Virtual Reality and Robotics in Medicine [1]

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Abstract

Virtual Reality and Robotics are teaming to revolutionize the art of Medicine, from student training, to diagnosis, anesthesia, surgery and rehabilitation. This paper surveys several key astpects of medical VR including organ modeling, tissue complience and cutting, and the Teleos Toolkit. This is followed by a review of medical robotics from the kinematics and safety points of view, including special-purpose manipulators and force feedback masters. Finally, we present applications in the areas of tumor palpation, epidural anesthesia, laparoscopic surgery, as well as open and telesurgery.

1 Introduction

The multisensorial human-machine interaction specific to Virtual Reality simulations has resulted in increased user immersion and interactivity, with benefits for training and learning [6].

In the medical field VR allowed, for the first time, the training of doctors on virtual patients as opposed to real ones. This met a growing need for surgical training in Minimally-Invasive Surgery (MIS) which is replacing classical open-surgery at an ever increasing pace. The advantage of using a VR-based simulator stems from the ability to repeat procedures as many times as needed, without hurting the patient. As opposed to cadaver traing, surgeon's actions and outcomes are sampled in real-time and analyzed by the computer running the simulation. Flexibility and motivation increase, while ethical concerns of animal use are alleviated. At the same time VR-based simulators allows residents to practice new and unusual surgical procedures [38].

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Another technology making an impact in the modern operating room is Robotics [42]. While the excellent repeatability and endurance of robots has been recognized and used in industry for many years, they are still novel to the medical community. However, today an increasing number of surgical procedures use robot assistants. These range from total hip replacement surgery [43] to prostatectomy [12] and neurosurgery [26]. The surgeon is not eliminated by the robot but his skills are enhanced by the mechanical device in a true partnership.

This paper looks at ways in which Virtual Reality and Robotics complement each other in establishing the state-of-the-art in medical procedures, specifically in surgery. Space here does not allow us to talk about body motor rehabilitation, dentistry, or radiology. Section 2 is a description of medical VR, namely organ modeling, collision detection, tissue cutting, intelligent agents and graphical user interfaces for surgical planning. Section 3 discusses medical robotics from general-purpose to special manipulator kinematics. Finally, Section 4 presents a number of medical applications, namely tissue palpation, needle insertion with force feedback, MIS simulators, open surgery and telesurgery.

2 Virtual Reality Modeling

The complex human anatomy, physiology and pathology make the modeling of the human body extremely complex. Not only are models more complex and dynamic, but highly dextrous surgical manipulation and interaction need to be simulated. Furthermore, the resulting contact forces and surface rugosities need to be fed back to the trainee. Most commercial VR applications do not have any force feedback to the user, but clearly this is not acceptable for surgical training and planning.

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2.1 Organ Models

Any virtual object geometry can be defined by its surface shape, texture and volume. Surface models use either a polygonal mesh or β-splines to define the external object shape. The β-spline approach is good for curved surfaces (such as those of various organs) but does not allow direct deformation [15]. Conversely, the polygonal approach allows surface deformation through direct vertex modification, but requires a large number of facets for the reproduction of intricate surface detail [6].

Any organ geometry can be classified as "generic" or "custom." A generic femur bone, for example, represents an average shape of this bone for adults (male or female). Such a model is adequate for teaching purposes, as well as training. Several commercial databases exist for organ shapes, notably the Dataset Catalog [44]. Which model to purchase depends not only on the application needs, but also on the computer power available. Complex models may take too long to render on a PC-based system.

Another source of organ geometry information is the "Visible Human Database" available on-line from the National Library of Medicine (/ftp://nlm.nih.gov/visible/). This represents a male and a female cadavers sliced at 1 mm resolution from head to toe and imaged. Each image was then used to obtain 3-D models of organs complete with very realistic textures. The Visible Human Database is availability without cost to scientists throughout the world.

When the VR application is a surgical planning for a given patient, then "generic" models are not adequate. In such cases the approach is to create a patiant-specific virtual 3-D model of the organ based on a series of 2-D CT or MRI images. An example is the model of the knee articulation required for arthroscopy training [2]. As illustrated in Figure 1, the model creation starts with the acquisition and preprocessing of an MRI data set. The series of 2-D images are segmented in order to obtain the boundaries of various organs (ligaments, bone and muscle). This binary data set is then interpolated in order to obtain a 3-D volume representation and reconstruct the surface. What results is usually a high-level of detail model with large number of polygons, unsuitable for real-time rendering. A decimation step is then needed to reduce the number of polygons to a manageable one, without sacrificing significant details. The resulting polygonal representation is then adequate for use by the surgical simulator.

Once a surface of desired level of detail is obtained the next step is to make the model dynamic, as opposed to static. In order to allow independent movement of various organ components it is necessary to define a hierarchy with parent–child relationships. The fingers of a hand become the "children" of the palm and follow their parent's motion. On the other hand children objects can move without affecting the position or the orientation of their parent. In the case of the knee model it is necessary define the same parent-child hyerarchy in order to allow various degrees of knee bending.

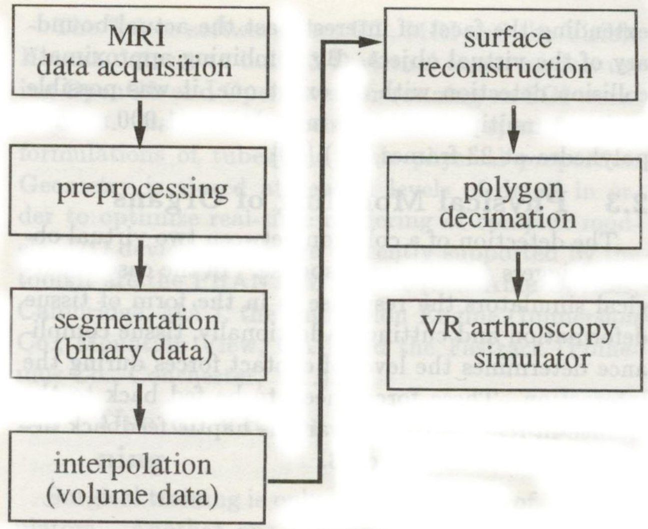

Figure 1: *Organ modeling based on segmentation of 2-D MRI data [Bauer et al., 1995]*

2.2 Collision Detection

Once organs have been modeled with sufficient detail and their various components hyerarchically organized they can be included in the virtual simulation. Interaction between the trainee and the simulator is mediated by i/o devices, which in turn map to virtual surgical tools (such as arthroscope, endoscope, etc.). The simulation therefore needs to detect when the user wants to interact with a given organ by determining when there is a "collision" between the organ and the virtual surgical tool.

Collision detection in most non-medical applications is approximate and involves interpenetration of bounding boxes. This fails for highly curved surfaces characteristic to various body organs. A more suitable way of detecting interaction with curved surfaces is to use bounding spheres of various radii. Such an approach was taken by Langrana [25] for collision detection during knee palpation.

Another approach to exact collision detection are Voronoi Volumes [27,34]. These are regions of space extending the facet of interest past the actual boundary of the virtual object. By combining approximate collision detection with an exact one, it was possible to detect multiple collisions in real time (1,000 moving polyhedra at 23 frames/sec) [10].

2.3 Physical Modeling of Organs

The detection of a collision between two virtual objects triggers a "collision response." In the case of surgical simulators the response is in the form of tissue deformation and cutting. Additionally, tissue compliance determines the level of contact forces during the interaction. These forces need to be fed back to the trainee in real time using various haptic feedback devices discussed in Section 3.

2.3.1 Tissue Deformation

When surfaces are defined by polygonal meshes it is possible to deform a given vertex, and define a region of influence which affects neighboring vertices [7]. Alternately one can define so-called "active surfaces" following the methods developed by Cover [11]. An active surface is an energy-minimization polygonal mesh, which after deformation will seek to return to a low-energy state. The energy minimization process is modeled with ideal springs attached to each mesh vertex. Springs are attached between each vertex and its neighbors and between the vertex current and rest (or "home") positions.

2.3.2 Tissue Cutting

Tissue cutting is a special case of tissue deformation in which the topology of the surface model is altered dramaticly. Song and Reddy [39] developed an approach for tissue cutting which uses a local finite element model in the vicinity of the point of interaction between the tip of the virtual cutting tool and the organ surface. Essentially, the vertex being cut, or the node in the polygonal mesh, is being replaced by two duplicate nodes. Furthermore, these newly-created nodes are pulled to a more stable energy configuration by virtual springs, such that visually the cut is enlarged. In order to model tissue cutting realisticly the researchers first measured the contact forces during actual cutting. Then they developed an instrumented wand measuring the trainee hand position and applied forces. The virtual organ tissue is cut only if the force exerted by the user on the wand exceeds the shearing resistance of the virtual object.

Another group working on tissue cutting simulation is headed by Reinig [35]. Their approach is to use texture-mapped surfaces obtained from the Visible Human database. Their algorithm looks at the intersection of the virtual scalpel blade with the current tissue surface. Then polygons are severed and new ones are created to represent the depth of cut. Texture maps for the new polygons are created from the database and the new surfaces are retracted to show the cut. This texture mapping makes surfaces look extremely realistic and is performed in real time.

2.3.3 Tissue Compliance

Modeling realistic tissue deformation and resulting contact forces is very complex, and requires finite-element analysis. Thus simplified approaches based on Hooke's law are generally adopted. Therefore elastic deformation can be modeled with

$$\mathbf{F} = K_{tissue} \Delta x \qquad (1)$$

where $\mathbf{F}$ is the contact force, K_{tissue} is the tissue stiffness (hardness) and Δx is the amount of deformation at the point of contact. An elastic tissue will produce forces as long as Δx is not zero, and it will push against the virtual tool even during retraction until its undeformed shape is regained [7]. When multiple points of contact are involved, then forces and moments are compounded [23].

In certain cases, such as when modeling palpation of malignant nodules, tissue stiffness is not constant. It is then necessary to account for a steeper resistance once the outer, more compliant tissue has been deformed. Dinsmore [13] approximated this dual-stiffness behavior with a two-segment linear law as shown in Figure 2.

A more accurate model for this linear-to-exponential force profile is given by Rosenberg [36]:

$$\mathbf{F} = (Kx_t)10^{\frac{log(W_f)}{D_s}(x-x_t)} \quad for \quad x_t \leq x \qquad (2)$$

where W_f is the "Webber fraction" related to the human force just noticeable difference and D_s is the position resolution of the haptic interface (in this case a force feedback joystick).

Theoretical modeling of contact forces needs to be validated by measurements of real forces during surgery. Sukthankar and Reddy [41] used a pair of laparoscopic forceps instrumented with ultra-miniature strain gages at the handle and on the tip. Signals from these strain gages were amplified, digitized and sampled by a PC for analysis. Forces at the tip were compared with those felt at the handle when squeezing soft, medium and hard objects. Experimental results showed that forces at the tip were significantly

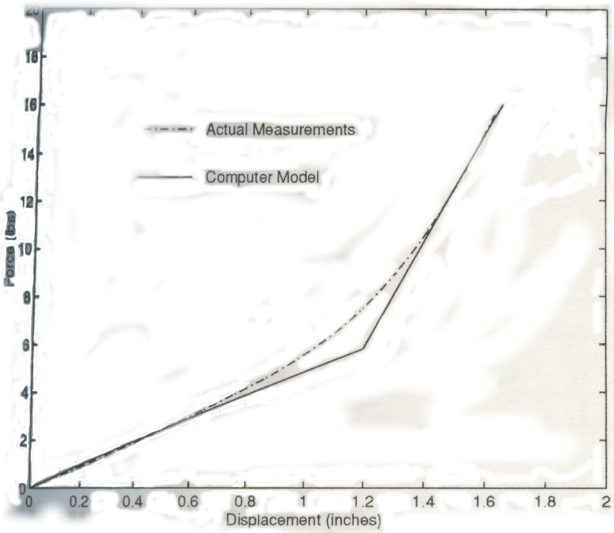

Figure 2: *Feedback forces for a dual-compliance ball deformation [13].*

different from those at the handle of the surgical forceps. Furthermore, there is a non-linear relationship between the two and this relationship is highly dependent on the material properties of the tissue in contact with the tool tip.

2.4 Active Organ Models

A virtual environment may contain passive and active organs, according to their degree of autonomy. An organ that can take actions without requiring the user's input is active. An example is the very detailed eye model developed by Hunter [18] in connection with their teleoperated microsurgical robot at McGill University. The microsurgical tool is operating on a virtual eye which has a very realistic appearance including eye lashes and blood vessels. Reflex behavior is built in the model such as a light-sensitive retina that closes when a light source is pointed towards the eye. Pupillary reflexes and ocular rotation are also incorporated.

2.5 The "Teleos" Surgical Modeling Toolkit

By now the reader should have an understanding of the difficulties of modeling a surgical simulator realistically. Furthermore, most medical specialists, who have a good understanding of human anatomy, physiology and pathology, are non-programmers. The "Teleos" Toolkit being developed by High Techsplanations (Rockville MD.) is designed to allow various medical specialists to author surgical training simulations without programming [30].

The Teleos software uses CT, MRI and the Visible Human dataset to build 3-D virtual organ models using OpenGL and OpenInventor running on SGI workstations. Its modeling centers around spatial spline formulations of tubes and their physical properties. Geometry is stored at several levels of detail in order to optimize real-time rendering of complex models. I/O devices which are currently supported by the toolkit are the PHANToM master (SensAble Devices, Cambridge, MA.), the Immersion Engine (Immersion Co., Mountain View, CA.) and the Fastrack (Polhemus Co., Conchester, VT.).

2.6 Use of VR for Preoperative Planning

Surgical training is only one application of VR simulators. Another one is *surgical planning* in which VR is used to build patient-specific models allowing complex surgical procedure rehearsal and refinement. In this way fewer mistakes are done during actual surgery, invasiveness is reduced and the outcome is improved. One example is the preoperative insertability analysis of hip implants. This is associated with total hip replacement surgery in which damaged femur joint is replaced with a custom metal implant. The femur has to be cut and drilled for about 15 cm and a the implant inserted with a tight fit. Robots have been recently used to perform the drilling stage. The implant selection is still done manually and is critical in assuring tight tolerances with the surrounding bone which shorten the time needed for the bone to grow into the implant porous surface.

Preoperative insertability analysis was developed by Joskowicz and Taylor [20] at IBM, using a CAD model for the implant and CT scans for the bone. The program models the implant and surrounding bone canal as a mesh of polygons. The insertion path is calculated automaticly as a sequence of interference-free configurations ending at the final position of the implant inside the bone. A visualization module allows the user to analyze the insertability problem, by viewing it interactively from various angles. The portions of bone canal can be selected and an insertion sequence can be animated to detect interference. The actual robotic system used in surgery, called "Robodoc" will be described later in this paper.

3 Medical Robotics

The use of robotics for surgery poses clear problems in terms of cleanliness, human-machine cooperation and patient safety. It is therefore necessary to consider both general-purpose robot kinematics [8], as well as special designs developed for surgical use [22].

General-purpose robots adapted for surgical use have the advantage of easy availability at reduced costs, ease of programming and simulation. Special-purpose architectures are more expensive but offer a clear advantage in terms of patient's safety.

An example of general-purpose robot used in surgery is the five-axis Scara robot incorporated in the Robodoc Surgical System [31]. The Scara robot was equipped with a high-speed rotary cutter used for machining the femur cavity during total hip replacement surgery. The robot wrist was retrofitted with a force sensor used to monitor drill contact forces, while a femural fixator assembly was rigidly attached to the robot base. This was necessary in order to maintain the fixed configuration of the bone versus the robot base. A color monitor was used to display preoperative planning simulations registered with the robot drill actual position. The Sacara robot was chosen for the task in view of its clearly discernable work envelope and fail-safe kinematics.

3.1 Special Robot Designs

Khodabandehloo [22] provides a set of criteria for selecting a surgical robot architecture. The tool motion should be achieved by moving a minimum number of joints with decoupled joint motion at the end effector. The system should allow for manual override and extraction of the tool and end-effector from the surgical site by moving one joint at a time. The work space of the manipulator should be internal to its structure which makes it well discernible by the OR staff. The manipulator structure should allow reasonable access to the patient.

A robot configuration which satisfies the above requirements is a spherical design as shown in Figure 3. As opposed to revolute manipulators, this design has no singularities, and each joint produces an independent motion. For example, the X translation does not cause Y or Z translation of the tool. Thus the robot control is simpler and safer. A failure of any joint of the spherical robot (except the tool axis) cannot bring the tool in contact with the patient. Furthermore, joint positional errors do not compound as in the case of a revolute robot. Thus calibration is easily done, and tool accuracy is improved. All motor drives are located below the operating table which maximizes access to the patient.

Another interesting special robot design for surgery is the endoscopic slave manipulator developed by Neisius [32]. The system consists of a robotic arm with six degrees of freedom used for gross positioning of a dextrous surgical instrument. The arm axes are mechanically coupled and have mechanical stops for

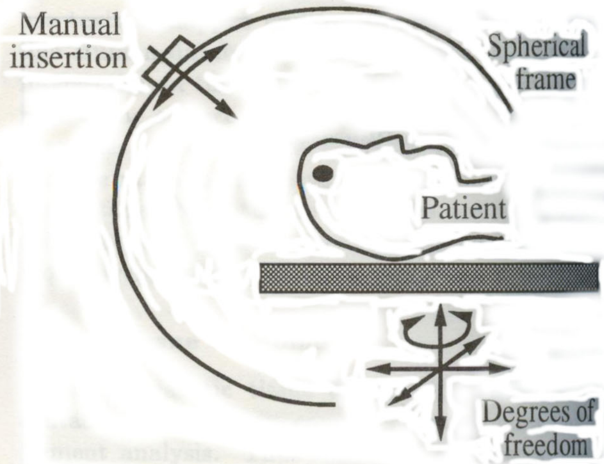

Figure 3: *Spherical robot used for brain biopsy [22] ©The MIT Press.*

increased safety. Three translation axes are used to position the invariant point of this spherical mechanism at the desired position next to the patient's abdomen. The dextrous surgical instrument is attached to the robotic carrier manually, using a quick-change device. This powered dextrous instrument has a multilink structure which allows the fine positioning and orientation of the surgical effector.

3.2 Haptic Feedback Manipulators

A special case of robots used in surgery are force feedback masters designed for VR simulations. Such haptic feedback interfaces differ from larger masters typically used in telerobotics since they ara more compact, light and avoid hydraulic power (which is dangerous and dirty). Haptic feedback masters can be further classified as general-purpose designs, or special-purpose kinematics for surgical training [9]. General-purpose haptic interfaces are joysticks [1], dextrous hand masters such as the Rutgers Master I and II [5,16], or arm masters such as the PHANToM [28]. Special-purpose designs are the instrumented laparoscopic forceps with tactile feedback [14], or the "Laparoscopic Impulse Engine" made by Immersion Co. (Santa Clara, CA.). Owing to the limited space available we will discuss only the PHANToM and the Impulse Engine.

3.2.1 The PHANToM Master

The "Personal Haptic Interface Mechanism (PHANToM)" is a desk-grounded pen-based mechanism designed for virtual force feedback [28]. As illustrated in Figure 4, the interface main component is a se-

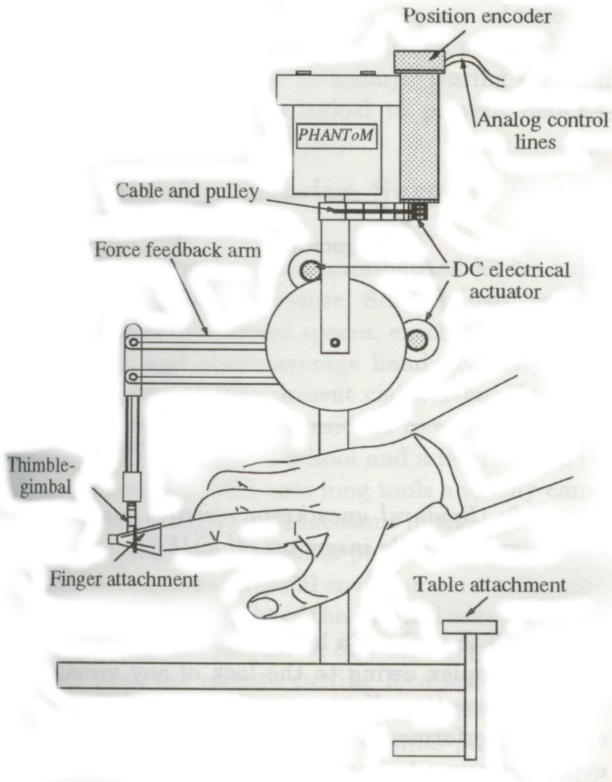

Figure 4: *The PHANToM Master (adapted from [28] ©ASME).*

rial feedback arm that ends with a fingertip thimble-gimbal support. Alternately the thimble can be replaced by a stylus. Of the six degrees of freedom of the arm, three translational ones are active, while the gimbal orientation is passive. It is thus possible to simulate single frictionless fingertip contact with virtual objects. Thus only translational forces (no torques) can be applied at the stylus (or fingertip). The arm design has certain very clever features. For example, two of the three feedback actuators are installed so that their weight counterbalances the arm weight. Since the PHANToM is statically balanced, there is no need for active gravity compensation through biased motor torques. The first rotation axis of the arm is located directly above the user's wrist, allowing for the alignment of the spherical workspaces of the interface and user's wrist. The workspace is approximately $8 \times 17 \times 25$ cm^3.

The PHANToM uses three DC brushed motors with optical encoders placed at the actuator shafts. Transmissions are done with cables and pulleys, with a simplified reduction mechanism which meshes two motor capstans with a single cable. The interface is perceived as having the same inertia and backdrivability (friction) in all directions. The peak output force of the PHANToM is 10 N, while continuous force (without actuator overheating) is only 1.5 N.

3.2.2 The Laparoscopic Impulse Engine

A system specifically designed for force feedback in MIS simulations is the "Laparoscopic Impulse Engine" [37]. This device allows surgical tools to be manipulated in five degrees-of-freedom within a $5 \times 9 \times 9$ inch workspace. The surgical tool can be tilted about the insertion port in two degrees-of-freedom by about 100^o and translated in-out by 4 in. Computer-controlled torques up to 60 oz-in can be applied about the pivot axes, while forces up to 2 lbs resist the translation motion. The two actuators used for tilting torques are connected to the tool handle through a small diameter capstan pulley and a large diameter capstan drum. This mechanism insures low inertia and friction, high stiffness and negligible backlash. The actuators (basket wound DC servo motors) are connected to the tool by high-tension aircraft cables and use optical encoders for position feedback. The tool translation is done by a precision ground shaft which slides through Teflon-coated bearings. Tension is produced by a cable fixed to either side of the linear shaft and to a small diameter capstan pulley.

4 Applications

Now that we have introduced the underlaying technology in terms of VR simulation modeling and robotic designs it is time to discuss some applications in surgical training and execution. This section starts with examples of training in palpation of malignancies, followed by needle insertion simulation for anesthesiology. Minimally Invasive Surgery and Open Surgery will be discussed next, followed by an example of Telesurgery using master-slave teleoperation for military applications.

4.1 Tissue Palpation

A classical diagnosis procedure today (still) is the palpation of patient's body. Of particular importance is the detection of malignancies hidden deep below the surface based on their characteristic haptic sensation. Malignancies tend to be harder than the surrounding tissue, and have less mobility when subjected to tangential forces. Peine [33] has developed a VR palpation system using an integrated force and tactile feedback manipulator. The manipulator consists of a two degree-of-freedom planar mechanism which provides force feedback to a finger support. The same support houses a tactile array used to convey small contact geometry information. This shape display was a 6×4

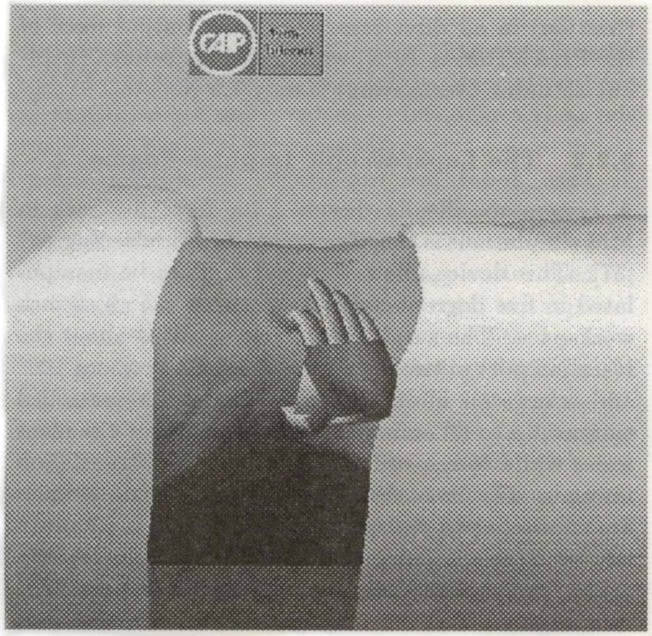

Figure 5: *Tumor localization simulation using the Rutgers Master II [25].*

array of shape memory alloy micro-pins with very high power/weight and power/volume ratios. The center-to-center spacing of these tactors was about 2 mm, with an output force of 1.2 N and a bandwidth of 6–7 Hz. Out of 300 trials over 50% resulted in tumor localization with an error of ±1 mm. This result illustrates the ability of the system to provide realistic palpation haptic sensation.

Langrana [25] are presently developing a system for training of liver and breast palpation in VR. As illustrated in Figure 5, a virtual hand interactively deforms the model of a female torso pushing against the liver. A Rutgers Master II worn by the user samples finger positions and provides resistive forces at the fingertip in proportion with the stiffness of the body region being palpated. It is thus possible to distinguish between pressing against the rib cage vs. pressing against the more compliant liver. A finite element model was used to create feedback forces for a harder nodule surrounded by softer tissue.

4.2 Needle Insertion

Once the patient's illness has been diagnosed, he/she may have to undergo surgery. If surgery is required, then the patient needs to be anesthetized first. "Epidural" or spinal anesthesia is a form of local anesthesia routinely used in obstetrics to lessen the pain of delivery. The procedure involves a delicate lumbar puncture in which a catheter is inserted into the spine with the help of a long needle. The needle insertion is complex owing to the lack of any visual cues, the long insertion distance and the proximity to the spine. If performed incorrectly it can be very painful, even dangerous to the patient. Thus careful training of medical residents has to be done before good haptic skills are perfected. Figure 6 [3] shows the anatomy in the needle insertion region and the corresponding force "signature." At first there is a slight force increase as the needle penetrates the skin and dermal regions of the back. Then resistance grows as the harder intervertebrae ligament is traversed. If the needle orientation is correct, the resident will feel a sudden drop in resistance once the ligament has been fully traversed. There is a final force spike when the dural membrane is punctured, prior to penetrating the CSF fluid and nerve fibers in the central spine region. If the needle orientation is incorrect, the needle tip lodges into the spine and resistance increases sharply (and so does the pain felt by the patient). In such cases the needle needs to be fully extracted and the lumbar punction attempted again.

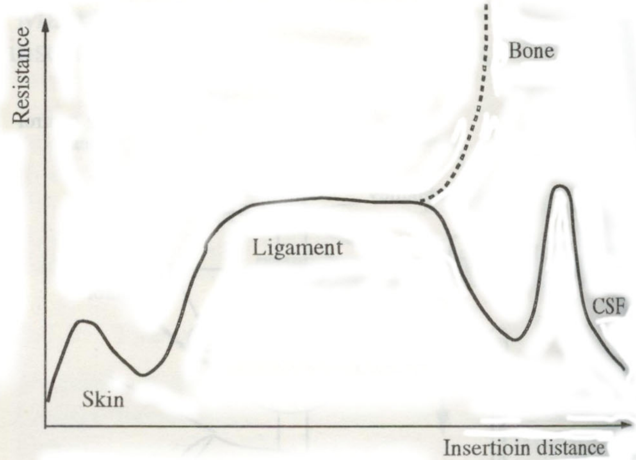

Figure 6: *Epidural anesthesia resistive force "signature" during needle insertion [3]* ©*IEEE.*

Bostrom [3] developed a prototype lumbar puncture simulator using a specially-designed 3 DOF haptic interface. This is a rather complex mechanism. A simpler design, using a single DC servo actuator was used by Brett [4]. A similar system is now commercially available from Immersion Co. and was incorporated in an Epidural Anesthesia Training Simulator by Stredney [40]. It uses a single degree-of-freedom haptic interface to provide resistive forces co-axial with the needle. The overall simulation system includes a high-performance graphics workstation and a voice activated interface. Residents can request additional visual feedback during the procedure (a section containing the current needle location). During section presentation the needle is locked to prevent dependency on the visual display [29].

4.3 Minimally-Invasive Surgery Simulators

Once the patient has been anesthetized he is ready for the actual surgical procedure. Surgery involves delicate maneuvers in confined spaces, excellent hand-eye coordination, and above-average hand dexterity and positional accuracy. The present cadaver-based training cannot possibly allow a resident to acquire all the necessary skills in medical school and a learning curve follows graduation. MIS uses long tools and tiny cameras inserted through small incisions in the body. The reduced hospital stay and faster patient recovery come at the price of a more stressful environment for the surgeon. He loses direct sight of the surgical area, since he has to look at video monitors, and he has poor tactile feedback from the remote cutting location inside the body. Under these circumstances the need for better VR training in MIS techniques becomes paramount.

Ziegler [45] built a very sophisticated Arthroscopy Training Simulator. As shown in Figure 7, the trainee manipulates tool handles that resamble an actual surgical camera and exploratory probe, inserted into a full-scale replica of a knee. The position of the tool tip the plastic knee, as well as the knee bending angle, are tracked in real time by Polhemus trackers. This information is then used by an SGI graphics workstation to move the corresponding virtual tools into the virtual knee and register any collisions. When collisions occur a four-DOF haptic interface produces resistive forces. The simulation computations are distributed between the "Haptic Simulation System" and the "Visual Simulation System." The HSS provides position data to the VSS which does collision detection and graphics rendering. Object data (compliance) and interpenetration distances are then sent by the VSS to the HSS which calculates contact forces based on a spring-damper model. It then transforms the feedback forces calculated at the tip of the virtual instrument to torques for the four feedback actuators inside the plastic knee. Active gravity compensation is also performed by the HSS, which functions as a "haptic renderer."

4.4 Open Surgery

Another area where Virtual Reality and Robotics benefit surgery is Open Surgery, such as total hip replacement and revision total hip replacement (RTHR).

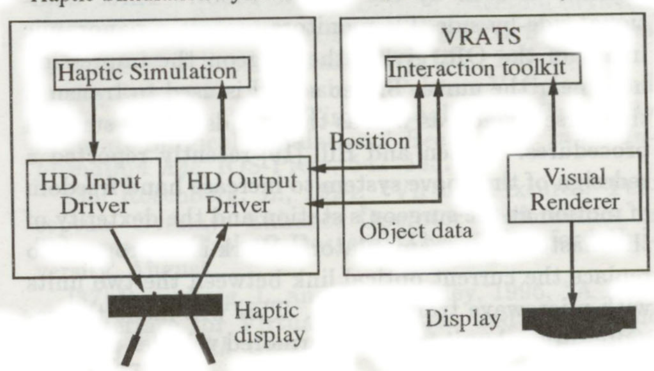

Figure 7: *Arthroscopy Training Simulator [45].*

In total hip replacement surgery VR is used for selecting custom implants and planing the robotic drill path, as discussed previously. The robot then machines the path with better accuracy then manual drilling by the surgeon. In *revision* total hip replacement, a new (longer) implant must be used to replace a failed implant [21]. Revision total hip replacement surgery is more complex than primary total hip replacement, since the area of the bone is more damaged by the first implant, and image segmentation is blurred owing to the metal-induced MRI artifacts. Thus images are less dependeable to build a 3-D model. Furthermore, the path is longer since the femur has to be drilled further to assure a strong support for the new implant. Thus preoperative path planning of the type used by the ROBODOC system is not sufficient. An intraoperative workstation has to be used to perform data acquisition and analysis, register and track the robot tool tip, and provide intraoperative decision support. Thus the surgeon has a much more active role during bone machining in RTHR surgery.

4.5 Tele-Surgery

A particular type of open surgery is tele-surgery in which the surgeon operates remotely on a patient using master-slave tele-robotic devices. While the technology has clear civilian use, the military is also interested in developing such a capability in order to reduce casualty and perform surgery as close to the battlefield as possible. Thus DARPA is funding research to develop a mobile telepresence surgery system [17]. The system consists of a master station, namely the surgeon console, and a remote surgical unit. The surgeon console has two master arms with force reflection, designed to look and feel like normal surgical instruments. The surgeon wears polarized glasses and looks at a screen displaying a stereo image of the remote patient, as seen by the remote robot. Three additional side-by-side TV monitors project a panoramic image of the OR, giving the surgeon the impression he is near the nurse. Stereo sound is used to transmit the nurse's voice, as well as the sounds during surgical procedures. Jensen and Hill [19] recently reported a redesign of the above system to increase hand freedom of motion at the surgeon's station and the dexterity of the master-slave manipulators. Work is in progress to replace the current optical link between the two units with microwave transmission. This will make the remote surgical unit mobile in armored vehicles near the battlefield.

5 Conclusions

The present discussion is necessarily limited and many other systems have been left out. In essence the flexibility of VR to build generic and patient-specific 3-D models and the robot excellent repeatability and good flexibility will be used more and more in medicine and especially for surgical training and execution. Several obstacles remaining are limited computing power, simple modeling toolkits, cumbersome i/o devices, and a lawsuit-prone working environment.

Acknowledgments

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