Preoperative planning and training simulation for risk reducing surgery

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Abstract

Today surgical education and training do not offer a realistic scenario to the medical students. Practical skills are mostly acquired by operating cadavers which offer material properties and physical behaviour different from living humans. Simulation systems can be used in this area to improve medical education and to offer a more authentic scenario to the future surgeons. Besides the field of training and education, surgical simulators can also be used for pre-operative planning. A big need for simulation can be determined for surgery in complex regions of the human body, such as the cranio-facial or the cardiac area. It is very important that no vital structures of the body are damaged during surgery which can be achieved by the use of an appropriate simulation system.

The main focus of this paper is the description of our approach for a risk reducing surgery simulation concept for use in pre-operative planning and medical training. We will introduce the existing system for simulation of surgical tasks in the cranio-facial and cardiac area. This system is based on volumetric models which can be manipulated using the Finite-Element-Method. Furthermore we will show how this system is modified and extended to suffice the requirements of risk reducing surgery. The determination and modelling of the risk regions will be explained and the system reaction will be illustrated. Finally we present some results of the existing simulation system and first outcome of our approach risk reducing surgery.

Introduction

In the regions of the head and the heart the anatomical conditions are very complex. In the cranio-facial area, a multitude of nerves, vessels and other structures not to be injured are located close to surgical regions [Schmidt et. al. 1997]. Additionally, the anatomical topography might be altered completely due to malformations, changes and defects caused by an accident or tumour. This severely restricts the surgeons' use of his specialized anatomical knowledge in this pathologically altered region. Moreover, due to the complex anatomical structure of the head region any kind of surgical manipulation is quite difficult to perform [Salyer 1992], [Austermann 1991].

In the heart region, anatomical complexities and surgical problems are of the similar complexity. First you have to access the heart in the chest without damaging the multiple vessels all around, the lungs or any other structure not to be injured. After that you have to be very careful in manipulating the heart itself as it is one of the most important organs of the body and must not be injured seriously.

Today the planning of surgical operations is done with the help of two-dimensional radiographs. Images of the surgical region provided by Computer Tomography (CT) or Magnet Resonance Imaging (MRI) provide the surgeon with two-dimensional information about the patient’s anatomy. Besides the lack of realistic three-dimensional images of the region of interest there is no possibility to combine the different information of various radiographic recording techniques. An image-based prediction of the operation result is not possible, either.

Our concept is based on a three-dimensional collection of image data using CT, MRI and surface scan-methods. Different structures of interest, especially bones, vessels, nerves and muscles are segmented. Patient-specific pre-operative planning, simulation or training tasks can be carried out by the surgeon using the image information present in the computer. The results of surgical manipulations can afterwards be visualized in the computer.

The goal of our research, which is part of a co-operation project in computer-aided surgery between the University of Karlsruhe, the University of Heidelberg and the German National Cancer Research Center, is to build a simulation system for the prediction of surgical operation results. The benefit of the system will be the comprehension of risk reducing simulation techniques to avoid injury of important body structures.

The paper is organized as follows. Section 2 presents an overview over the state of the art. In section 3 the existing simulation system is described. Section 4 contains our approach for risk reducing surgery. Some results of our approach are summarized in section 5. A conclusion and an overview over the future work is given in section 6.

State of the art

During the last years many simulation concepts have been presented which are partly developed to take over educational and training functions. Other systems are dedicated to planning tasks but can be easily used for medical training as well.

A visualization and simulation concept for interactive planning of cranio-facial operations is presented in [Keeve 1997]. The system enables the surgeon to specify manipulations interactively in patient-specific models based on radiographic image data. In [Weingärtner 1998] a system for pre-operative planning and education of surgeons is introduced. The scope of this work is a simulation of the temporomandibular joint based on a kinematic model. Functional and graphical models of the matication muscles have been included in the model as well.

A training system for endoscopic surgery in the laparoscopic region is described in [Kuhn et. al. 1996]. This system, called the “Karlsruhe Endoscopic Surgery Trainer“ is dedicated to indoctrinate medical students in minimal invasive surgery. A second approach for a virtual reality based simulation in the abdominal area is presented in [Bro-Nielsen et. al. 1998]. This simulation concept offers various virtual reality techniques to optimize the human-machine-interface.

In the knee area a simulation for arthroscopic knee surgery is being developed [Gibson et. al. 1997]. The system will combine real-time volume rendering with volumetric object representation and an haptic feedback.

Another area of interest for surgical simulation are eye diseases. In [Schill et. al. 1998] a biomechanical simulation concept is presented which is dedicated to indoctrinate eye surgeons to the removal of virtreous humour in the eye under pathological conditions.

Due to the enormous anatomical complexity surgical simulation systems for the cardiac area are not widely spread so far. A first approach for a simulation of the heart dynamics has been shown by [Dierberger 1993].

A non area-specific simulation system for training and simulation of operations is presented in [Ikuta et. al. 1998]. This virtual endoscope system contains a force sensation and is intended to help surgeons improving their technical skills.

Virtual cutting in volume data

The simulation concept that is described here is the result of a Ph. D. work finished at the Institute for Process Control and Robotics in 1997 [Mazura 1997]. This section contains an overview over the simulation concept which is illustrated in figure 1.

Data acquisition and pre-processing

The first step in this surgical simulation is the acquisition of radiographic image data. Individual patient data is received by use of CT and MRI. Noise and artefacts are deleted from the images and after that the CT and

MRI data is merged by the algorithm of [Pokrandt 1996] to combine the different information received by the distinct radiographic techniques.

In the resulting merged voxel data different types of tissue are identificated and segmented. Currently, the tissue classes bones, muscles and soft tissue can be distinguished. The segmentation is done with a semi-automatic segmentation algorithm [Weingärtner 1998].

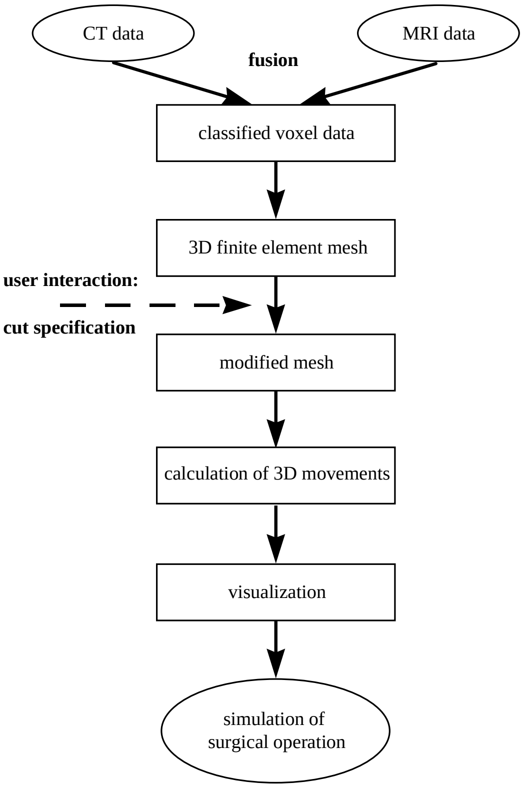

Figure 1: Steps of the virtual cutting simulation

Mesh generation

The classified voxel data is used to generate a 3D finite element mesh. For the mesh generation an automatic method is used. The mesh has an octree structure with tetrahedrons as basic entities. In comparison with cubes, tetrahedrons offer advantages in accuracy, conformity, regularity and orientation of the basic elements. All of these properties are important to guarantee consistent and proper results in finite element calculations [Mazura et. al. 1997a]. For the representation of an object with tetrahedrons a pattern set has been created which can easily be used to generate a tetrahedral model. In widely homogeneous regions coarse grained tetrahedral nets are used for meshing, in more complex regions finer grained nets are used.

Cut specification

After the data has been meshed, an incision can be specified by the user either with a mouse or a haptic input device. To specify an incision, you determine two surface points and respective vectors fixing the cut depth and orientation. A bilinear cut surface is then calculated between the two surface points and the endpoints of the vectors. You also have to specify force vectors opening the incision, otherwise you won’t see any result of the modification.

Mesh modification

Due to the specification of a cut surface the finite element mesh is modified. Cut points are transferred to vertices or mid points of edges of tetrahedrons. All possible cut configurations for tetrahedrons have been analyzed and symmetric situations have been merged together. The result of this procedure is a pattern set of 42 non-symmetric ways in which a tetrahedron can be modified by an incision. All tetrahedrons touched by the cut plane are divided into some smaller tetrahedrons according to previously defined dividing strategies for the 42 cases. It is very important, that the resulting mesh still satisfies the conditions for consistent and proper calculations mentioned above.

Calculation of movements

The calculation of the 3D movements specified by the force vectors is done with the finite-element program ABAQUS. Figure 2 shows some results of these calculations.

Visualization

The visualization of the simulation results is performed on a Silicon Graphics Workstation using the visualization toolkit KaVis [Schaude et al., 1997], which has been developed at the Institute for Process Control & Robotics. This visualization toolkit is based on Open Inventor [Wernecke, 1994]. KaVis allows advanced multi display technique, with the possibility of stereo display. It is also possible to include virtual devices like a data glove or a force-feedback tool. KaVis has been developed for telemanipulation of robots but has been extended for use in medical applications. Some main features are the possibility of measuring the distance between any points of any objects, real-time movement of objects as well as three-dimensional visualization and real-time movement of the observer’s position. Further properties are the possibility of changing colour and texture of the displayed objects, loading individual geometric models of a patient form CT or MRT and the easy extensibility of the library.

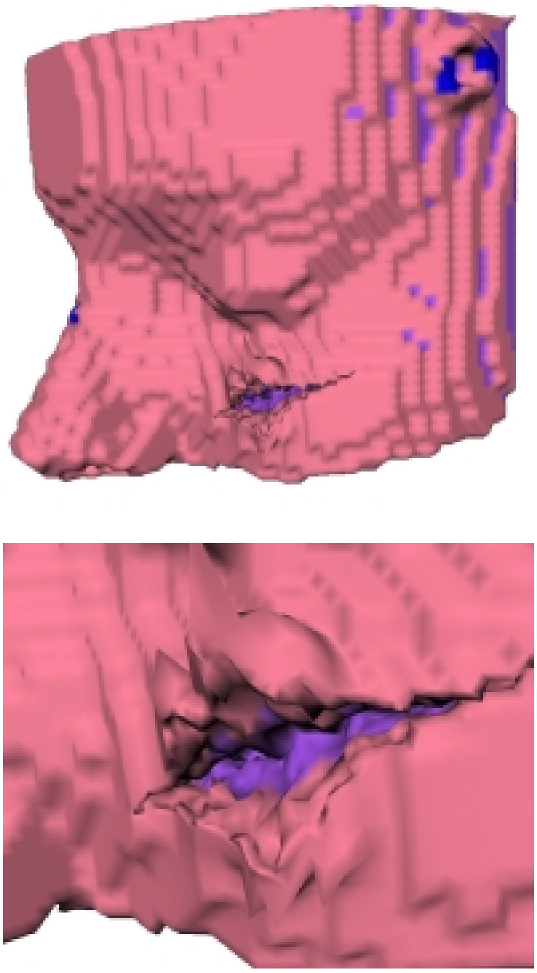

Figure 2: Results of the cutting simulation at different magnifications.

For the visualization of simulation results in KaVis, a triangular surface data set has to be created out of the volumetric models. This conversion is done by the Splitting-Box algorithm [Weingärtner 1998], which is an enhancement of the Marching-Cubes algorithm [Cline et al., 1988].

Risk reducing surgery

As mentioned above, in the cranio-facial and cardiac area do exist many nerves, vessels, organs and other structures not to be injured. We call these structures risk structures. Each risk structure can be expanded by adding a tissue specific safety area, the border region. We call the result of the expansion the risk region of the respective risk structure. Those parts of a risk region exceeding a certain threshold value must not be touched during a surgical operation in order to maintain the structures defining the risk regions.

Modelling of risk regions

In our approach, we assign tissue specific risk values to the different risk regions. Inspired by the use of potential fields in robotic applications we decided to model the risk regions by so called risk potentials. A functional description of any risk structure is in a first approach given in terms of a constant function, the border region can be described by an exponential function. In Figure 3 the risk potential functions of the border regions for the tissue classes bone and blood (vessels) can be seen.

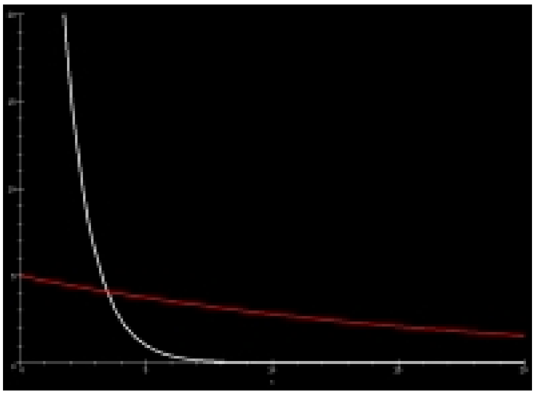

Figure 3: Risk potentials for the border region of tissue classes bone (white) and blood (grey)

Regarding the border of a risk structure as originator of a mathematical formulation, the risk potential for the bone is given by the following equation whereby d is the distance of a point from the borderline of the regarding risk structure (positive values of d are located inside the risk structure):

$$f(d)=\begin{cases}100 & :d<0\\ 100*e^{-\frac{d*\ln(2)}{0.75}} & :d\geq 0\end{cases}$$

The risk potential of the vessels is described by this equation:

$$f(d)=\begin{cases}5 & :d<0\\ 5*e^{-\frac{d*\ln(2)}{12}} & :d\geq 0\end{cases}$$

Figure 4 shows a calculation of the risk potentials for a transversal cut in the femoral. Brighter grey values denote a higher risk. In the centre of the image the very bright but small risk region of the femur can be seen. The risk regions of the different vessels filled with blood are not that bright but they are quite more extensive.

Approach for risk reducing surgery

Based on the risk modelling presented above it is possible to simulate risk reducing surgical operations. In a first approach we are currently working at a direct coupling of the risk values to the haptic feedback of the interface device. The surgeon who specifies an incision in the simulation system will be able to feel the risk regions. The exponential functions defining the risk regions may therefore be used as input functions for the force-feedback definition.

A knowledge based approach for a risk reducing cutting simulation is outlined in figure 5. The risk potential modelling with exponential functions is already available. Anatomical atlases are widely spread and accessible. The next steps of our work will be the establishing of tissue specific vector fields representing model information such as tissue orientation, density, elasticity and similar. The combination of the risk potentials and the vector fields enables us to value different incisions regarding the risk they cause. Besides, vector fields provide us with better quantitative valuation of an incision than risk potentials. Out of the valuation an automatic optimization of the incisions may be derived. The cut valuation is also the basis for a force-feedback driven risk reducing interactive cut specification.

For the realization of the concept described above we will use the hardware configuration shown in figure 6. The three basic areas of this hardware structure are the multi mode user interface, the modelling and calculation machines and, finally, the simulation and visualization.

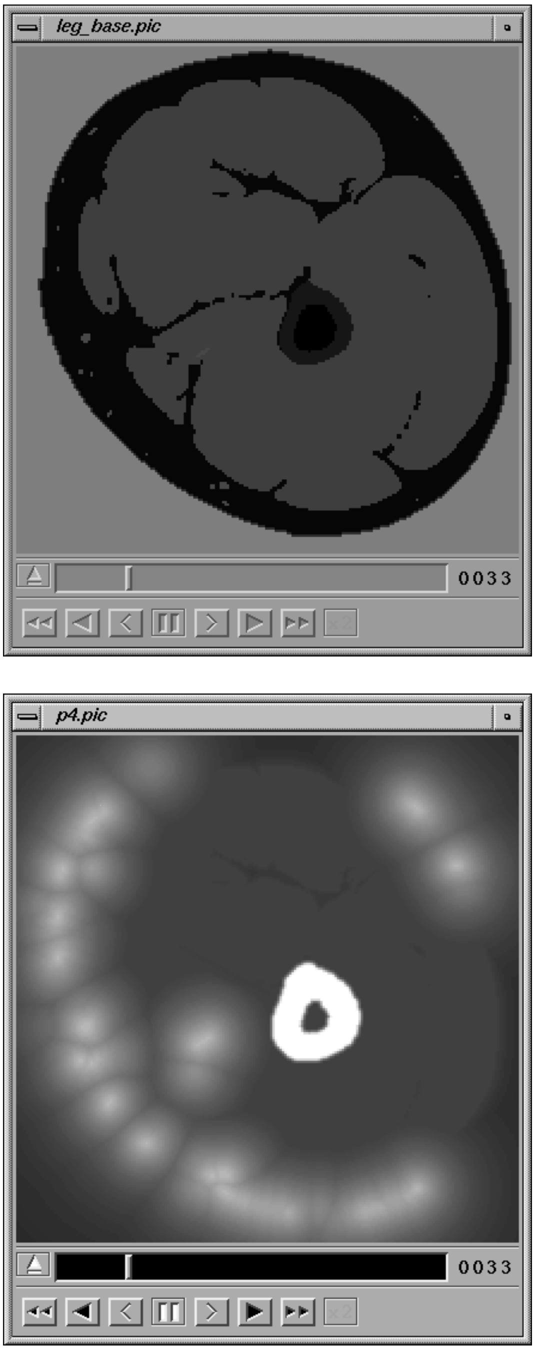

Figure 4: Original image of a transversal cut in the femur region and calculated risk potentials.

For the user interface we decided to combine traditional devices like a keyboard or a mouse with 3D interface techniques given by a space mouse or haptic interface

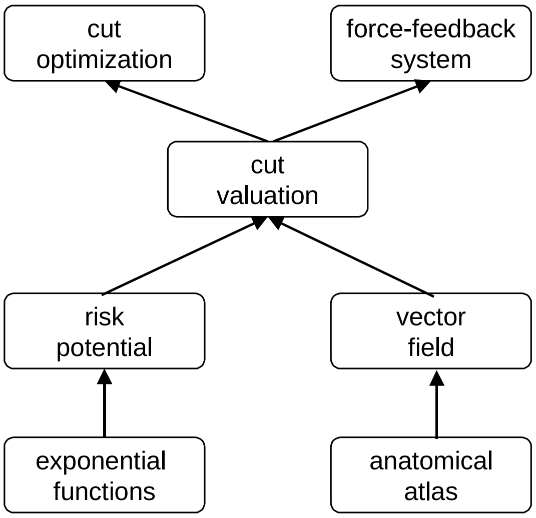

Figure 5: Concept for cut optimization with application of risk potentials in order to realize risk reducing cutting.

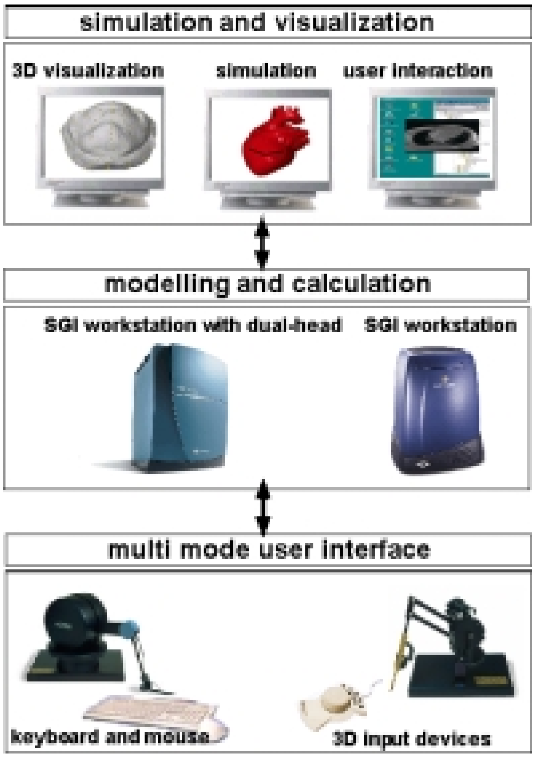

Figure 6: The hardware concept for the simulation of risk reducing surgery

devices. Modelling and calculation tasks are executed on two SGI workstations. For the presentation of the results we use a combination of three monitors. One monitor is used to handle the basic user interaction. Another possible task for this monitor is the presentation of video tapes of real operations in order to compare them with the actual simulation results. The second monitor is used for the specification of actions in the simulation system. The visualization of simulation results is performed on the third monitor. This hardware configuration from our point of view is a good approach for a training and education system in the field of risk reducing surgery.

Results

The simulation system we presented in section 3 provides us with sufficient results in the field of non risk reducing surgery. The CPU time for the computation of an incision in the cranio-facial area as shown in figure 2 takes about ten minutes on a IBM RS6000 / SP parallel machine. After the calculation of the deformation, only the visible triangular patches were selected for visualization to speed up rendering time.

First experiments in computation of risk potentials provide us with promising results as shown in figure 4. We used data of the Visible Human's femur region for modelling and visualization of different risk structures and risk potentials. Currently we're performing some experiments with images of our main regions of interest, the cranio-facial and cardiac regions.

Conclusion and future work

In this paper we presented our existing approach for pre-operative simulation of the results of surgical interventions. The main focus of the paper was on the possibilities of extending our existing system for use in risk reducing surgery. We showed first results of our technique for modelling so called risk regions.

The scope of our future work will be on the realization of the missing parts of our approach for risk reducing cut optimization presented in figure 5. This will enable us to implement a knowledge based system for risk reducing surgical manipulations under consideration of alternatives in the manipulation process. Also the existing simulation system has to be improved in the fields of real-time performance and visualization techniques.

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