Applications of Virtual Reality In Surgery

Amol Pednekar and Ioannis A. Kakadiaris
Department of Computer Science
University of Houston
Houston, TX 77204-3475, USA
{vedamol,ioannisk}@cs.uh.edu

Abstract

Virtual reality (VR) has revolutionized many scientific disciplines by providing novel methods to visualize complex data structures and moreover by providing means to manipulate this data in real-time in a natural way. Among the most promising fields for the application of VR systems are engineering, education, entertainment, military simulations and medicine. This paper reviews applications of VR in medicine, and surgery in particular. Key applications are identified and relevant methods, technologies, system issues, and needs are discussed. Finally, we review the challenges of the field and the opportunities for further research and development.

1 Introduction

Virtual reality has revolutionized many scientific disciplines by providing novel methods to visualize complex data structures and moreover by providing means to manipulate this data in real-time in a natural way. Among the most promising fields for the application of VR systems are engineering, education, entertainment, military simulations and medicine. Medicine is entering a period of profound technological transition, driven by the need to provide improved care at lower cost.

In this paper, we explore how virtual manipulation and exploration can be used for education and training, pre-operative planning, intra-operative assistance and post-operative assessment of innovative surgery techniques. Table 3 provides a summary of select applications of VR in surgery.

2 Areas of Application

Existing VR applications in surgery can be broadly classified in three categories: a) education and training, b) pre-operative planning, and c) intra-operative assistance as summarized in Table 1. These computer-aided surgery [90] applications are geared towards various human organs as summarized in Table 2.

Education and Training
• Practicing surgical procedures [82, 7, 25, 18, 31, 66, 70, 12, 87, 57] [93, 73, 76, 75, 11, 44, 84, 97, 64, 63] [50, 49, 86, 62]
• Skill assessment [50, 21, 49, 86, 80, 28, 62, 45, 63]
Diagnosis/Pre-Operative Planning
• Diagnosis [2, 46, 100]
• Design & optimization of procedures [76, 75, 33, 57, 12, 87]
• Design of implants [52]
• Exploration of surgical options [76, 33]
Intra-Operative Assistance/Guidance
• Intra-Operative Assistance/Guidance [49, 66, 70, 9]

Table 1: Taxonomy of the applications.

2.1 Education and Training

Currently, surgical manipulative skills are learned mainly by observing an expert surgeon, practicing skills on animals, cadavers, or inanimate trainers, and supervised practice during surgeries on humans. High expenses associated with these training methods [50] limit the number of times each surgeon can practice the technique.

With VR-based education and training systems surgeons are able to: navigate through the anatomy, practice established procedures, practice new procedures, learn how to use new surgical tools, and assess their progress. In particular, surgeons can practice and experience surgical techniques and procedures on greater variety of pathologies and complications without waiting for a patient with a specific disease, they can repeat and replay these procedures, and students will have an objective evaluation and benchmarking of their performance based on actual procedural dexterity acquired, without putting the patient at any risk. The training simulators are developed as a practical medical training course which can be used as part of surgical

Prostate	Biopsy [98, 13]
Blood vessels	Venipuncture [63],Anastomosis [49] Angioplasty [87], Stent replacement [87] Intravenous catheterization [86]
Brain	Neurosurgery [76, 75, 33, 76, 75]
Face	Maxillofacial Surgery [15, 67]
Eye	General Eye Surgery [84], Virectomy [68] Laser photo coagulation [31]
Ear	Otological surgery [29]
Nose	Paranasal sinus surgery [97]
Heart	Coronary Angioplasty [64] Cardiac Catheterization [87] Pacemaker leads replacement [87]
Lungs	Bronchoscopy [12]
Abdomen	General laparoscopy [7], Trauma [11]
Pancreas	ERCP [73, 45]
Liver	[85]
Gall bladder	Cholecystectomy [93, 25]
Female Reprod. organs	Gynaecologic laparoscopy [16, 50, 76]
Hip	Hip replacement [48]
Knee	Arthroscopic Knee Surgery [49, 66, 70, 38] Palpation [58]

Table 2: Taxonomy based on the organ under consideration.

education for medical students. Training simulators have their own training protocol with a number of steps with increasing level of difficulty, enabling a student to develop the psycho-motor skills that are essential for a safe clinical practice. A VR-based educational system that includes multi-sensory feedback similar to the one the surgeons will meet in real cases, will allow procedure optimizations without any danger for the patients. Each step is composed of a training part and an evaluation part [50]. Task-level procedures have been subjected to analysis, and the training transfer is about 25-28% [79]. However, the big challenge is to simulate with sufficient fidelity for skills to be transferred from performing with the simulation to performing surgery on patients. The proficiency with which the skills are performed can then be measured and the performance can be assessed [30, 49, 51, 72, 50]. Virtual environments will also enable a research surgeon to practice new strategies or compare approaches proposed by colleagues. Similarly it can help the development of innovative surgical instruments. Due to increasing regulations concerning human and animal protections, and due to lack of other efficient learning systems, such an approach has a tremendous scholarly and industrial potential (for a review in learning see [43]).

2.2 Diagnosis and Pre-operative Assistance

VR-based visualizations built using pre-operative patient data provide an intuitive and highly interactive method of navigating through a patients' anatomy, allowing very accurate and reliable diagnosis. In pre-operative planning, the aim is to study patient data before a surgery and to plan the best way to carry out that surgery. The requirements for the pre-operative planning systems are: a) the (multimodal) data from the specific patient are available, b) the data are accurate, and c) the model can be build as fast and as automatically as possible.

2.3 Intra-operative Assistance

Many surgical procedures require precise localization of the targeted structure, in order for the surgeon to operate on that tissue while minimizing damage to adjacent structures. The task becomes even more difficult when the structure under question is deep within the body. In addition, the patient might move during the operation or tissue might shrink. In intra-operative assistance, pre-operative surgical plans can be transfered to the operating room and can be used for guidance by registering the pre-operative data with intra-operative data and by using augmented-reality visualization [60] pre-operative surgical plans can be transfered to the operating room and the surgeon can mark internal landmarks.

2.4 Image-guided, Robotically-Assisted Surgery

Image-guided and/or robotically-assisted surgery are gaining rapid acceptance in the medical field. With a VR-based system the surgeon is provided with visual access to areas originally not visible, while the haptic feedback provides the impression that his/her hands are inside the patient. Furthermore, this immersion makes it feasible for the surgeon to treat patients remotely in inaccessible or hazardous locations with great effectiveness, as if they were present at the remote site. These systems can be naturally extended to include collaboration [23, 61], and telemedicine [17, 22, 42] involving sharing of information across individual staff and across geographic locations. The delay over the network is the biggest problem as it can prove life-threatening. VR systems have also been used for robotically-assisted surgeries [15] and to preplan the surgery so that all the options for conducting a particular surgery can be explored and medical outcomes can be simulated in advance [52, 48, 91]. VR systems become especially important in surgical procedures which involve micro-motions and highly repetitive tasks [71].

3 Requirements for Surgical Simulators

The development of VR surgical simulation can be summarized as the use of medical imaging, computer graphics, biomechanical analysis, and virtual environments to simulate surgery for medical education, training, pre-treatment planning, and intra-operative assistance. Visual realism and realtime interactions are essential in surgery simulation. Realtime interaction requires that any action from the operator generates an instantaneous response from the stimulated organ, whatever the complexity of its geometry. Moreover, since all the organs in the human body are not rigid, their shape may change during an operation. Consequently, the realism of the deformations is another key point in surgery simulation. This realism can be enhanced by the introduction of devices which allow for a better immersion in the virtual world. For example, the integration of force feedback systems to generate such sensations is of prime importance, almost as important as visual feedback. When coupled with precise computations of the forces, it may be possible for the surgeon to feel haptic sensations close to reality. In the following sections, we will examine the common elements of the VR-based systems that have been developed for surgery applications.

3.1 Data Acquisition

The first step in the development a surgery-related VR system is the acquisition of accurate data, in order to be able to realistically reconstruct the organ under consideration [5]. For the VR systems that are geared toward education, the organ models are obtained through databases of generic models. One such database relates to the data obtained through the Visible Human Project [1]. For the VR systems that are geared towards patient specific procedures (e.g., diagnosis, planning) the models are being build from patient data. Accuracy of patient data is of immense importance. In pre-operative surgery planning and image guided surgeries critical decisions are taken based on the available models of patient anatomy.

3.2 Imaging Modalities

Patient data may come from several sources since different imaging modalities are suitable for different types of organs [95]. Imaging modalities being used currently are: Computer Tomography (CT), Spiral CT and Open CT, Magnetic Resonance Imaging (MRI), tagged MRI, MRA for arteries, MRV for veins, and Open MR, Positron Emission Tomography (PET), (which is very sensitive to active tumor tissue but it does not measure its size), and Ultrasound (which can be used for imaging of heart, brain, abdominal organs, and vascular imaging). A table summarizing the state of the art imaging modalities can be found at [32].

3.3 Fusion of Multi-modality Data

To incorporate multidimensional properties of human organs, multi-modal images need to be registered and fused together. This is of paramount importance in understanding how different aspects of anatomy are related to each other (e.g., blood vessels and bones).

3.4 Segmentation

Once patient data are available the aim is to extract as much of useful information available within it. The general concept of finding, extracting, and characterizing features is called segmentation. A number of segmentation techniques have been developed, usually classified as structural and statistical methods (a good overview of current segmentation methods is provided in [32]). Highly automated, reliable and fast segmentation methods are very important to the development of VR-based intra-operative surgery assistance systems is highly automated, reliable and fast segmentation methods.

3.5 Registration

Registration is the process of establishing a common reference frame between pre-surgical data and the corresponding patient anatomy. Once a common reference frame is established, pre-surgical data can be used to visualize anatomical structures as an overlay to intra-operative data, position radio-surgical equipment, guide a surgeon's tool movements, and guide robotic tool movements. Considerable amount of research is done in registration [3]. Registration techniques can be categorized in marker-based techniques [94], techniques that use anatomical features [74] or frameless techniques [56]. Fiducial-based registration is to use features (e.g., crest lines or extremal points) that are intrinsic to the data itself [74, 41, 34, 36].

3.6 Modeling

Computer models of human organs for surgical simulators are generally designed using two methods: reconstruction from medical images (CT, MRI, PET), or hand crafted with a modeling tool. A number of teams are focused on modeling the anatomy and visual presentation of organs without commensurate physiological fidelity. However, geometric only modeling of anatomical structures is not enough for medical simulation. A notable exception is the work of Kaye and Metaxas on modeling the mechanical cardiopulmonary interactions [53].

Tissue parameters settings are very critical in designing realistic organs. Currently this is done in two ways a) interactive adjustment by experts to satisfy the surgeon [4], and b) explicitly measuring the parameters. Examples of measuring the parameters are the work by Hunter, for biomechanics testing and interferometry for the eye and mechanical testing for the knee cartilage [5]. To achieve realism in surgical simulators inclusion of medical realism is also important. Simulating the effects of drugs that are being used during surgery and the patient's response depending on the dosage increases the value of the simulator. For example, HT Medical's PreOp Endovascular Simulator [87] integrates pharmaceuticals such as thrombolytic agents. For cardiovascular and pulmonary function, blood flow and air exchange in the heart and lungs must be visualized. For the musculoskeletal system, biomechanical analysis capability should be included to show how the system moves, what the internal forces are, and how they interact. Simulation is also important in pre-operative planning where one wants to study the outcomes of interventions, such as in neurosurgery, bone implants or reconstructive plastic surgery. Realistic physiological movement and joint reaction forces in the musculoskeletal systems can be determined by simulation on biomechanical models [20]. Moreover, safe and optimal rehabilitation programs, in order to regain functional use of the limbs and joints, can be designed using a model of the reconstructed region.

Deformable Models: To simulate the response of organs to surgical actions, researchers endowed the geometric models with physical properties and applied the laws of physics [27, 89]. With today's increasing computational power, the community is exploring developments in physics-based deformable model techniques for modeling soft tissue [54]. Most widely used deformable models are mass-spring models, finite element models, and parametric models with B-spline representation [25, 26]. Computing the responses of the models to the surgical actions in real-time still remains an interesting challenge [10, 77].

Visualization and Rendering: Organs can be visualized as either surface or volumetric models. Surface models are constructed using boundary vertices to form a polygonal mesh. The drawback of surface models is that the interior of the object is missing. Volumetric representation is preferred where an object gets mutilated to expose originally unseen interior (e.g., by cutting or incision) [37]. Recent advances in volume rendering [99] allow increased speed and flexibility. Both representations can be combined to provide real-time and realistic interactive surgery simulation [59].

Texture Mapping: Visual realism is added to plain geometrical models by texture mapping. Surface texture mapping can be achieved using synthetic textures or photographs of organs [65]. However, if generic texture maps are used, then diseases which do not distort the anatomy (many infections, very flat and superficial cancers etc.) can not be diagnosed. Once the problem of accurate, real-time registration is solved, it will be possible for virtual organs to not only be anatomically correct but have precisely accurate coloration.
Apart from modeling human organs there is a need to provide models for every instrument that surgeons use and give to each one of these different characteristics to make it as realistic as possible [18]. For example, for an eye surgery simulator [84] we need to model the surgical knife, scissors, forceps and the phaco emulsifier.

3.7 Interaction

As in all VR systems, the various data are presented to the user/surgeon through a number of displays, the user navigates through the data and interacts with them. As a result of this interaction, the user receives feedback that could be multi-modal (visual, force, tactile and auditory) depending on the task.
Collision Detection: Collision detection is a complex and well known problem in computer graphics. However, when the realtime constraint is added, the difficulty is considerably increased. With physicallybased models, most of the external forces are contact forces and in surgery simulation, the deformation is mainly driven by user interactions so an efficient collision detection algorithm is necessary. Simulators using triangular mesh models use computation of intersection points between two triangles for collision detection. Algorithms using hierarchical bounding boxes are used to speed-up the process [50]. The algorithm presented in [25] considers a collision occurring between a simple rigid object and a complex deformable body. (For a review of other collision detection techniques required for force feedback the reader is referred to [40]).
Position Tracking: Navigating through and interacting with the data requires tracking of various parts of the human body and instruments. In general, tracking can be accomplished through mechanical, optical, magnetic, and acoustic devices (for a thorough review of tracker technology the reader is referred to [35, 83]). In addition, the user can give commands using a speech interface [93].

3.8 Interface

To achieve maximum immersion in virtual environment the user must be provided with all possible feedbacks which s/he will be receiving in real life. Visual, haptic, tactile and auditory feedbacks go long way in providing realism to surgery simulators.
Visual Display: Visual feedback is the first step towards sense of presence in the virtual world. The display modalities that have been used in surgery-related VR-based systems depend on the task at hand. The most common approach is to use stereoscopic monitors, specialized workbenches (e.g., [49, 88]), and head-mounted displays (HMDs) to convey 3D information. For the first two modalities the user's sense of immersion is less strong as compared with HMDs but higher resolutions can be afforded. The issue of resolution is of paramount importance since one of the main objectives is to visually represent the data in an accurate and realistic manner. Despite the recent strides in HMD technology, the resolution is low and they require tracking. Concerning the specialized workbenches, an immersive surgical table has been presented recently [8].
Force Feedback: To increase the sense of immersion, force feedback mechanisms are included that output forces

to the user as a result of the force that the user applies to a specific location at the dataset (for a thorough review of force and touch feedback in VR the reader is referred to [14]). Surgeons depend on the haptic sensation during both diagnosis and performing surgery. Force feedback systems output forces from the system based on the forces applied to the system. Thus the user feels forces from virtual objects as a response to the forces s/he applies. For example, in the eye surgery simulator [81], the user interacts with data through a virtual surgical instrument controlled by a hand-held 6 DOF tracked stylus. In the VR-systems that we reviewed, force feedback is achieved either through general force-feedback mechanisms, or through customized designs. The general mechanisms include the PHANTOM [92], the Rutger's Force Feedback Glove [39] which is an integrated force sensing exoskeleton, and the CyberGlove [85]. The specialized mechanisms include the Laparoscopic Impulse Engine, the Virtual Laparoscopic Interface, the pantoscope [6] and HIT Force Feedback Device. The Laparoscopic Impulse Engine [24] has 5 degrees of freedom for motion and tracking. The benefit is that the surgeon is manipulating instruments as if s/he was performing a real procedure. Going a step further, the Virtual Laparoscopic Interface [24] allows two hand manipulation each with 5 degrees of freedom. In addition, Bertec Corporation has developed haptic interfaces suitable for catheterization which tracks axial and rotational displacement of wire, catheter and sheath to measure pinch force and shear slip force.

Tactile Feedback: The purpose of tactile feedback is to convey a sense of the feel of an organ's shape, texture, and response to pressure to the surgeon. Tactile sensation can be generated using a number of different methods. For example, micro pins give an impression of complex surface textures and edges by reproducing pressure distribution across tissue contact on finger tip. Based on this approach a variety of small tactile sensors intended to be mounted on a laparoscopic manipulator have been designed [78, 47]. Piezo-electric and electro-tactile devices vibrators vibrate a surface against a finger tip at various frequencies. Finally, pneumatic systems convey shape, texture and edges, by dynamically filling pockets in the glove with air.

Auditory Feedback: Sound adds one more dimension to surgeons perception. For example, it can convey position information and provide feedback on whether a path is being accurately followed. Sound is currently used more for instructions to trainee and to indicate some mistake on part of surgeon. For example, a Bronchoscopy simulator generates coughing sound as the bronchoscope touches the bronchial wall [12].

System Integration: Integration of various models and model-components is a challenging task and requires collaboration of large interdisciplinary team. Integration of the model should be facilitated by image databases, anatomical modeling software, knowledge of tissue material properties, computationally efficient methods for tissue deformation, bleeding, cutting and tearing.

4 Challenges and Future Work

This review reveals that further research is needed in the all the components of the systems: modeling, simulation, visualization, display, interaction and feedback. In particular in modeling, there is need for better methods for registering multi-modal data and automating the segmentation of the patient specific data. fMRI, elastography and open CT [69] will be the new modalities that will offer additional information. In simulation, better models for the behavior and the characteristics of the tissues are needed along with progress in computing realistic deformation in real time. Also, there is a need for modeling the physiological response and modeling blood and fluid flow. In visualization, current limitations on rendering speed poses limitations on the size and therefore the fidelity of anatomical models. In display technology, displays with higher resolution and better tuned to human perception will help the process. Further developments are needed in the areas of interaction devices along with (remote) force, tactile, auditory and olfactory feedback [55]. For example, the ability to feel tissue will be a valuable tool for procedures that require palpation, such as artery localization and tumor detection. Furthermore, smells are extremely important because not only do they help distinguish specific substances, but also they give a sense of reality to a situation. The absence of olfaction is a serious limitation of current training and telepresence systems. Possible effects from long term use of these systems need to be studied further along with what type of design metaphors will enhance the surgeon's performance in VR. Finally, the sociological implications of the new technologies (e.g., how is this technology going to be perceived by the doctors and how from the public?) need to be studied methodically.

References

[1] M. J. Ackerman. The visible human project. *Journal of Biocommunication*, 18(14), 1991.

[2] A. M. Alyassin and W. E. Lorensen. Virtual endoscopy software application on a PC. In *Proc. of MMVR 6*, San Diego, CA, Jan 28-31 1998.

[3] N. Ayache. Medical computer vision, virtual reality and robotics. *Image and Vision Computing*, 13(4):295–313, May 1995.

[4] N. Ayache, S. Cotin, and H. Delingette. Efficient linear elastic models of soft tissue for real-time surgery simulation. Technical Report 3510, INRIA, 1998.

[5] N. Ayache, J. Duncan, S. Gibson, E. Grimson, R. Kikinis, N. Magnenat Thalmann, and D. Metaxas. Modeling techniques for medical applications. In *SIGGRAPH'99*, Los Angeles, CA, August 1999. Course Notes 33.

[6] R. Baumann. Force feedback for minimally invasive surgery simulator. In *Proc. of MMVR 4*, pages 564–579, San Diego, CA, Jan 17-20 1996.

[7] C. Baur, D. Guzzoni, and O. Georg. VIRGY: A virtual reality and force feedback based endoscopic surgery simulator. In *Proc. of MMVR 6*, San Diego, CA, Jan 28-31 1998.

[8] G. Bellaire, G. Graschew, F. Engel-Murke, S. Neskakis, P. Newmann, and P. M. Schlag. The OP 2000 high immersive surgical table for simulation and training. In *Proc. of the 3rd International Immersive Proj Tech Workshop*, Fraunhofer Institute Center, Stuttgart, Germany, May 10-11 1999.

[9] G. Bellaire, F. Hasenbrink, G. Graschew, M. Göbel, and P. M. Schlag. The OP 2000 medical augmented immersive environment. In *Collaborative Virtual Environments'98*, pages 33–40, Manchester, June 17-19 1998.

[10] M. Bro-Nielsen. Fast finite elements for surgery simulation. In *Proc. of MMVR 5*, San Diego, CA, Jan 22-25 1997.

[11] M. Bro-Nielsen, D. Helfrick, B. Glass, X. Zeng, and H. Connacher. VR simulation of abdominal trauma surgery. In *Proceedings of Medicine Meets Virtual Reality 6*, pages 117–123, San Diego, California, January 28-31 1998.

[12] M. Bro-Nielsen, J. L. Tasto, R. Cunningham, and G. L. Merril. PreOp endoscopic simulator: A PC-based immersive training system for bronchoscopy. In *Proc. of MMVR 7*, pages 76–82, San Francisco, CA, Jan 28-31 1999.

[13] G. Burdea, G.Patounakis, and V. Popescu. Virtual reality training for the diagnosis of prostate cancer. In *Proc. of the VR Annual International Symposium*, pages 190–197, Atlanta, GA, Mar 14-18 1998.

[14] G. C. Burdea. *Force and Touch Feedback for Virtual Reality*. John Wiley & Sons, July 1996.

[15] C. R. Burghart, J. E. Muenchenberg, and U. Rembold. A system for robot assisted maxillofacial surgery. In *Proc. of MMVR 6*, San Diego, CA, Jan 28-31 1998.

[16] H. K. Cakmak and U. Kuhnapfel. The Karlsruhe endoscopic surgery trainer for minimally invasive surgery in gynaecology. In *Proc. of the 13th Int. Cong. on Computer Assisted Radiology and Surgery*, page 1050. Paris, June 1999.

[17] M. C. Cavusoglu, F. Tendick, M. Cohn, and S. S. Sastry. A laparoscopic telesurgical workstation. *IEEE Transactions on Robotics and Automation*, 15(4):728–739, Aug 1999.

[18] Biomedical Interactive Technology Center. Eye surgery simulation. http://www.bitc.gatech.edu/

[19] Biomedical Interactive Technology Center.Simulated cardiac catheterization. http://www.bitc.gatech.edu/bitcprojects/

[20] Edmund Y. S. Chao. Surgical simulator and virtual reality modeling in orthopaedics. http://www.cs.cmu.edu.

[21] Ciné-Med. Ciné-med's surgical simulation. http://www.cine-med.com/cinemed/vr/sursim.html.

[22] J. Coleman, A. Goettsch, and A. Savchenko. TeleInViVo: Telemedicine: on the desktop and on the road. *IEEE Computer Graphics and Applications*, 17(2), March 1997.

[23] J. Coleman, M. Maurer, and A. Savchenko. Collaborative testbed for maxillofacial surgery. *Computer Graphics Topics*, 9:16–18, 1997.

[24] Immersion Corporation. Laparoscopic impulse engine. http://www.immerse.com/

[25] S. Cotin, H. Delingette, and N. Ayache. Real-time elastic deformations of soft tissues for surgery simulation. *IEEE Trans. on Vis. and Computer Graphics*, 5(1), Jan-Mar 1999.

[26] S. A. Cover, N. F. Ezquerra, J. F. O'Brien, R. Rowe, T. Gadacz, and E. Palm. Interactively deformable models for surgery simulation. *IEEE Computer Graphics and Applications*, 13(6):68–75, Nov 1993.

[27] H. Delingette. Towards realistic soft tissue modeling in medical simulation. In *Proc. of IEEE: Special Issue on Surgery Simulation*, pages 512–523, April 1998.

[28] M. Dinsmore, G. Langrana, G. Budea, and J. Ladeji. Virtual reality training for palpation of subsurface tumors. In *Proc. of the VR Annual International Symposium*, pages 54–60, Albuquerque, NM, 1997.

[29] A. B. Dobrzeniecki, M. Soelvsten-Soerensen, T. Frisch, P. Larsen, T. A. Darvann, and S. Kreiborg. The visible human ear: High-resolution volume data for simulating otological surgery. In *5th International Workshop CAS '99*, Erlangen, Germany, October 14-16 1999.

[30] M. S. Downes, M. C. Cavusoglu, W. Gantert, L. W. Way, and F. Tendick. Virtual environments for training critical skills in laparoscopic surgery. In *Proc. of MMVR 6*, pp. 316–322, San Diego, CA, Jan 28-31 1998.

[31] P. Dubois, J.-F. Rouland, P. Meseure, S. Karpf, and C. Chaillou. Simulator for laser photocoagulation in opthamology. *IEEE Transactions on Biomed. Engg.*, 42(7):688–693, 1995.

[32] N. Ezquerra, I. Navazo, T. Morris, and E. Monclus. Graphics, vision & visualization in medical imaging: A state of the art report. In *Eurographics'99 State-of-the-Art Reports*, Milano, Italy, Sept 1999.

[33] The Virtual Centre for Health Informatics. Neurosurgery simulator. http://www.vision.auc.dk/

[34] Center for Medical Robotics and Computer-Assisted Surgery (MRCAS). Surgical robotics for orthopaedics. http://www.mrcas.ri.cmu.edu/

[35] W. Frey, M. Zyda, R. McGhee, and W. Cockayne. Off-the-shelf, real-time, human body motion capture for synthetic environments. Technical Report NPSCS-96-003, CS Dept., Naval Postgraduate School, Monterey, CA, June 1996.

[36] H. Fuchs, M. A. Livingston, R. Raskar, D. Colucci, K. Keller, A. State, J. R. Crawford, P. Rademacher, S. H. Drake, and A. Meyer. Augmented reality visualization for laparoscopic surgery. In *MICCAI*, pages 934–943. Cambridge, MA, October 1998.

[37] S. Gibson, C. Fyock, E. Grimson, T. Kanade, R. Kikinis, H. Lauer, N. McKenzie, A. Mor, S. Nakajima, H. Ohkami, J. Samosky, and A. Sawada. Volumetric object modeling for surgical simulation. *Med. Img. Anal.*, 2(2):121–132, 1998.

[38] S. Gibson, J. Samosky, A. Mor, C. Fyock, E. Grimson, T. Kanade, R. Kikinis, H. Lauer, N. McKenzie, S. Nakajima,

H. Ohkami, R. Osborne, and A. Sawada. Simulating arthroscopic knee surgery using volumetric representations, real-time volume rendering and haptic feedback. In *Proceedings of the Conference on Virtual Reality, Robotics and Medicine II*, pages 369–378, Grenoble, France, March 1997.

[39] D. Gomez, G. Burdea, and N. Langrana. Modeling of the Rutgers Master II haptic display. In *Proc. of the 4th Annual Symp. on Haptic Interfaces for Virtual Env. and Teleoperator Systems*, pp 727–734, San Francisco, CA, 1995.

[40] A. Gregory, M. C. Lin, S. Gottschalk, and Russell Taylor. A framework for fast and accurate collision detection for haptic interaction. In *Virtual Reality '99*, pages 38–45, Houston, TX, March 13-17 1999.

[41] W. E. L. Grimson, G. J. Ettinger, S. J. White, T. Lozano-Pérez, W. M. Wells III, and R. Kikinis. An automatic registration method for frameless stereotaxy, image guided surgery, and enhanced reality visualization. *IEEE Transactions on Medical Imaging*, 15(2):129–140, April 1996.

[42] J. W. Hill, P. A. Holst, J. F. Jensen, J. Goldman, Y. Gorfu, and D. Ploeger. Telepresence interface with applications to microsurgery and surgical simulation. In *Proc. of MMVR 6*, pages 96–102, San Diego, CA, Jan 28-31 1998.

[43] H. Hoffman and D. Vu. Virtual reality: Teaching tool of the twenty-first century. *Acad. Med.*, 72:1076–1081, 1997.

[44] R. J. Hollands and E. A. Trowbridge. A PC-based virtual reality arthroscopic surgical trainer. In *Proc. of Simulation in Synthetic Environments*, pages 17–22, New Orleans, 1996.

[45] D. Hon. Ixion's realistic medical simulations. *Virtual Reality World*, 2(4):58–62, July/August 1994.

[46] L. Hong, S. Muraki, A. Kaufman, D. Bartz, and T. He. Virtual voyage: Interactive navigation in the human colon. In *Proc. of 24th Annual Conf. on Computer Graphics and Interactive Techniques*, Los Angeles CA, Aug 3-8 1997.

[47] R. D. Howe, W. J. Peine, D. A. Kontarinis, and J. S. Son. Remote palpation technology. *IEEE Engineering in Medicine and Biology*, 14(3):318–323, May-June 1995.

[48] R. V. O'Toole III, D. A. Simon, B. Jaramaz, O. Ghattas, M. K. Blackwell, L. Kallivokas, F. Morgan, C. Visnic, A. M. DiGioia, and T. Kanade. Towards more capable and less invasive robotic surgery in orthopaedics. In *Proc. of the Conf. on VR, Robotics in Medicine*, Nice, France, April 1995.

[49] Boston Dynamics Inc. http://www.bdi.com/

[50] A. C. Jambon, P. Dubois, and S. Karpf. A low-cost training simulator for initial fromation in gynecologic laparoscopy. In *Proc. of the Conference on Virtual Reality, Robotics and Medicine II*, pages 347–356, Grenoble, France, March 1997.

[51] R. Johnston, S. Bhoyrul, L. Way, R. Satava, K. McGovern, J. D.Fletcher, S. Rangel, and R. B. Loftin. Assessing a virtual reality surgical skills simulator. In *Health Care Technologies*. Washington, DC, 1996.

[52] T. Kanade, A. M. DiGioia, O. Ghatta, B. Jaramaz, M. Blackwell, L. F. Kallivokas, F. Morgan, S. Shah, and D. A. Simon. Simulation, planning, and execution of computer-assisted surgery. In *Proceedings of the NSF Grand Challenges Workshop*, Washington, D.C., March 1996.

[53] J. Kaye, F. P. Primiano Jr., and D. N. Metaxas. A 3D virtual environment for modeling mechanical cardiopulmonary interactions. *Medical Image Analysis*, 2(2):169–195, 1998.

[54] E. Keeve, S. Girod, R. Kikinis, and B. Girod. Deformable modeling of facial tissue for craniofacial surgery simulation. *Computer Aided Surgery*, 3(5):pp. 228–238, 1998.

[55] E. P. Keller, R. T. Kouzes, and L. J. Kangas. Transmission of olfactory information for telemedicine, interactive technology and the new paradigm for healthcare. In *Proc. of MMVR III*, pages 168–172, San Diego, CA, Jan. 1995.

[56] R. Kikinis. Registration method for frameless stereotaxy, image guided surgery, and enhanced reality visualization. *IEEE Trans. on Med. Img.*, 15(2):129–140, April 1996.

[57] U. Kühnapfel, C. Kuhn, M. Hübner, H.G. Krumm, H. Maaß, and B. Neisius. The Karlsruhe endoscopic surgery trainer as an example for virtual reality in medical education. In *Minimally Invasive Therapy and Allied Technologies*, pages 122–125. Blackwell Science Ltd, 1997.

[58] N. Langrana, G. Burdea, K. Lange, D. Gomez, and S. Deshpande. Dynamic force feedback for virtual knee palpation. *Artificial Intelligence in Medicine*, 6:321–333, 1994.

[59] W. Lin and R. A. Robb. Realistic visualization for surgery simulation using dynamic volume texture mapping and model deformation. In *SPIE Conference on Image Display*, volume 3658, pages 308–314, San Diego, CA, Feb. 1999.

[60] A. Liu, E. Bullitt, and S. M. Pizer. Augmented reality visualization for laparoscopic surgery. In *MICCAI*, pages 952–963, Cambridge, MA, October 1998.

[61] M. Maurer, J. Coleman, M. Maurer, A. Savchenkoand, J. Daniels, D. Hoffman, and P. Bono. Collaborative and interactive system for total joint replacement surgery for the temporomandibular joint. In *Proc. of MMVR 6*, San Diego, CA, Jan 28-31 1998.

[62] A. D. McCarthy and R. J. Hollands. Human factors related to a virtual reality surgical simulator: The sheffield knee arthroscopic training system. http://www.brunel.ac.uk/ẽmstrrb/

[63] G.L. Merril and V.L. Barker. Virtual reality debuts in the teaching laboratory in nursing. *Journal of Intravenous Nursing*, 19(4):182–187, July/August 1996.

[64] J. Merril, S. Allman, G. Merril, and R. Roy. Virtual heart surgery: Trade show and medical education. *Virtual Reality World*, 2(4):55–57, July/August 1994.

[65] J. R. Merril, G. L. Merril, R. Raju, A. Millman, D. Meglan, G. M. Preminger, R. Roy, and R. Babayan. Photorealistic interactive three-dimensional graphics in surgical simulation. In *Interactive Technology and the New Paradigm for Healthcare*, pages 244–252. Washington DC, 1995.

[66] W. Muller and U. Bockholt. The virtual reality arthroscopy training simulator. In *Proc. of MMVR 6*, San Diego, CA, Jan 28-31 1998.

[67] P. Neumann, G. Faulkner, M. Krauss, K. Haarbeck, and T. Tolxdorff. MeVisTo-Jaw: A visualization-based maxillo-facial surgical planning tool. In *Proc. of SPIE Medical Imaging*, volume 3335, San Diego, CA, February 21-27 1998.

[68] P. F. Neumann, L. L. Sadler, and J. G. Gieser. Virtual reality virectomy simulator. In *MICCAI*, pages 910–917, Cambridge, MA, October 1998.

[69] C. H. Nimsky, O. Ganslandt, B. Tomandl, and R. Fahlbusch. Advantages of open MRI (0.2 T Siemens system) and future developments. In *5th International Workshop CAS '99*, Erlangen, Germany, October 14-16 1999.

[70] Department of Computer Science at the University of Hull. Virtual environment knee arthroscopy training system. http://www2.dcs.hull.ac.uk/VEGA/medic/

[71] P. Oppenheimer and S. Weghorst. Immersive surgical robotic interfaces. In *Proc. of MMVR 7*, pages 242–248, San Francisco, CA, Jan 28-31 1999.

[72] D. Ota, B. Loftin, T. Saito, R. L., and J. Keller. Virtual reality in surgical simulation. *Computers in Biology and Medicine*, 25(2):127–137, 1995.

[73] J. W. Peifer, W. D. Curtis, and M. J. Sinclair. Applied virtual reality for simulation of endoscopic retrograde cholangiopancreatography (ERCP). In *Proc. of MMVR 4*, San Diego, CA, Jan 17-20 1996.

[74] X. Pennec, C. R.G. Guttmann, and J.-P. Thirion. Feature-Based registration of medical images: Estimation and validation of the pose accuracy. In *MICCAI*, pages 1105–1114. Cambridge, MA, October 1998.

[75] A. Radetzky. ROBOSIM: A simulator for minimally invasive neurosurgery. http://www.umi.cs.tu-bs.de/arne/robosim/robosim.html.

[76] A. Radetzky. SUSILAP-G SUrgical SImulator for LAParoscopy in Gynaecology. http://www.umi.cs.tu-bs.de/arne/SUSILAP.html.

[77] A. Radetzky, C. Wimmer, G. Kleinszig, M. Brukner, L. M. Auer, and D. P. Pretschner. Interactive deformable volume graphics in surgical simulation. In *International Workshop on Volume Graphics*, pages 221–237, Swansea, United Kingdom, March 24-25 1999.

[78] Robotics and Intelligent Machines Machines Laboratory. Medical robotics. http://robotics.eecs.berkeley.edu/ mcenk/medical.

[79] R. M. Satava and S. B. Jones. Current and future applications of virtual reality for medicine. *Proceedings of the IEEE*, 86:484–489, March 1998.

[80] M. Schill. Minimally invasive surgical training by virtual reality. http://www.vrweb.com/WEB/DEV/MEDICAL.HTM.

[81] M. Schill and O Koerner. Development of a system for real-time simulation of an intraocular eye surgery. http://www-mp.informatik.uni-mannheim.de/groups/vipa/

[82] Plastic Surgery Information Service. Virtual reality becomes reality for plastic surgeons. htp://www.plasticsurgery.org/mediactr/virtual2.htm.

[83] D. A. Simon. Intra-operative position sensing and tracking devices. In *Proc. of CAOS*, pages 62–64, June 1997.

[84] Michael Sinclair and John Peifer. Socially correct virtual reality: Surgical simulation. *Virtual Reality World*, 2(4):64–66, July/August 1994.

[85] N. Susuki, A. Hattori, A. Takatsu, T. Kumano, A. Ikemoto, Y. Adachi, and A. Uchiyama. Virtual surgery system using deformable organ models and force feedback system with three fingers. In *MICCAI*, Cambridge, MA, October 1998.

[86] HT Medical Systems. CathSim intravenous training system. http://www.ht.com/products_cathsim.htm.

[87] HT Medical Systems. PreOp endovascular simulator. http://www.ht.com/products_endovism.htm.

[88] Pyramid Systems. http://www.pyramidsystems.com/

[89] G. Székely, Ch. Brechbühler, R. Hutter, A. Rhomberg, and Schmid. Modeling of soft tissue deformation for laparoscopic surgery simulation. In *MICCAI*, pages 550–561, Cambridge, MA, October 1998.

[90] R. Taylor, S. Lavallee, G. Burdea, and R. Moesges. *Computer-Integrated Surgery*. MIT Press, 1995.

[91] R. H. Taylor, J. Funda, B. Eldridge, K. Gruben, D. LaRose, S. Gomory, M. Talamini, L. Kavoussi, and J. Anderson. A telerobotic assistant for laparoscopic surgery. *IEEE Engineering in Medicine and Biology Magazine*, 1995. Special Issue on Robotics in Surgery.

[92] SensAble Technologies. http://www.sensable.com/

[93] C. S. Tseng, Y. Y. Lee, Y. P. Chan, S. S. Wu, and A. W. Chiu. A PC-based surgical simulator for laparoscopic surgery. In *Proc. of MMVR 6*, San Diego, CA, Jan 28-31 1998.

[94] M. Y. Wang, C. R. Maurer Jr., J. M. Fitzpatrick, and R. J. Maciunas. An automatic technique for finding and localizing externally attached markers in CT and MR volume images of the head. *IEEE Trans. on Biom. Engr.*, 43(6):627–637, 1996.

[95] J. A. Waterworth. Virtual reality in medicine: A survey of the state of the art. http://www.informatik.umu.se/j̃wworth/medpage.html.

[96] S. Weghorst. Appendix E. Formal evaluation of the madigan endoscopic sinus surgery simulator. http://www.hitl.washington.edu/publications/r-97-34/

[97] S. Weghorst, C. Airola, P. Oppenheimer, C.V. Edmond, T. Patience, D. Heskamp, and J. Miller. Validation of the Madigan ESS simulator. In *Proc. of MMVR 6*, pages 399–405, San Diego, CA, Jan 28-31 1998.

[98] J. Xuan, Y. Wang, I. A. Sesterhenn, J. W. Moul, and S. K. Mun. 3-D model supported prostate biopsy simulation and evaluation. In *MICCAI*, pages 358–367, Cambridge, MA, October 1998.

[99] S. You, L. Hong, M. Wan, K. Junyaprasert, A. Kaufman, S. Muraki, Y. Zhou, M. Wax, and Z. Liang. Interactive volume rendering for virtual colonoscopy. In *Proc. IEEE Visualization '97*, pages 433–436, October 19-24 1997.

[100] Y. Zhu, J. Z. Chen, X. Fu, and D. Quammen. A virtual reality system for knee diagnosis and surgery simulation. In *Virtual Reality '99*, page 84, Houston, TX, March 13-17 1999.

Ref.	Input Data	Type	Model	Def.	CD	Surgical Action	Physiological Response	Texture Mapping	Feedbacks				Evaluation
									Visual	Force	Tactile	Auditory	
[75]	MRI	PS	VO	Yes	Yes	-	-	Yes	M	Yes	No	No	-
[33]	CT, MRI X-Ray	D	VO	FEM	-	C,RT	-	No	M	No	No	No	Yes
[68]	CT, MRI	D	SU	MS	-	C,P,S	-	No	SG	Yes	No	No	No
[81]	-	D	SU	Yes	Yes	-	-	Yes	M, SL	Yes	No	No	Yes
[18]	-	D	VO	Yes	Yes	C,GR,ST	-	PM	SS	Yes	YEs	No	-
[19]	X-ray	D	SU	No	Yes	MN		No	M	-	No	No	-
[87]	CT, MRI	D	VO	Yes	Yes	SP,	-	-	M	Yes	-	No	-
[86]	CT, MRI	D	VO	Yes	Yes	-	-	-	M		AT	No	Yes
[49]	-	D	-	Yes	Yes	GR,PR,SUT	-	Yes	M	PHN	-	No	Yes
[12]	CT, MRI	D	VO	Yes	Yes	MN	-	Yes	M	Yes	Yes	Yes	Yes
[7]	-	D	SU	MS	Yes	B,C	BL,VF	AM	M,SS	LIE,PAN	No	No	Yes
[85]	MRI	D	SU	SF	Yes	I,P	-	Yes	HMD	CG	Yes	No	Yes
[57]	HM	D	SU	NN	SPC	C,GR	-	Yes	M,SG	LIE	No	No	Yes
[73]	-	D	SU	-	Yes	PR	-	PM	M	Yes	No	No	Yes
[25]	CT, MRI	D	SX	QE	SPC	P	-	No	M	LIE	No	No	Yes
[93]	HM	D	SU	Yes	Yes	C		Yes	M	Yes		ME	Yes
[11]	MRI	D	SU	FEM, MS	GH	C	BL	No	M	PHN	No	No	Yes
[50]	HM	D	TM	No	Yes	C	-	PM	M	No	No	No	Yes
[76]	-	-	SU	EM	Yes	C	-	No	M	LIE	No	No	Yes
[52]	CT, MRI	D	PSM	FEM	-	-	-	No	HMD,M	-	No	No	-
[66]	MRI	D	SU	Yes	Yes	MN	-	Yes	M	Yes	No	Yes	Yes
[45]	-	D	-	Yes	Yes	C,GR,PR,T	-	-	M	Yes	Yes	No	Yes
[84]	-	D	SU	Yes	Yes	C,GR,PE,ST	-	PM	M,SG	Yes	Yes	No	-
[96]	PH	D	SU	No	Yes	C,MN	-	PM	M,SG	Yes	-	Yes	Yes
[64]	TS	-	VO	Yes	TS	ST	-	-	M,SG	Yes	-	Yes	Yes
[63]	-	-	SU	MS	Yes	NI	BL	-	M	Yes	-	Yes	Yes

AT	AccuTouch	HM	Hand modelled	PH	Cryosection photographs	SM	Simplex mesh model
AM	Animated texture mapping	HMD	Head Mounted Display	PHN	PHANTOM	SP	Stent placement
B	Burning	I	Incision	PHR	Physciological Response	SPC	Space section or partitioning
BL	Bleeding	LIE	Laparoscopic Impulse Engine	PM	Photo-mapping	SS	Stereoscope
BS	B-spline surfaces	M	Monitor	PR	Probing	ST	Stretching
C	Cutting	ME	Microphone & Earphone	PS	Patient specific	SU	Surface model
CG	Cyberglobe	MS	Mass-spring models	PSM	Polyhedral surface mesh	SUT	Suturing
CD	Collision detection	N	Navigation	QE	Quasi non-linear elastic model	T	Knot tieing
D	From database	NI	Needle insertion	RT	Tissue removal	TM	Triangular mesh model
EM	Elastic mesh model	NN	Nodal net model	S	Suction	TS	Teleos software package
FEM	Finite element method	P	Picking or pinching	SF	Sphere-filled	VF	Vaporization of fatty tissues
GH	GHOST	PAN	Pantoscope	SG	Stereo Glasses	VO	Volumetric model
GR	Grasping	PE	Photoemulsification	SL	Stereo LCD display	VT	Video texturing

Table 3. Summary of select VR-based surgery-related systems.

References