Physically Based Virtual Surgery Planning and Simulation Tools for Personal Health Care Systems

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Abstract. The virtual surgery planning and simulation tools have gained a great deal of importance in the last decade in a consequence of increasing capacities at the information technology level. The modern hardware architectures, large scale database systems, grid based computer networks, agile development processes, better 3D visualization and all the other strong aspects of the information technology brings necessary instruments into almost every desk. The last decade's special software and sophisticated super computer environments are now serving to individual needs inside "*tiny smart boxes*" for reasonable prices. However, resistance to learning new computerized environments, insufficient training and all the other old habits prevents effective utilization of IT resources by the specialists of the health sector. In this paper, all the aspects of the former and current developments in surgery planning and simulation related tools are presented, future directions and expectations are investigated for better electronic health care systems.

Keywords: Virtual surgery physically based modeling, electronic health care, patient specific surgery, simulation tools.

1 Introduction

The computer models of the physical objects get closer to "real" if both visual and behavioral aspects of the models are well defined. Visual reality specifies how model will be understood and viewed by the users, on the other hand behavioral aspects of the model determines physical effects of the interactions or changes by the environmental variables, factors or usually forces. Haptic devices sit between the model and user interaction to let users experience real life experiment. These three important aspects must be contained in a single framework and let users real time interaction in ideal approach.

Virtual surgery is one of the most promising areas which physically based modeling techniques need to be applied carefully. Surgery practices can be supplied by the cadavers or animals to let young surgeons practice enough before any real surgery. A computer simulation system could potentially save time and money and reduce the need for the cadavers and animals and supports ethics in learning surgery. However, surgery simulation must be realistic to be useful tool in surgery with respect to tissue deformation, tools interaction, visual rendering and real time response. For

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given surgical simulation, soft tissue deformation accuracy and computation time are the two main constraints. Delingette [1] has summarized the different types of applications according to scientific analysis and surgery planning in figure 1.

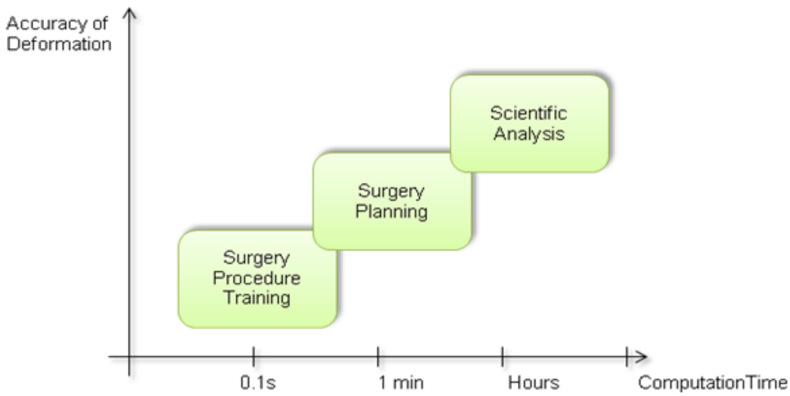

Fig. 1. Required computation time versus accuracy of deformation

Although there are various practices in the area of modeling virtual surgery and deformable objects, physically based modeling methodologies draw attention to achieving desired accuracy. The mass-spring, finite element, mixture of finite difference and boundary element, particle dynamics are the mostly used methods in the area of physically based modeling techniques. In order to supply requirements such as tissue deformation, tool interaction or real time responses, simulation system needs to balance complexities between the each component of the system. In section two, focus will be given to specifically physically based approaches, which are used for modeling virtual surgery. In this category the two widely used classical approaches, mass-spring systems and finite element methods will be presented. In section three current virtual simulators are briefly summarized and future expectations are discussed.

2 Previous Studies in the Area of Physically Based Virtual Surgery Simulators

Physically based methods explicitly use the laws of physics to model objects, calculating internal and external forces in order to determine an object's deformation. Recent research in the context of surgery simulation has developing on physically based models. By modeling the physics as accurately as possible, the aim is to achieve that the models can achieve visual realism for generic models, and perhaps physical accuracy where specific patient data or other object data is known. It should keep in mind that physically based methods uses some assumptions and approximations to model real life object. Material data may not be available in some situations or data captured can be taken in vivo or from cadavers, in some situations data captured from animals and assumptions are made for human organs [2]. Patient specific information is another concern which may change simulation results compared with the real deformation results. Patient's age, sex, health and other factors change simulation parameters and as a result, simulation outputs [3]. Volumetric organ geometry may be extracted from three-dimensional medical images (CT scan images, for instance) of given patients. It may be useful to build a 'standard' model of a given organ, in particular in the context of teaching surgical gestures. On the contrary, when simulator is used for the rehearsing of a given surgical procedure, the anatomy of a given patient must be extracted from his medical images [4].

Several mathematical models have been proposed in the literature for representing the deformable objects and biomechanical behavior of soft biological tissues. The choice of a deformable model must take two contradictory elements: the simulation realism and the computation cost for implementing this model into account.

2.1 Mass-Spring Models

Mass-spring models are easy to construct and both interactive and real-time simulations of mass-spring systems are possible even with today's desktop systems. For applications where the model exhibits non-linear behavior such as soft tissue of cloud dynamics, non-linear or inelastic dynamics can be applied to approximate this type of behavior. Another well-known advantage is their ability to handle both large displacements and large deformations.

Animation of the human face interactions and mimics is the area where mass-spring models are widely used. Terzopoulos and Waters [5] used hexahedral lattice constructed using mass-spring approach to model face and face animation. In this system Terzopoulos and Waters developed 3D hierarchical model of the human face for facial image synthesis and facial image analysis. Terzopoulos and Waters generated facial tissue consisting of three layers of elements representing the cutaneous tissue, subcutaneous tissue and muscle layer for the realistic results. The springs in each layer have different stiffness parameters in accordance with nonhomogeneity of real facial tissue. To account for the incompressibility of the cutaneous fatty tissues, Terzopoulos and Waters included a constraint into each element which minimizes the deviation of the volume of the deformed element from its natural volume at rest. Explicit Euler method solution approach is handled to solve discrete Lagrange equations of motion for the dynamic spring system of coupled differential equations numerically. The forces, accelerations, velocities and positions of each node evaluated in each time step. The Adams-Bashforth-Moulton numerical procedure can be evaluated to maintain convergence of the system and can be used in the case of large stiffness values but its computational complexity per time step that suppresses overall interactive performance of the system. Muscle parameters used to animate physically based model of face extracted directly from video images using physically-based vision techniques and details can be found in reference [6].

Thalmann et al. [7] exploit a generalized mass-spring model of Jansson's et al. which call molecular model where mass points are in spherical mass regions called molecules. Elastic forces are then established between molecules by a spring like connection with integration of properties of real biological materials to define the stiffness of its spring like connections. To validate their model, Thalmann et al. [8] arranged a test setup to compare results with obtained by a Finite Element static analysis. Besides the visual results and displacement of the key points in the modeled object, almost same deformation results are obtained.

3D boundary models of organs are reconstructed from segmented MRI data to model human hip joint as an application of Thalmann et al's molecular spring-mass model. Surface molecules are used to generate contact avoidance forces. An anatomy-based kinematical model of human joints used to simulate motion on the hip joint and evaluate stress and strain on cartilage surfaces. However model used in application is linear elastic and isotropic.

As mentioned before, selection of correct spring constants is a challenging task and is the weakest part of the mass-spring models of soft tissues. In practice, most parameters are mostly determined by trial and error based on the visual results of the simulation. Duysak et al. [9] implemented a learning algorithm using two levels of neural networks to find spring constants for face tissue modeling which produce more realistic and accurate results. Duysak et al's model uses the changes of length and velocity of the springs as input and total spring force as the training signal.

2.2 Finite Element Models

Mass-spring models consider objects as composed of individual particles where as finite element methods (FEM) assumes that material is distributed in a continuum throughout the body. One presents Lagrangian view and the other FEM, considered as an Eulerian view of matter. FEM idea is that continuous function on a domain can be approximated by using other functions defined in smaller domains.

Keeve et al. [10] used displacement-based finite element approach to achieve a result of anatomy-based 3D finite element tissue deformations in implant operations at facial tissues. Generic facial mesh is used to map general anatomical structures to the individual patient data. Using this information, 3D finite element model which is based on a linear formulation is created. The finite element calculations of a 2583 six node prism element took 10.7 minutes using a SGI High Impact workstation.

Niederer and Hutter [11] have taken advantage of reduced integration scheme to decrease finite element calculation of volume integration of the female abdominal cavity deformation. The viscoelastic material with hyperelastic behavior is implemented in deformable organ model.

Vuskovic et al. [12] modeled uterus with fallopian tubes under assumption of homogenous and isotropic materials using FEM formulation. A further simplification is added only concentration on tissue deformation moreover, implementation of cutting or perforation is not included in the proposed model. For mechanical description of soft tissues Vuskovic et al. specified 2nd Piola Kirchoff stress and Green-Lagrange strain tensor relation and used Veronda-Westmann like material definition. For the model based on Veronda-Westmann type material, the constants (material parameters) must be carefully determined. Vuskovic et al. applied pipette tissue aspiration method into pig kidney cortex to measure mentioned constants above.

Inoue et al. [13] implemented surgical simulator system and considered presurgical simulation of liver surgery in which the organ surface and internal vascular system are displayed in desktop environment. Deformation volume rendering, FEM and a haptic device with force sensation feedback are used in the system implementation. In order to stabilize the deformation computation by the FEM with a dynamic solution procedure, the process is managed by distributed processing using shared memory and multiple CPUs.

Kim et al. [14] presented a novel multiresolution approach to balance computational speed and accuracy of computations. When tool-tissue interaction occurs, the "action area" is restricted to only a zone in the vicinity of the tool tip. High resolution model is used governed by user's choice of tool tissue contact location. The rest of the domain is modeled using a relatively coarse model.

3 Discussion of the Physically Based Modeling Approaches in Personal Health Care

Although the continuum mechanics based two common methods, mass-spring and FEM and their applications in virtual surgery are frequently used in literature, one must follow the following standard techniques for fully functional virtual surgery simulator:

- CT, MRI or another type of image accusation of specific organ
- Segmentation of organ images, geometric representation
- Generation of surface meshes
- Volumetric mesh generation
- Calculation of tissue specific material properties
- Implementation of constitutive relations
- Handling force and tools interactions including haptic interfaces
- Rendering of tissues and other geometric objects

Klapan et al. [15] summarized necessary steps and required components of the overall surgery system for computer assisted 3D CAS and tele-3D surgery. The most important question; "execution of personalized features in virtual surgery" arise from particular investigation of steps defined above. A first difficulty appears during segmentation stage of the images obtained from CT or MRI related data. Currently; segmentation of organ geometry handled by operator controlled software where tissue intensity levels are selected by "*try and extract*" method from 2D image data. The main drawback of the user handled segmentation is long operation times where geometric representation may take days up to weeks based on the complexity of the organ or tissue under investigation. The material property of the organ therefore intensity level determines boundaries which are frequently mixed with other surrounding tissues at intermediate points. The relative determination of organ boundaries based on the operator perception or experience is another disadvantage of manual segmentation processes. Campadelli et al. [16] proposed fully automatic gray level based segmentation framework that employs a fast marching technique to overcome difficulties in manual segmentation stage. Segmentation process of female kidney obtained from CT data and meshing stage is presented at figure 2.

The continuum based modeling studies entail element level surface or volumetric meshes to calculate required stiffness matrices that arise from constitutive equations. Mesh generation is another bottleneck in personalized virtual surgery simulations. The quality of the mesh directly affects speed and accuracy of the overall simulation where large numbers of meshes reduce the speed of the simulation or poorly meshed geometry results inaccurate calculations. The segmentation software mostly supports

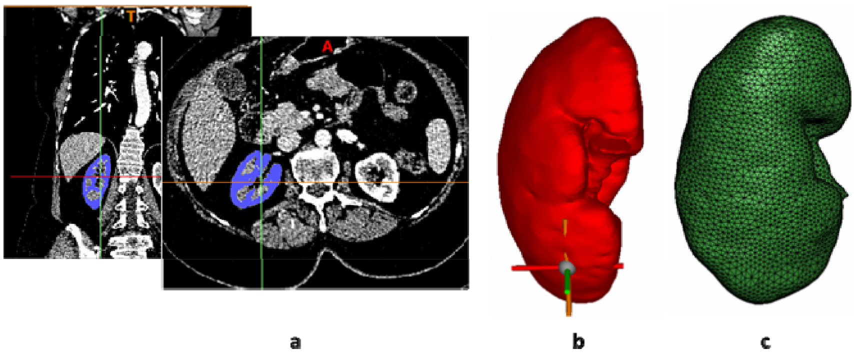

Fig. 2. CT images (a) segmented volumetric object (b) after mesh generation (c)

generation of surface meshes which may require additional software to generate volumetric meshes from surface mesh. Data exchange between different software is required in the cases where volumetric mesh generation is not applicable inside in segmentation software. Analogous to segmentation part, mesh generation is another operator driven process which requires additional afford of medical technician, detailed investigation of overall geometry and mesh corrections are needed at broken or discontinuous parts of the segmented geometric object to produce quality meshes. The mesh reduction and mesh smoothing are two advanced remeshing methodologies which also depend on operator input and experience to reduce total number of elements in calculation domain if real-time simulation experience is desired. Michihiko et al. [17] proposed patient specific modeling method which uses small tetrahedral elements for objective shape and they also introduced “form factor” that indicates degree of complexity of objective shape for automated modeling. Luca et al. applied [18] 3D level set approach to overcome difficulties in semiautomatic procedures at mesh generation stage of blood vessels to introduce patient-specific modeling of blood vessels at clinical level. Reitinger et al. [19] stated that hundred percent error-free automated algorithm is not yet available due to high shape variation, low contrast and pathological data set findings. Information preserving data structure which combines a tetrahedral mesh and binary tree is implemented in their mesh partitioning algorithm.

Human organs, specifically soft tissues have complicated material characteristics such as non linearity in every aspect including contact, geometric and material, anisotropy, large deformation, hysteresis, non homogeneity. Moreover, soft tissues are layered where each layer has its own material properties. Time dependent behaviors of soft tissues are known as viscoelasticity is almost common property for every organ. The selection of correct material property for simulated organ is a very important step which directly affects accuracy of virtual simulator. The measuring techniques of soft tissue material properties can be classified into two main categories: ex vivo and in vivo where most of the measurements are done in ex vivo environment in the past. The organ under investigation is dead in ex vivo measurements. The standard material testing procedures are applicable if material properties are measured outside the body (In vitro measurements). A tissue part generally protected in organ bath or sterilized environment is transferred to the laboratory for measurements. The accurate results can be obtained under known boundary conditions and applied forces with the exact definition of material part in vitro measurements. Miller [20] has designed an unconfined compression experiment to find material constants of the brain tissue. The analytical as well as numerical results to the unconfined compression experiments are presented and validated using commercial FEM software ABAQUS. Abramowitch and Woo [21] implemented uniaxial tension test followed by one hour stress relaxation for the six goat femur-medial collateral ligament to find viscoelastic material properties. The bootstrapping analysis is used in their work to uniquely define material constant. However, recent studies focus on measuring material properties of tissues inside the body (in vivo) specifically in living condition (in situ) due to considerable material property changes of death organs.

The several methods and devices are developed to determine material properties of soft tissues in living condition inside the body. The most frequently used approaches are the aspiration and an indentation experiments in the area of in situ measurements. Kauer [22] applied an aspiration technique to ex-vivo kidney measurements and in-vivo and ex-vivo on human uteri. The in vivo experiments on the human uteri were performed intra-operatively during hysterectomies. Srinivasan and Kim [23] characterized the nonlinear viscoelastic properties of intra-abdominal organs using data from in vivo animal experiments. A total of 10 pigs are used in their indentation experiments where robotic arm controlled stimuli is applied into pigs liver and kidney. Gefen and Margulies [24] presented non-preconditioned and preconditioned relaxation response of porcine brain obtained in vivo, in situ and in vitro at anterior, mid and posterior regions of the cerebral cortex during four mm indentations at 3 and 1 mm/s. They have founded that long term time constant of relaxation significantly decreased from in vivo to in situ modes. Researchers generally construct finite element formulation of soft tissue to compare experimental results with the FEM model and use optimization algorithms to find correct material parameters through inverse solution. The determination of correct material parameters which may vary between different patients is still an open-ended question of personalized virtual surgery applications. Researchers showed that different circumstances including age, gender, life style even psychological conditions change the material properties of living organs. These changes are an important bottleneck of the personalized VR simulators.

All the topics discussed in earlier studies such as surface meshes, volumetric model, material parameters etc. must be combined in a simulation framework where constitutive equations are required for the mathematical presentation of the organ under investigation. The basic blocks of sample simulator framework are given at figure 3. Scientists in the area of virtual surgery simulation have used different constitutive relations to model organ-force interaction and smooth deformation responses. The two frequently used approaches mass-spring and FEM and their applications presented in the previous sections implement different constitutive relations. These relations may either be a simplest linear relation between stress and strain or a strain energy presentation of material such as Ogden, Neo-Hookean, Arruda Boyce or Yeoh type.

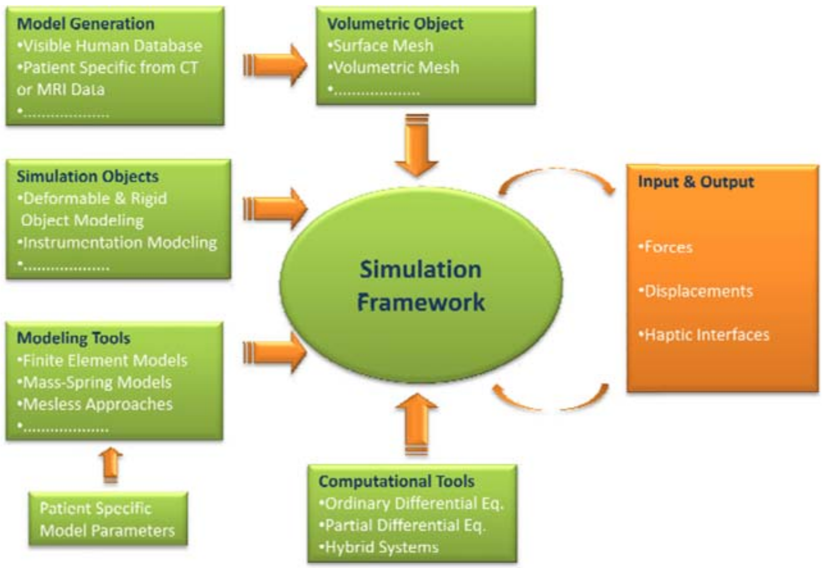

Fig. 3. Parts and steps of the virtual surgery simulator

The fast rendering algorithms and handling user input via haptic interfaces are the other important parts of the virtual surgery simulators. Generally open source rendering and visualization tools such as OpenGL, VTK or Open Inventor type libraries are included in simulation frameworks. Surgeons must feel the interaction forces exerted during tools - tissue interaction as real as possible. Open haptic is one of the open source promising solutions in haptics community for interacting with haptic devices. Real time update rates are possible with the help of computer graphics rendering techniques such as space partitioning, local search and hierarchical data structures. In the point based haptic interaction, only end point of the haptic tool and virtual organ collision is considered. Thin structure of real surgical instruments embarrasses use of point based haptic interactions due to accuracy problems. Tool is modeled using finite line segments in ray based haptic interaction where it has several advantages over point based methods such as feeling torques and rotations.

4 Conclusion and Future Directions

Virtual reality applications have been successfully applied to various areas during the past 50 years. Areas like nuclear energy, aerospace, marinetime, flight simulators which have high risk having direct affect on human life are the main application areas of virtual reality. Even though there has been a growing interest on virtual surgery applications during the past 20 years, the virtual surgery simulators have not still reached the required accuracy. With the use of virtual surgery applications, surgeons may gain the opportunity to test different critical surgery scenarios in a low- cost, ethical environment.

Current simulators use standard geometry data from visible human database. Customization feature is a very important fact for virtual surgery simulators where improvements on automatic segmentation tools will help implementation of personalized data. The ability of transferring volumetric representation of patient specific data into centralized database must be common for future surgery simulator frameworks in a hospital environment.

Material properties of soft tissues change significantly between different patients or depending on various environmental conditions. Furthermore various researchers have measured different material properties for the same body parts even though they have run the same experiments with similar measurement devices. Therefore personalized measurement of material properties is still an open-ended question for virtual surgery simulators.

The simulation results directly affected by mathematical models used in simulator framework. Complexity and solution time eventually increases if new model parameters are added. Depending on the personalized operation procedures; selection option of important tissue properties and required mathematical model within a central framework is one of the feature expected from virtual surgery simulators. Application frameworks like GIPSI, SOFA, PML are still in development to provide required flexibility.

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