of freedom in position and force sensing for each device.

A major performance question for the Surgical Workbench is the impact of network latency on collaborative haptic tasks. We implemented an experimental testbed in which the user had to replicate a movement stored on the server. This is comparable to a training situation in which the user must learn a movement, such as suturing. In actual operation, the user performed the initial movement using a haptic device, and the movement coordinates were stored on the server. The user then attempted to replicate the movement and the server applied corrective forces based on the difference between the current and the stored movement. A simulated network was placed between the server and the client, and a different delay was introduced for each trial movement. The bandwidth requirement was low, 64 Kbits per second for a reporting rate of 200/sec. It is noteworthy that there was no graceful degradation in the performance of this task. As the delay increased and the corrective forces were mistimed, the movement rapidly became unstable. A delay of 70–100 ms will make a stored slow movement unstable. For stored rapid movements, the acceptable delay is much reduced.

Usability and learning outcome tests remain to be conducted on the Surgical Workbench.

Discussion

We have implemented two simulation-based learning environments, one for anatomy and one for surgery. The tasks in the environment range from low to high computation and bandwidth requirement, and have differing sensitivity to network latency. The tasks also range widely in the complexity of the underlying engineering implementation.

The appeal of these simulation environments is significant both to students and to health care professionals. We are in the process of evaluating these environments for usability, validit,y and learning outcome.

Our future work will focus in two areas: deployment and testing of the existing simulation programs on a gigabit network, and integration of the programs with the curriculum. Gigabit connectivity will allow testing the applications as they would run for remote clients connected via Internet2 (or the Next Generation Internet). The limiting factors will be network congestion and the rate at which the servers can generate, and the clients process, the data streams, because of multiple simultaneous data streams. Latency will continue to be determined by the inherent response times of the server and the intervening network connections.

Conclusion

We have developed two new simulation-based learning environments, the Anatomy and Surgery Workbenches. The environments support collaborative learning and teaching over the Internet as well as individual study. These environments include large 3D haptic and graphic models, a large collection of dissection images with demand for high network bandwidth and other supporting resources. We have begun testing the usability and performance of these workbenches in classroom as well as laboratory situations. Because the individual applications are supposed to be usable over the Internet, using remote computation servers, we are testing performance where the bandwidth and latency are unpredictable.

Simulations as learning tools are engaging and, if these tools are validated for accuracy and learning outcome, they promise to be valuable new learning environments. Anatomy and surgical procedures require both a conceptual understanding of three-dimensional anatomy and a hands-on manipulation of tools and tissue. Such resources are not available widely, are expensive, and may be culturally disallowed. Simulation technology, using high-performance computers and graphics, permits realistic real-time display of anatomy. Haptics technology supports the ability to touch and feel this virtual anatomy through the use of virtual tools. The Internet permits world wide access to resources. We have brought together high-performance servers, high bandwidth communication using the Next Generation Internet, and complex bimanual haptics to simulate a tool-based learning environment for wide use.

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