Surgical Simulator for Hysteroscopy: A Case Study of Visualization in Surgical Training

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Abstract. Computer-based surgical simulation promises to provide a broader scope of clinical training through the introduction of anatomic variation, simulation of untoward events, and collection of performance data. We present a haptically-enabled surgical simulator for the most common techniques in diagnostic and operative hysteroscopy- cervical dilation, endometrial resection and ablation, and lesion excision. Engineering tradeoffs in developing a real-time, haptic-rate simulator are discussed.

Keywords: surgical simulation, hysteroscopy, haptics

1. INTRODUCTION

Surgical simulators have the widely acknowledged benefits of allowing the introduction of anatomic variation, simulation of untoward events, and collection of surgical performance data. Just as with aircraft piloting, medical procedures require repetitive practice for maintaining competence, errors are potentially disastrous, and the ability to train using "what-if" scenarios can be invaluable. Further, the sense of touch is essential for realistic surgical simulation and is especially true for minimal access surgical procedures[1]. These procedures require extensive training because the surgeon's ability to see the operating field and the ability to manipulate objects in it are severely restricted.

Currently, operative hysteroscopy[2,3] is taught by in vitro methods using inanimate objects such as sheep bladders or bell peppers through which water is perfused while the lens of an operative videoendoscope is placed into the cavity, and prescribed manipulations performed. These include grasping individual seeds of the vegetable with a grasping forceps, and resection of strips of normal mucosa by electrosurgical electrodes. Neither pressure sensation during entry, nor tissue response from withdrawal of the electrode is identifiable because of the lack of realistic force feedback.

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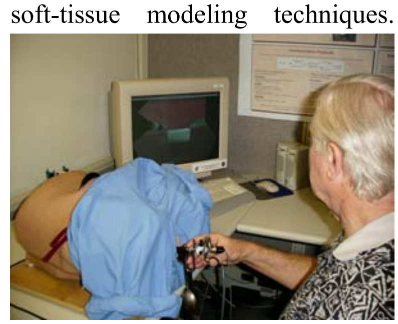
Though increasing adoption and frequency of hysteroscopic procedures may reduce the frequency of blind procedures such as traditional dilation and curettage, simulators with force feedback[4,5] offer major benefits for the training of these procedures as well, since blind procedures rely entirely sense of touch. Further, exposure to simulators during residency may make new surgeons more inclined to use them for periodic refresher training or more advanced applications like surgical rehearsal using patient-specific imaging data. They may also be used by certifying agencies for establishing surgical competency and by hospital quality assurance committees that evaluate complications of surgical practice.

2. MATERIALS AND METHODS

A virtual-reality-based surgical simulator for diagnostic and operative hysteroscopy was produced. It involved the production and integration of a 3-D anatomical model with specialized haptic devices and a surgical simulation system employing soft-tissue modeling techniques. Development also included a user interface to allow the selection of various procedures and to present data concerning task completion times, forces exerted during procedures, etc.

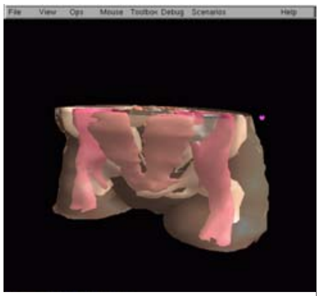


Dr. Heinrichs performing a simulated endometrial ablation

The simulator gives the operator a realistic simulation of surgical maneuvers used during cervical dilation and hysteroscopic procedures that allow skills transfer to actual operations. Operators begin the procedure by reviewing guided curricula, case histories, and instructions, then perform a simulated cervical dilation and progress to diagnostic and operative procedures. The system is capable of simulating both diagnostic and operative hysteroscopy (including removal of intrauterine lesions and endometrial ablation, including resection).

Anatomical Model

The Stanford Visible Female (SVF) is a collection of digitized serial photographs of a cryosectioned 32 year-old cadaveric female pelvis. Hand segmentation was performed of the 95 digital cross-sections, which were then registered from fiducials and anatomic structures. The tissue and organs were extracted into over 1600 masks for 3-D model development. This data set is similar to that of the Visible Human Project. However, the specimen is that of a 32 year old reproductive age female, in contrast to the 59 year-old post-menopausal Visible Human Female which reflects the atrophic signs of post-menopause. However, the SVF data set is limited to the pelvic region, the sections are thicker, and CT or MRI images of the specimen are unavailable.



Rendering of Stanford Visible Female pelvic dataset

Haptics Interface

A modified Laparoscopic Impulse Engine provides the force feedback response.

Haptic Device Specifications	
Sensing Degrees of Freedom	6
Force feedback Degrees of Freedom	3
Workspace	10cm x 10cm x 10cm
Maximum Force	5-10 Newtons
Surgical Tool Position Precision	0.1 mm
Surgical Tool Orientation Precision	0.3 degrees
Backlash	below perceptible limits
Maximum Latency	4 msec
Data Rate	>1000 Hz

The simulator uses an off-the-shelf rubber and plastic pelvis model (Gaumard Co.) to represent external female anatomy and to hide the haptic feedback hardware. Since the mannequin had not been designed for precise fixation, minor modifications were necessary. As part of this task, engineers created a custom, instrumented hysteroscopic handle to support this application area. The extension/ retraction trigger was sensed and fed into an analog-to-digital converter to allow programmatic access. In addition, a floor pedal was wired to the system to simulate the pedal used for activating the current during cauterizing procedures.

Instrumented Handle

Haptic device internals (left), and with mannequin (right)

The Haptic Device Controller (HDC) is a networked computer that is equipped with custom electronics to control the haptic interface device. This controller reads the haptic device's position and orientation and transmits it over the network via a TCP/IP connection to the simulation server. In addition, it also receives force vector commands from the simulation server over the network and applies these forces to the user. The Haptic Device Controller also performs various safety checks and maintains high-fidelity haptic sensations through force interpolation. By separating the simulation system into two parts, the haptic rendering of forces can progress at the maximum possible rate unencumbered by the cycle time of the simulation.

Simulation System

The core software for modeling the physics of soft tissue dynamics is the *spring* system developed by the National Biocomputation Center, and has been previously used for surgical planning and analysis, a microsurgery training simulator, suturing simulators, and other applications. The visualization component of the system allows the user to view the mesh data in monoscopic or stereo as wireframe, solid, or semitransparent objects. The software is written in C++ using the OpenGL, GLUT, and GLUI visualization libraries and runs on many different computing platforms. For this project, the simulation ran on a Sun Ultra60 Elite3D graphics workstation with two 500 MHz UltraSPARC processors and 1GB of main memory. The software is multithreaded and dedicated one processor to graphics and the other to communication, collision detection, and simulation.

Soft-Tissue Modeling

In the system, a soft tissue object is modeled as nodes (point masses) connected by edges (springs), which are grouped in triangles for the purpose of visualization. Forces are exerted on each node by the adjacent springs, by damping, by torsion between adjacent triangles, and by the surgical instruments controlled by the user. Known physical properties of tissue are used to provide appropriate values for these forces and ensure realistic simulation. Simple and fast iterative numerical methods (Euler, Runge-Kutta, or quasistatic) calculate each nodes position and velocity based on these forces, which can then be used to deform the object in real-time at haptic rates (>1000Hz). The system uses constraints to limit processing requirements to provide for increased scalability while maintaining adequate update rates.

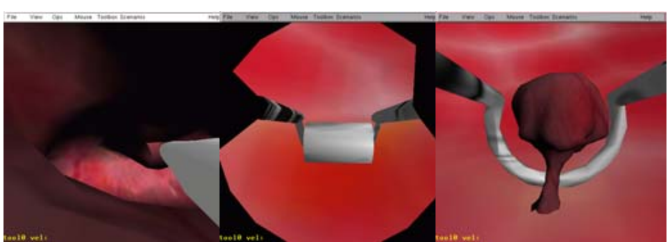
Collision Detection

Real-time, haptic-rate collision detection[6] was performed by a modified hierarchical Bounding Spheres algorithm[7]. Modifications to this algorithm were made to support rapid update of the bounding sphere tree for deformable objects[8] , as well as a number of other enhancements to bound the regions of detection and update to increase performance to haptic rates.

Instruments/Interactions

Several different surgical instruments and their corresponding interactions were implemented. For the dilation procedure, a set of four cervical dilators of different diameters (2mm, 4mm, 6mm, 8mm) was created. These dilators interacted with the tissue by a triangle-triangle collision, which led to a force-based displacement of the deformable tissue (in this case, the vagina/cervix). The user can feel the force profile of pushing past both the outer and inner os of the cervix and into the endometrial cavity.

For endometrial ablation, a roller ablator was created and interacted with the tissue by progressively yellowing, then browning the area of contact between the roller and the endometrium when the floor pedal was triggered by the user. Finally, to simulate cautery of intrauterine polyps, a loop cautery instrument was created which interacted with the uterus in the same way as the roller ablator (yellow/brown discoloration at the area of contact when activated by the user), but also cut and released the simulated polyps upon activated contact. Each of these tools detected contact with the uterine surface and polyps (if present) and generated appropriate forces.



Simulation images: cervical dilation (left), endometrial ablation (middle), polyp resection (right)

Simulation User Interface

The simulator also includes a shell user interface containing the instructor and student front-end for the simulator. The interface allows the student to view general or skill-specific instructions, as well as select the various procedures.

3. RESULTS

This system realistically simulates the procedures identified above. Initial feedback from highly experienced surgeons (over 20 years of experience) using the system has been positive, with validation of the anatomical model, visual display, and force feedback as being similar to those encountered during real procedures. While a complete evaluation is planned, these reviewers have indicated that further refinement of forces and visual appearance is desirable before wide deployment.

4. DISCUSSION

Challenges during the production of the simulator included refining the datasets to produce 3D meshes suitable for simulation, maintaining constant and high haptic and simulation update rates in the face of large geometries, providing rapid collision detection, and producing an appropriate force calculation.

The production of an anatomical model for use in mass-spring simulation subjectively requires an order of magnitude more effort to ensure the correct dynamics. In the case of the SVF dataset, the existing surface meshes were suitable for visualization, but required additional effort and software to extrude the surface mesh into a 3D mesh, and to ensure that the surface normals used for haptic interaction were correct. Further, a reorientation of the SVF data was required because during hysteroscopic procedures, the cervix-uterine body angle is straightened by cervical traction. Finally, the SVF did not include surface textures, which had to also be generated from other sources. The size of the resulting deformable meshes were vagina/cervix (2059 elements) and uterus (1985 elements), and nondeformable meshes of the pelvis (2000 elements) and skin (988 elements) for visualization purposes.

The soft-tissue simulation engine used a quasistatic solver, which is appropriate for heavily damped tissues, and ignores velocity and damping forces in return for significantly improved performance. This solver operates at roughly 1.8 million element updates per second, which would have provided a simulation update time of over 900Hz for the vagina or uterus. However, by tracking the interactions of tools and the resulting spread of the deformation region, our actual performance was often significantly higher (over 7000Hz).

Collision detection posed some of the greatest challenges. The insertion of a dilator into the simulated vagina/cervix is a worst-case scenario for most collision detection algorithms since there is nearly complete overlap of one object by the other. The first implementation using the hierarchical bounding spheres algorithm supported an update rate of only 4Hz. By identifying the regions of possible interaction of the dilators and anatomical model, we were able to enhance the algorithm to prune significant portions of the hierarchical tree and attain an update rate of over 400Hz which, with 10,000Hz local haptics interpolation at the HDC, provided acceptable force sensation.

Instrument interactions during the collision of the dilator within the cervix were somewhat complicated due to the force being nearly tangent to the surface. This initially produced forces inconsistent with the task. We later ameliorated this effect by providing an additional weighting function to the force contribution that took into account the angle of collision between the probe and the surface.

While some of the issues discussed above are specific to the particular domain of hysteroscopy, many are evident in other applications. By carefully tuning the tradeoffs of any simulation system within the domain of application, a truly usable system can be realized.

5. CONCLUSION

Surgical simulators for hysteroscopy and other gynecologic procedures offer the promise of improving training in a low risk environment. Different anatomical variations and pathologies can be presented and surgeon performance can be quantified. The system presented here required domain-specific tradeoffs and additional research to achieve a haptic-rate simulation system.

Future work includes extending the system as discussed above. First, the introduction of many more datasets, representing anatomical variations and pathologies, is planned in the near term. Improvement is also needed in the ability to segment and prepare such meshes, not just for visualization, but also for simulation is also needed. Third, identifying key metrics for the objective evaluation of surgical performance is also planned in the near term. Finally, developing and integrating pedagogically supported simulation systems with, and into, surgical curricula is necessary, a challenge not to be underestimated in complexity. While this simulator is a good first step in the production of enabling technology, its real utility depends on further research and development and integration into the training process.

6. ACKNOWLEDGEMENTS

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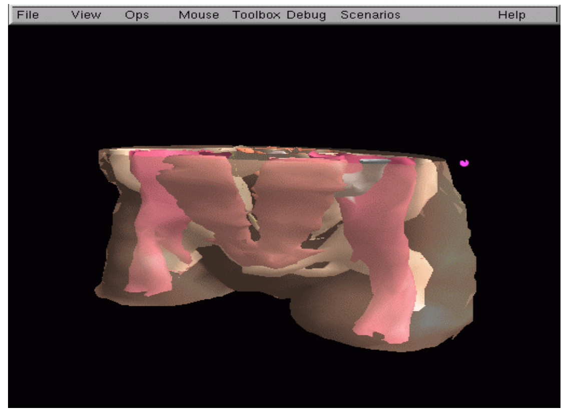
REFERENCES

1. Baumann, R; "Force Feedback for Virtual Reality Based Minimally Invasive Surgery Simulator," Health Care in the Information Age, IOS Press and Ohmsha, 1996, Ch. 63.
2. Bayer SR, Soto-Hunnicut JA. Dilatation and Curettage and Cervical Conization, in Operative Gynecology, (Eds.) Gershenson DM, et al. WB Sanders, Co., (1993) p. 260-2.
3. Rydfors JT, Heinrichs WL. Dilatation and Curettage, in Anesthesiologist's Manuel for Surgical Procedures (Eds.), Jaffe RA, Samuels SL. Raven Press, pp. 497-8, 1994.
4. Voss, G; Bockholt, U; Los Arcos, J; Müller, W; Oppelt, P; Stähler, J; "Lahystotrain - Intelligent Training System for Laparoscopy and Hysteroscopy", Proc. Of Medicine Meets Virtual Reality 8, IOS Press, pp. 359-364, 2000.
5. Kuhnapfel, U; Cakmak, H; Maass, H; "Endoscopic surgery training using virtual reality and deformable tissue simulation", Computers and Graphics, v24(1), pp. 671-682, 2000.
6. Lin, M; Gottschalk; "Collision Detection Between Geometric Models: a Survey", Proc of IMA Conference on Mathematics of Surfaces, pp. 37-56, 1998.
7. Quinlan, S, "Efficient Distance Computation Between Nonconvex Objects", Proc. IEEE Int Conf on Robotics and Automation, pp. 3324-3329, 1994.
8. Sorkin, S; "Distance Computation Between Deformable Objects", Honors Thesis, Computer Science Department, Stanford University, June 2000.

Dr. Heinrichs performing a simulated endometrial ablation



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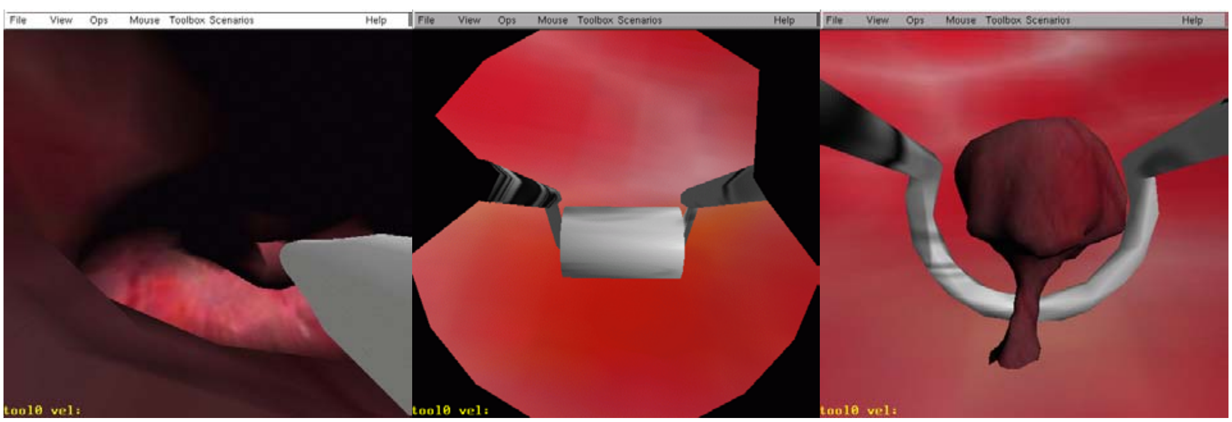
Haptic device internals (left), and with mannequin (right)



Simulation images: cervical dilation (left), endometrial ablation (middle), polyp resection (right)