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Exploring Virtual Reality in Surgery Planning and Trauma Care

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Abstract— Interactive 3D visualization of human organs is becoming essential in medical field for aiding surgeons' knowledge of complex anatomies. Recent researches highly focus on the development of virtual environments since they are programmable, flexible and provide realistic experience. Virtual reality serves as a tool for interaction between the surgeon and the patient model. This helps the surgeons to plan the surgeries in an efficient way irrespective of its complexity. Trauma condition refers to serious life threatening injuries that cause psychological shock. Virtual reality based traumatic surgery simulation provides hands-on experience for surgeons. This paper reviews the state-of-the-art techniques of virtual reality in surgery simulation and trauma care.

Index Terms: surgery planning, surgery simulation, surgery training, trauma care, virtual reality

I. INTRODUCTION

Virtual Reality (VR) is an experience, an interface between human and computer generated environment in a naturalistic way. Varied applications of VR are in medical surgery simulation, neuropsychological assessment, rehabilitation, assistance for accident trauma care, telesurgery, military, education, architectural design evaluation, gaming, entertainment, rapid prototyping etc. Visualization of complex medical data is mandatory for better planning and simulation of surgeries. VR for surgical planning has gained wide acceptance throughout. It provides surgeons and physicians with medical avatars – real like body parts that can interact with external devices like surgical instruments [1]. This has created revolution in developing surgery techniques with the primary goal of minimizing patient's suffering, time and complexity of operation.

Minimally Invasive Surgery (MIS) [2] is the practice of operating the patients with minimal damage, reduced post-operative pain and minimal hospital stay. It is a technique which requires a lot of training for the surgeons before operating because of its minimal vision, minimal mobility of surgical instruments, complexity and perfect synchronization of hand and eye. However the recent developments in surgery simulation systems have made teaching and performing surgery an easier task even for interns.

MIS (Laparoscopy) has increasingly been practiced for surgery in orthopedics, otolaryngology, abdominal surgery, gynecology, gastroenterology etc. In neurosurgery, an interactive simulator, Dextroscope, is being actively involved to improve the planning processes. Cyberscalpel is a surgical planning tool created by NASA researchers, for treating the astronauts when they are in space. ProMIS, a mixed reality simulator system for laparoscopic surgery comprises software and a number of models for training. The movement of hand, position, velocity and direction of surgical instruments can be tracked.

AYRA [3] is an efficient tool to plan surgical simulation. It contains all surgical tools and runs on conventional PCs. Here the 2D radiological images can be viewed as an interactive 3D model with proper preprocessing and segmentation. This model is prototyped to get a physical biomodel from an industrial manufacturing environment. Such models are used in reconstruction surgery like maxillofacial surgery, craniofacial surgery, orthopedics, etc.

Road accidents are increasing alarmingly in all parts of the world. According to the Ministry of Road Transport and Highways – Transport Research wing, New Delhi, India, around 5 lakh accidents had occurred in the year 2011 which keeps on increasing every year. This implies the necessity of post accident trauma care throughout the country. Accident is a crucial situation where the extent of injuries and the availability of expert physicians are unknown. Apart from these, the injured person must be given proper treatment without any delay. This necessitates trauma care units.

A virtual environment which approximates working on real patients serve as a tool to better train the surgeons evaluate and treat the patients in emergencies. Simulation of a wide variety of accident cases in VR will enhance the performance of the physicians and interns in trauma surgery.

This paper reviews some important virtual reality based simulation methods for planning and training in liver, vascular, hip joint, urethral, dental, orthognatic cardiac and abdominal trauma surgeries. Section II of this paper discusses the role of VR in surgery simulation and planning and Section III explains the role of VR in post accident trauma surgeries.

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II. ROLE OF VR IN SURGERY SIMULATION AND PLANNING

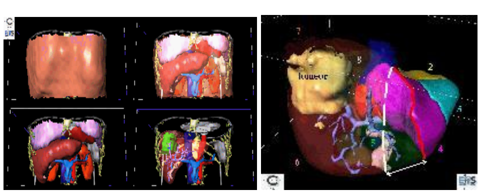
A. VR application in Liver Surgery

Liver is one of the largest organs of the human body, located below the right lung. It is divided into two lobes – right and left lobes. Liver cancer consists of malignant hepatic tumors in or on the liver. The main causes cited for it are

- chronic hepatitis B and C infection.
- cirrhosis of the liver.
- diabetes mellitus.
- exposure to toxins.
- smoking.

The only cure for liver cancer is liver resection, Hepatectomy – removal of diseased tissues. Liver resection strategies are mainly classified into anatomical resections and atypical resections. Anatomical resections are removal of liver segments and are preferred when the tumor is inside the liver .Atypical resection is preferred when the tumor is in the peripheral section of the liver. Preoperative planning helps to make appropriate decision of the resection strategies.

[4] and [5] have proposed tools for liver surgery planning. Key indices influencing surgery are tumor location and size and postoperative liver function. Hence, Preoperative planning plays a vital role in Hepatectomy. In general, surgeons rely on CT images for this purpose. They mentally visualize the 3D model of the organ from the stack 2D slices. Due to the anatomical variations; this kind of visualizations may lead to misinterpretations. An Augmented Virtual (AR) reality scheme is used to plan the hepatic surgery. This scheme [4] begins with the 3D modeling of the 2D CT liver image of the patient. As an initial step, all the functional organs in the abdomen are modeled to 3D. The organs other than liver (heart, lungs, spleen, kidneys) are cropped out using appropriate thresholding and gray level histogram techniques as shown in Fig 1(a). The patient liver is then delineated by the morphological deforming of the liver template (Fig 1(b)) which is embedded into the 2D imaging technique. With this liver model, the segmentation is carried out to categorize the voxels as - hepatic tissue, lesions and vessels. This classification is further refined using topological and geometrical constraints to automatically delineate the hepatic vein and the portal vein.

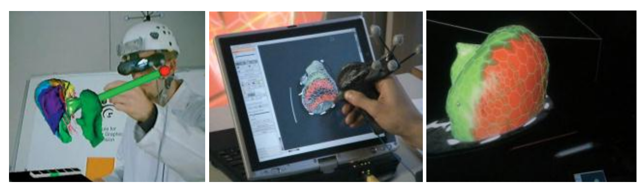


(a) (b)

Fig. 1. (a) Anatomical structure delineation (b) Patient liver segments

In [5], Nicolau *et al.* developed a tool, a prototypal augmented reality guiding abdominal surgery. This tool allows simulating any kind of coelioscopic surgeries and provides a realization of virtual resections. With the ribs as the landmark, the 3D visualization of the liver is superimposed on the real operative video of the patient via an optimal registration model. More commonly, the *Extended Projected Point Criteria (EPPC)* [6] is used for the registration purpose. Thus this system makes the preoperative 2D data more informative and proves to be highly efficient.

The center for Medical Diagnosis systems and visualization, Germany in the early 90's presented two desktop based systems, Hepavision and Surgery planner for planning liver transplantations and resection. This used the portal vein tree and hepatic vein structure to generate the resection. Visualization and adjustment of safety margins is possible. User interaction however is limited. In 2006 [7] developed a tool, Liver Planner to help physicians find the best resection plan for individual patients. This is an immersive tool with the following hardware components: a stereoscopic large screen projection system, a Tablet PC, an eye of Ra input device, and shutter glasses. It has three main phases: image analysis stage, segmentation refinement stage and treatment planning stage. Image analysis is segmentation of tissues and vessels. In tissue segmentation, segmentation of liver and tumor has been performed by an extended multi object fuzzy connectedness. For segmentation of the diaphragm dome surface a 3D active appearance model (AAM) is used and for segmenting heart from liver, AAM matching algorithm is used. A model based vessel mining approach based on tube detection filter and the nearest neighbor approximation is used to segment vessels.Fig.2 shows the anatomical resection simulation.



(a) (b) (c)

Fig.2. (a) Automatic selection and removal of segments of liver with a tracking pencil (b) user draws contour on Tablet PC (c) segmentation refinement results

The refinement stage is an interactive stage which corrects for errors in the segmented regions. Direct deformation tools for correcting small defects and template shape tool for correcting large defects are made available in the Liver Planner. The treatment planning stage includes interactive branch labeling, liver segment approximation, safety margin calculation and spatial analysis tools. Compared to a 3D desktop based planning system, hardware cost is the most crucial factor in a Liver Planner.

B. VR application in Vascular Surgery

The surgical procedures followed by surgeons need a lot of training and practice. The advances in virtual reality systems aid doctors in the pre operative training. [8] describes a virtual reality toolkit for minimal invasive vascular surgery. The software framework is constituted of the following five modules:

- *graphics rendering engine* - provides 3D graphics application programming interface and interactive user interface

- *physics engine* - provides collision detection and soft body dynamics
- *interface module* - includes load .bullet file module and GUI module
- *math module* - in charge of computing the force simulation and the force feedback
- *core module* - in charge of providing useful APIs for applications especially for basic soft body dynamics and simulation

Depth buffer and night vision techniques are incorporated to the software to provide more effective virtual reality simulation as in Fig 3.

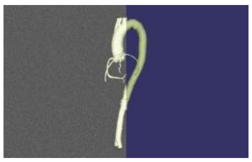


Fig. 3. A 3D simulation of the X-ray vascular structure

The toolkit also encompasses soft body dynamics, to simulate the motion and properties of deformable objects. The simulation can be obtained by using the following approaches: mass-spring model, rigid-body based deformation and energy minimization methods. This software toolkit enables users to create more views on multiple screens and more graphics contexts on one view as in Fig 4.

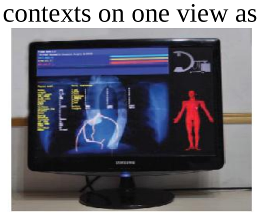


Fig. 4. User interface

In order to provide effective interaction between the surgeons and the toolkit, the simulator is controlled by *keyboard interactive mode* and *haptic device mode.* The robotic guide wire operating system serves as the haptic device to provide the real effect of VR.

C. VR application in Hip joint surgery

Structural abnormality is cited to be the main cause of hip joint disease. Osteotomy is the remedial measure performed to remove the necrotic part of the femoral head from the bearing section of the acetabulum in order to replace with the healthy part of the femoral head [9].However the preoperative planning for this surgery is done using the Computed Tomography (CT) images according to the experience of doctor. By using the virtual reality system, efficient preoperative strategies can be planned. This VR system has two modules: the data preparation and the mechanical analysis module. The data preparation module produces a three dimensional image (Fig 5) of the hip joint using Visual Studio.Net and visualization toolkit and the mechanical analysis is realized using Quest 3D. On an assumption that the joint surface consists of numerous small triangular planes, the authors have formulated a rigid- body spring model to help analyze the pressure distribution on the hip joint. Thus the results of osteotomy help in increasing the success rate of surgery.

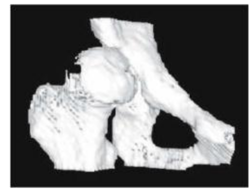


Fig. 5. 3D model of Hip joint

D. VR application in urethral surgery

Yet another application [10] where VR surgery simulation systems are applied is for training Transurethral Resection of the Prostate (TURP). The prostate gland is located next to the bladder in human males. Benign enlargement of the prostate known as Benign Prostatic Hyperplasia (BPH), results in blockage of urine. This creates the need for removing the inner lobes in order to relieve the obstruction.

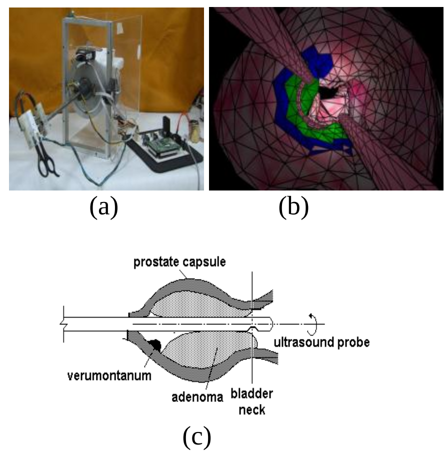
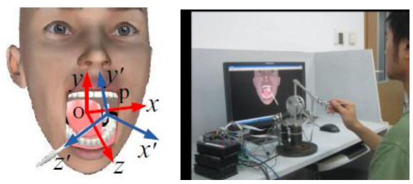


Fig. 6. a) device that emulates a real resectoscope b) Graphic prostrate model and resecting loop c) Transurethral ultrasound imaging of prostrate

The simulator includes a 3D deformable tissue model of the prostate (Fig 6b) from the ultrasound images [10] by a modeling software to simulate resection of the tissue. Realistic simulation of the movements of the surgeon has been obtained through a disk ring array which consists of an embedded electronic system (Fig 6a). This consists of five microcontrollers for movement monitoring and these movements reflect the interaction between surgeon and tissue model.

E. VR application in dental surgery

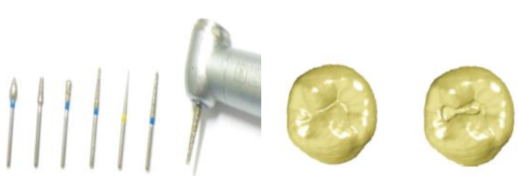
Realistic haptic devices and graphical displays are the recent training systems used for dental simulation. These haptic devices can simulate cutting, dental implants, exploration etc. A light weighted prototype haptic device, iFeel designed by Li, Chang and Wang [11] outputs a 3D force similar to the force generated in real operation. The performance characteristics of the haptic device are decided based on the Degree of freedom (Dof), maximum output power, workspace, stiffness and resolution. Dof is the freedom to move freely in the oral cavity which is 6 degree. Maximum output power is the maximum exertable force on the device which is designed as 5N.Workspace is both translational and rotational workspace and the posture tool was created in the virtual tool named Phantom Omni. The size and posture of the virtual oral cavity are similar to the real tool (Fig.6a) and the tools posture in virtual surgery can be recorded. The simulated device has maximum stiffness criteria of 14.5 (N/mm). All the above said characteristics are analyzed quantitatively and iFeel3 as a dental mirror is shown in Fig.7b.



(a) (b)

Fig. 7. (a) Virtual dental environment (b) iFeel3 used as a dental mirror

Another paper on dental simulation [12] deals with haptic sensation features on tooth grinding and preparation. Tooth grinding is shaping the tooth for further treatment. Grinding operation is by high speed rotating burs. The force applied for this operation should neither be too high nor too low. Higher force might damage the tooth tissues and lower force might cause prolonged painful treatment. That is why, appropriate haptic sensation features has become important for planning operations. In using haptic systems, the fidelity of the feedback force and stability of the mechatronic device are the most important things to be taken care of. A simplified feedback force based on grinding force model has been developed in [12]. The feedback force is generated by the grinding interaction between the tooth and the dental bur (Fig. 8a) on the hand piece. The factors that affect the grinding force are the shape of the bur, behavior of the hand piece and different tooth sections and environment. In dental surgery, the tooth is static and the grinding tool undergoes rotational and translational velocities. The different forces acting are calculated using virtual coupling to retain stability. A voxel-based grinding simulator has also been developed to overcome the force discontinuity and the feedback force generated is shown to be consistent with the real grinding. These methods are implemented in Visual Studio 2005 with Open Haptics and OpenGL and have been integrated into a dental training system. These simulation platforms have been effective in creating better alternative for traditional training with plastic teeth or removed teeth from patients.



(a) (b)

Fig. 8. (a) Bur in different shapes (b) prepared cavity

F. VR application in orthognatic surgery

The common task of plastic surgeons is to correct the dislocated bone fragments up to the complete modeling of facial regions. In these cases, individual anatomy and physiology sounds to be important. [13] presented a computer assisted modeling, planning and simulation system to aid surgeons to effectively perform the surgical corrections. This allows the surgeons to first work on a 3D virtual model of the patient before actual surgery. The most important factor here is the anatomy and physiology of the patient's skull before any disproportions. This is accomplished by the studies on facial proportions and characterization of faces along with the database of healthy morphological anatomies. The 3D model of the deformed skull is obtained by the projection of 2D X-ray images as shown in Fig 9.

Fig. 9. 2D planning in orthognatic surgery using x-ray image

In addition to the 3D reconstruction, the changes in the soft tissues due to the bone dislocation and teeth location must also be focused. The 3D model of the tissue boundaries are obtained from a sequence of tomographic images with sub voxel accuracy resulting in a surface model with millions of triangles. Such a model should not only represent the anatomically and topologically correct tissue surfaces, but also the mixed tissue volumes. The actual dislocations can be determined by the measuring the distances and angles between the characteristic points. This is referred to as the cephalometric analysis. The characteristic points can be fixed either in the image data or on the skull and skin surface respectively. For a standard 3D cephalometric analysis, the patient model is aligned with the sagitttal median and the Frankfort Horizontal plane. Comparison of the individual skull shape with a statistical reference, would generate proposals for reconstruction. As the cephalometric analysis provides the deviation of the facial bones from the symmetry and the functional analysis provides the functional impairment, osteotomy is the way to treat the dysplasia. This requires thorough planning.

The computer generated osteotomy has its base on draw-and-cut principle [14]. The initial step is to draw the osteotomy lines and then to compute path to the surfaces to be cut. The transection of nerves, vessels and underlying teeth roots can be revealed by mapping the cut surfaces and the tomographic images. The mobilized parts of the model are made to be rotated and translated with single degree of freedom over a rotational axis. Another aspect to be taken care of in osteotomy is the collision detection and avoidance. When more than one bone has to treated simultaneously, prior knowledge of soft tissues becomes inevitable. The soft tissues are modeled using the geometric model of the individual tissue volume or using mechanical model that describes the deformation of the biological tissues. The bones and the soft tissues lie on the same boundary and hence the tissue deformation can be computed from the displacement of boundaries. This system also integrates anisotropic and non linear elasticity properties of the tissues.

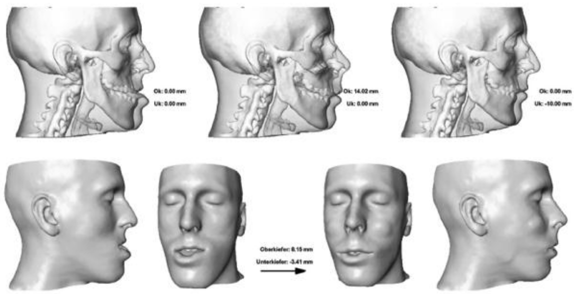


Fig. 10. Bimaxillary osteotomy with soft tissue simulation

This system as a whole thus provides vivid patient information for surgical training and education.

G. VR application in Cardiac surgery

To evaluate the congenital heart disease in children, 3D Echocardiographic Intracardiac Endoscopic Simulation System (3DE IESS) was introduced in [15]. This provides better understanding of intracardiac structures than 2D echocardiography. Since heart is in constant motion with complex anatomy, 2D imaging provides only partial information about the temporal and spatial relationship between structures. Similar to all other surgeries, the existing method of visualization of heart for surgery from 2D imaging modality is only through mental reconstruction. The authors of this paper have generated the 3DE datasets using a 2 to 4 MHz matrix array transducer and stored in a CD-ROM for post processing and data analysis. The intra cardiac anatomy of the heart is examined using VR and any point inside the heart can be analysed with the help of virtual eye. The virtual eye can be rotated at any angle with the help of mouse and visualization of interior of the atrium and ventricle are also possible. The software for the echocardiographic analysis system has been written in Visual C++ 6.0 and graphics and visualization is performed using VTK (Visualization ToolKit, Kitware, Inc.). On experimental analysis on patients using 2D and 3D echocardiography, it was found that 3DE provides more reliable and better understanding of heart structures in cases with complex heart diseases. Inspite of its efficient visualization, the process is time consuming. Fig.11 shows the virtual endoscopic view of a normal heart from the pulmonary artery.

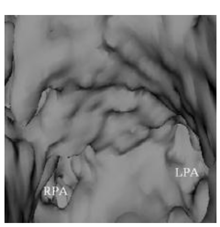


Fig.11. Virtual endoscopic view of a normal heart by 3DE IESS, LPA-Left Pulmonary Artery, RPA-Right Pulmonary Artery

III. ROLE OF VR IN POST ACCIDENT TRAUMA CARE

A. VR Simulation in Abdominal trauma surgery

Trauma is an emergency condition that cannot be taken risk of. Training the physicians to deal with traumatic injuries can be done by simulating the cases in virtual reality. One such simulation to remove a shattered kidney is presented in [16]. The simulator includes a special horizontally mounted computer system that provides the visualization of the patient's abdomen which is attached with head-like and legs-like dummies to give a realistic effect of a patient as shown in Fig. 12.

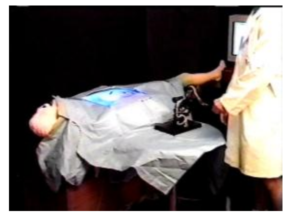


Fig.12. General setup of the simulator

The patient records and the training details are provided in the GUI form by the software embedded with the simulator system. The software is composed of 6 modules each of which takes care of different simulator components. To achieve better efficiency, the software modules are maintained distributed in two systems - SGI ONYX-2 and SGI IMPACT which share memory.

The deformations of the abdominal structures are modeled using standard mass-spring system. In order to maintain the default shape of the mass-spring surface, strut springs are used for anchoring. The real structures deform when any external stimulus like incisions occur. This can be achieved by a set of basic operations applied to individual triangles of the surface. The cutting can occur across any direction to any dimension and all the related deformities should reflect in all other abdominal parts. The arteries and tubular structures are modeled using simple linear mass-spring model.

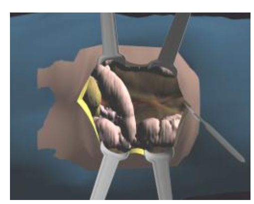


Fig.13. Abdominal part after initial incision by user

The blood flow during the accident and the incision is modeled using diffusion algorithm on the surface of polygonal models. The simulator system is incorporated with GHOST software package to provide collision detection and force feedback. With these availabilities, the simulation of shattered kidney removal can be well exposed and thus improve the physicians' expertise to deal with similar cases in the future.

IV DISCUSSION

This paper discussed about the technological advancements in VR and its tremendous support to the field of medicine.

Anatomy and abnormality is patient specific; surgical simulation and pre operative planning provides better visualization and interaction with patient's inner anatomy. This helps training surgeons and interns in minimal invasive surgery rather than using cadavers, plastic models etc. Moreover, the skills learnt using simulators guide in reducing errors significantly in live surgery. The efficacy of the virtual environment depends on the freedom of interaction between the user and the simulated environment. With adequate infrastructure and training, VR emerges as a life saving tool in trauma management also.

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