VIRTUAL ARTHROSCOPIC KNEE SURGERY TRANING SYSTEM

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ABSTRACT

Surgical training systems based on virtual reality (VR) and simulation techniques may represent a more cost-effective and efficient alternative to traditional training methods. This paper describes a training system ESSO of virtual arthroscopic knee surgery. It is developed as a joint project between the Chinese University of Hong Kong and Tsinghua University. An overview of the current state of development is presented. The virtual model used in this system is constructed from the Visual Human dataset. It simulates the real-time deformation of soft tissue with topological change by using finite element analysis. We also present the user with a force feedback device to give the realistic feelings of the operation.

1. INTRODUCTION

Minimally invasive microsurgical techniques are currently revolutionizing the practice of surgery in such diverse specialties as orthopedics, otolaryngology, gastroenterology, gynecology and abdominal surgery. It offer more advantages than the conventional open surgery with less trauma, reduced pain and quicker convalescence for the patients and have been widely applied in the last ten years. However, in endoscopic surgery, the restricted vision, poor hand-eye coordination and limited mobility of surgical instruments easily causes unexpected injury to the patients. Therefore, the experienced skill and excellent hand-eye coordinate are necessary for surgeons to execute a minimally invasive surgery successfully and safely. But, there is no better way for training and simulating surgical skill except using cadavers and animals. The anatomy of animals differs from that of human anatomy, and the cadaver can not be used repeatedly for many times.

Virtual reality based simulation systems provide a very elegant solution to train novice medical officers and interns to acquire the demanding endoscopic surgical skill. A great deal of research effort has been directed toward developing such systems in the past few years. Some recent simulation systems for laparoscopic surgery and arthoscopy surgery have been presented in [1-7]. While most of them are based on high-end workstations for real-time visualization, some of these simulators still lack force feedback, or cannot simulate topological change of the anatomic structure. And the virtual model is relatively simple.

The proposed virtual arthroscopic simulation system in this paper provides a complicated virtual model of the knee anatomic structure which is created from the Visual Human volume data. It simulates the deformation of soft tissue with topological change by using finite element analysis (FEA). We also present the user with a force feedback device to practise navigating and operation like clips and cutting, etc.

2. SYSTEM ARCHITECTURE

The hardware of the system is composed of an input device, the central computer, and a display screen. The input device gives not only the 4 DOF navigating parameters, but also the force feedback from the collision during navigating and operation on soft tissues. The central computer takes all the computation work like FEA, collision detection and realistic rendering. The display device can be a normal PC screen or a high end graphics projection table like BARON. Fig 1 shows the software architecture of our system. It is consisted of two parts, the preprocess stage and the on-the-fly stage. The major task of the preprocessing is of modeling of human organs which include both the surface model and tetrahedral model for FEA computation. The second stage gives all the functions

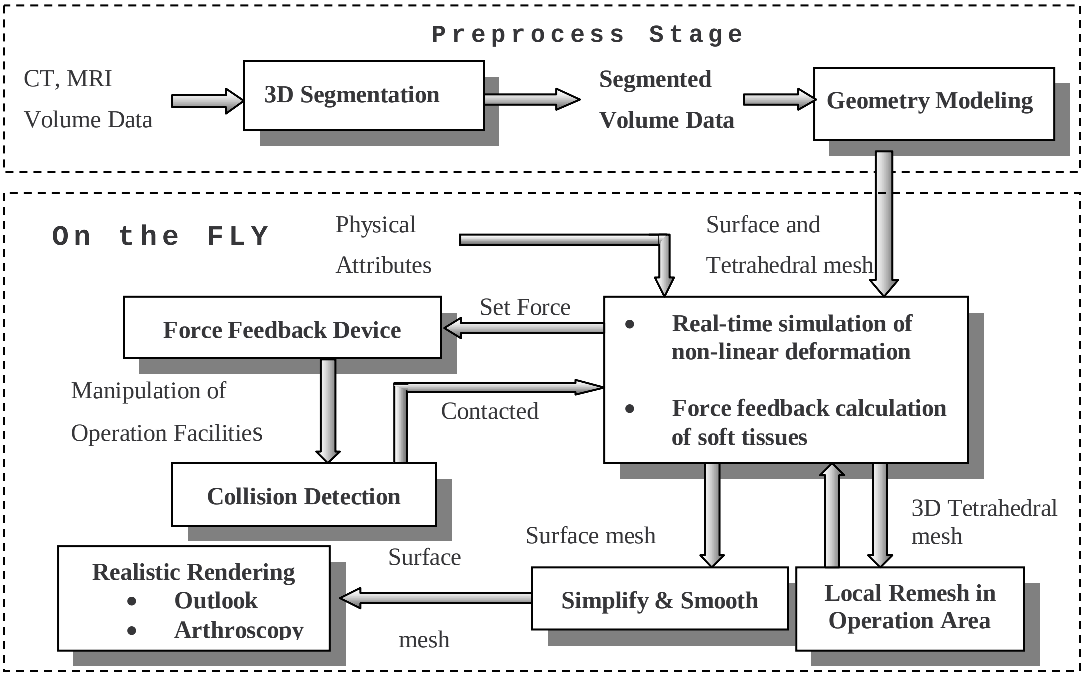

Fig 1 The system architecture of the virtual arthroscopy training system

necessary for the simulated operations, like collision detection, simulation of soft tissue deformation with topology change, real-time local remeshing and realistic rendering.

3. MESH GENERATION OF HUMAN ORGANS

In order to obtain a physically realistic surgery simulation, it is needed to generate the accurate 3D meshes for finite element analysis (FEA) to simulate serials of actions in the surgery. The Visible Human Project (VHP) has provided the input medical images and driving force necessary to develop strategies and techniques to create numerically consistent quantitative data representations of anatomical geometries. The knee model presented in this paper is created from VHP color images. MRI or CT images from real patients can also be used to construct the geometrical model in this system.

The process (Fig. 2) of modeling for human organs takes the following steps::

1. Segmentation: Slices 2100-2350 from VHP image dataset are used for segmentation of outlines for organs of interest. In our system, we present the user with an interface to get the contours automatically by using seed based method and fully functional edition of contours interactively.
2. Surface boundary meshes are created from serial 2D contours by using the 3D reconstruction algorithm. Because each contour is identified by its two neighboring tissues, there is no correspondence problem in this situation. The method of GANA [8] was used to construct the surface triangle mesh.

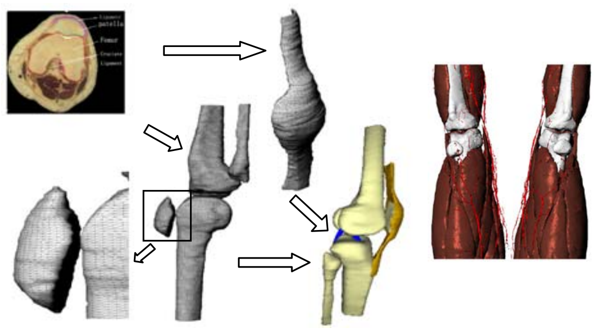

Fig 2 The procedure of mesh generation on the base of 2D medical images

3. Tetrahedral mesh generation. Because FEA is a very computational intensive work, to achieve real-time FEA computation and rendering, only the operating target organ, like cruciate ligament and meniscus, are represented in the format of tetrahedral mesh. Because Delaunay triangulation guarantee the well-shape of the final mesh. We just follow the idea of our method to the incremental insertion algorithm in Delaunay triangulation category under the constraint of the boundary surface.

4. Mesh smoothing. To get better appearance, some smooth methods should be used to improve the quality of both the surface model and the tetrahedral model. Smoothing is a technique that adjusts the node coordinates to improve the appearance of a mesh, and/or improve the shape of surface triangles. During smoothing the topology of the model is not modified, only the geometry. A common and effective technique is Laplacian smoothing. It moves the central point to a new place according to the average positions of its neighbors.

4. COLLISION DETECTION

In the simulation system, the collision detection algorithm is widely used in many situations, like collision between arthroscopic camera and organs during navigating, or between scalpel and ligament during cutting. Classical collision detection methods are almost based on rigid objects. Hierarchical structures of the objects to be detected are created before the simulation and the structures will not change too much in the simulation. But most of them are not suitable for deformable objects in surgery simulation. To maintain bounding boxes of the objects during the simulation, we choose AABB tree for collision detection because AABB tree is much easier to get the bounding box after deformation. Differences between the collision detection for rigid objects and deformable objects are mainly on that the second one must preserve the correctness of bounding boxes of the objects in scenes during simulation, including surface deformation, removing triangles and inserting triangles.

5. SIMULATION OF SOFT TISSUE DEFORMATION WITH FLEXIBLE CUTTING

Previous works on soft tissue deformation can not obtain physically realty and real-time interaction simultaneously. We present a new type of FEM, called hybrid FEM, can do this. Since the effects of non-linear property and topology change on the deformation of soft tissue often appear locally around the operating position, only the FEM for that limited region should be updated dynamically, while the model for other regions can be maintained constant. Therefore, we can use a complex FEM, which can deal with non-linear deformation and topology change, to model the small-scale dynamic region, while using a linear and topology constant FE model, which holds the advantages of accelerated ones by using pre-computation, to model the large-scale constant region.

In this system we also present a cutting algorithm for soft tissue simulation. The basic idea of the algorithm is that subdividing individual elements by tracking the actual intersection points between the cutting tool and the individual elements and generating the cut surface between these intersection points. The degenerated cutting situation, like the subdivision of the degenerated elements and the direction change of cutting tool, is also considered in our system to obtain the most flexible cutting simulation. Fig 3 shows a simple example of the cutting.

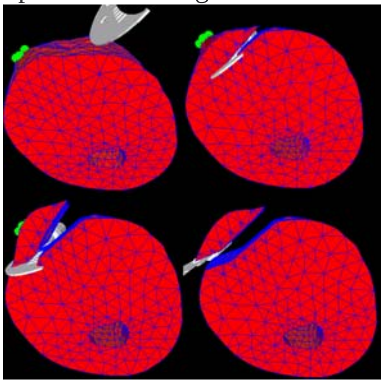

Fig 3 Cutting of the tissue

During the operation, there are many subtle tetrahedral created after each step of the scalpel cutting. The increment reduces the efficiency of deformation and collision detection. And the number of tetrahedra will rise monotonously if there is no any special process. In our system, we present a tetrahedral meshes simplification method to keep the number of the tetrahedra at a proper level. It decimate tetrahedra by degenerating appropriate edges.

5. FORCE FEEDBACK DEVICE

The simulator must allow the trainee surgeon to perform a standard inspection. Although fairly simple, a standard inspection requires that the trainee be able to recognize the major landmarks in the knee, triangulate both the arthroscope and a probe, and be able to move both around the compartments of the knee without damaging either the arthroscope or the knee itself.

In order to simulate the motion of the arthroscope and surgical instruments, a set of mechanism (Fig 4) that has four degrees of freedom (DOM) was developed. The three DOMs: pitch, yaw and insertion enable the tips of the arthroscope and instruments move in a three-dimensional space. And the fourth rotation DOM enables surgeons to be able to look around the immediate vicinity of the 30 degree arthroscope tip by spinning it about its axis.

In order to track the movement and position of the tips of the arthroscope and surgical instruments and produce force feedback, three DC motors with encoders were used in the developed input device. The device interacts directly with the tissue deformation engine in the central computer. The fourth DOM was only tracked to determine the orientation of the arthroscope and with no force feedback.

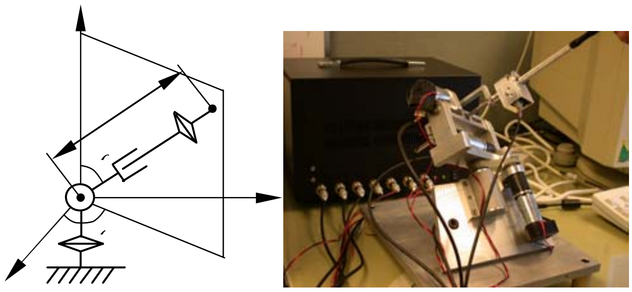

Fig 4 The input device simulating the arthroscopy

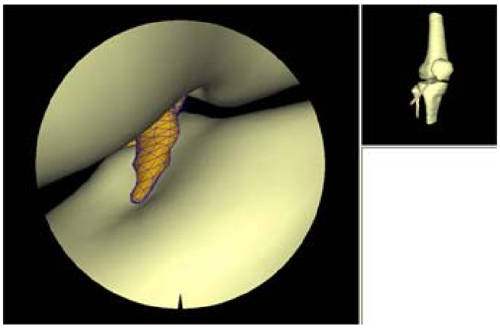

Fig 5 The interface of the system

7. RESULT

The simulation system is developed under the windows2000 operating systems on PC platform (PIV 1.5G, Nivdia Geforce 3 graphics card). Fig 5 shows the simulated arthroscopic view on the screen. The offset viewing angle (0, 30 degrees) and field of view are adjustable, and the camera rotation relative the scope body is included.

The proposed virtual reality environment can be used as a platform to support the simulation and operation of various kinds of endoscopic surgery and could serve as an excellent example for introducing the latest IT technology to the medical applications.

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