3D Anatomical Modelling and Simulation Concepts

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Abstract

Nowadays, a large panel of medical acquisitions devices are made available producing a large amount of information such as high-resolution volumes, temporal sequences or functional images. Although this information helps scientists and physicians better understand the human anatomy and physiology, it becomes more-and-more difficult to analyse and visualise it. In this context, anatomical and functional models that combine multi-modal information are highly demanded. These models are successfully used in medical simulations such as virtual surgical interventions (e.g., bone, liver surgeries) or physiological process analysis (e.g., tumour growth, cartilage degeneration). They improve the diagnosis and assist the physicians. In this tutorial, we will present the current research issues towards the creation of patient-specific anatomical models and their functional simulation. Various topics in medical modelling/simulation will be addressed, focusing on computer-graphics based approaches, such as deformable models in image segmentation, data fusion, interactive physically-based simulation and cost-efficient visualisation. Examples will be given in the musculoskeletal, cardiac and vascular domains. All speakers are partners of the EU project "3D Anatomical Human" led by MIRALab - University of Geneva.

Categories and Subject Descriptors (according to ACM CCS): Computer Graphics [I.3.3]: Viewing algorithms—Computer Graphics [I.3.5]: Physically based modeling—Image Processing and Computer Vision [I.4]: Segmentation—Life and Medical Sciences [J.3]: Health—

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1. Introduction

The objective of this tutorial is to train students and researchers in the various domains involving the modelling and simulation of the human body for medical purposes. Nowadays, a large panel of medical acquisitions devices are made available producing a large amount of information such as high-resolution volumes, temporal sequences or functional images. Although this information helps scientists and physicians better understand the human anatomy and physiology, it becomes more-and-more difficult to analyse and visualise it.

In this context, anatomical and functional models that combine multi-modal information are highly demanded. These models are successfully used in medical simulations such as virtual surgical interventions (e.g., bone, liver surgeries) or physiological process analysis (e.g., tumour growth, cartilage degeneration). They improve the diagnosis and assist the physicians. For instance, the EU project "3D Anatomical Human" and the Swiss Project "Co-Me" are projects that bridge complementary approaches for modelling and simulating the human musculoskeletal system.

In this tutorial, we will present the current research issues towards the creation of patient-specific anatomical models and their functional simulation. The generation of patient-specific model is very challenging but of paramount importance in the domain of Health. In fact, generic anatomical and physiological models cannot express the variability that exist among individuals and that lead to different diagnosis and treatments. The tutorial is divided in three main parts: (i) anatomical modelling from medical data, (ii) Physically-based simulation of biological tissues and (iii) medical visualization and related applications. Various examples will be given to illustrate the challenges of modelling, simulation and visualization. It will be shown in particular how computer graphics techniques can play an important role in the medical field.

2. Anatomical modelling from medical data

The various human systems (e.g., vascular, neuronal, musculoskeletal) are composed of different complex and heterogeneous elements. Modeling (even partially) one of these systems remains a big challenge due to the complexity of geometry, mechanical behavior and interactions. Initially, generic models derived from biomechanical and anatomical studies on cadaveric specimens were proposed. Although these models remain extremely useful to understand and teach the human anatomy and physiology, there is an increasing demand of individualized (i.e. patient/subject-specific) models to capture the differences that exist among individuals. Indeed, correct medical diagnosis can be only given from patient-specific information.

If we consider the musculoskeletal system, various attempts were conducted to model it based on computer-assisted techniques. Scheepers et al. [SPCM97] and Aubel and Thalmann [AT01] described approaches based on anatomical concepts and constraints (e.g., bone-muscles attachments via tendons). Teran et al. [TSB*05] or Blemker and Delp [BD05] proposed more complex anatomical models considering essential biomechanical parameters such as fibers direction. Some of these models were adapted for simulation (FEM-based [FMT*04, BD05] and FVM-based [TSB*05] models) but most of them were not subject-specific or relied on unrealistic simplifications. Moreover, numerous manual operations and corrections were usually required.

In order to build subject-specific model, the most appropriate way is to rely on medical data such as medical imagery. In the domain of static acquisition, radiography has been the first modality for in-vivo imaging of internal organs based on X-rays. Computed tomography (CT) combines various X-rays projection to deliver 3D images of the anatomy. These modalities remain invasive and are not able to highlight some soft structures without enhancement techniques (e.g., contrast agent injection). Magnetic Resonance Imaging (MRI) is considered as not invasive [SFDM91] and much more flexible in terms of protocol and imagery. In fact, MRI can provide dynamic images and combine different gradient or fluid flow/ fiber directions giving birth to new imaging techniques. For instance, diffusion tensor MRI can be coupled with fiber tracking techniques to provide essential biomechanical parameters of muscles (e.g., [HSV*05]).

Image-based anatomical modeling is surely one of the most promising way to create these subject-specific models [BAGD07, SJL*07]. Anatomical modeling from medical images addresses in particular the problem of image segmentation and registration. Segmentation consists in extracting anatomical structures from medical data acquisitions, dividing an image in non-overlapping and homogeneous regions (each one corresponding to a unique structure of interest, e.g. an organ). Usually, clinical datasets are corrupted by artifacts due to data acquisition (e.g., noise), sampling and processing (e.g, partial volume effect). Moreover, the human anatomical system is extremely complex and large differences exist among individuals. As a result, no segmentation method has proven to be generic, automatic and robust. Direct segmentation approaches only use the image information to identify regions and classify them in an iterative manner. Segmentation can be also achieved via registration techniques. Registration aims at finding the transformation that maximizes the similarity between various sources, while preserving a certain regularity of the transformation. Registration depends on various components such as the nature of features to be registered (geometric, iconic, etc.), the similarity measure, the problem regularization and the resolution method.

The tutorial will also cover computer graphics techniques that can be used to devise more adapted segmentation methods. Deformable models of Terzopoulos et al. [TW88], originally presented in a computer graphics context, gave birth to novel approaches in medical imaging analysis [STG98, MT96]. Deformable models can adopt various kind of representations (e.g., active contours [KWT87], physically-based deformable models [GMMT06], implicit based on the Levelset framework [OS88, MSV95]) and were successfully applied to segmentation. Recent advances in the computational power of graphics processing units (GPUs) resulted in a new generation of fast GPU-based segmentation and registration methods [HLSB04] (e.g., Levelsets-based segmentation [LCW03, Kla07], Mutual Information-based registration [SB07, TEE*08]). Most of the methods are interactive since the segmentation/registration evolution is observed and controlled during the computation. However, GPU architectures may impose some constraints (sometimes too restrictive), like the choice of data structures and the type of numerical integration schemes.

Direct segmentation can be in many cases noise-sensitive, not robust and quite inaccurate. By considering input and output sources, the registration framework uses in a sense some more prior knowledge with respect to direct segmentation. Compared to mere direct segmentation approaches (e.g., basic global thresholding), registration approaches are more efficient but still special care is required when devising them. For instance, the use of prior knowledge can considerably improve segmentation approaches by enforcing constraints: valid shape variations across population (e.g., for explicit [CHTH93, SMT08] and implicit [LGF00, YD04] deformable models), topological constraints [GMMT06] or assumptions on structures variability (smoothness, curvature) and aspect (e.g., tubular-like shape [AB02]). Priors can derive from training datasets that can be for example reused in Bayesian or classification methods. We will present results of musculoskeletal segmentation that can be furthermore coupled with other modalities [MTCS08, CAVMT09] to produce high-level models (see figure 1). Such models are then used for anatomical and functional simulations.

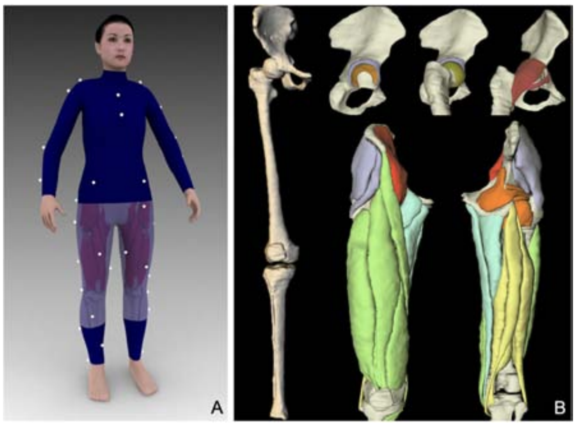

Figure 1: *A) example of 3D scanner, Motion Capture and reconstructed data fusion B) reconstructed data from MRI datasets [MTCS08].*

3. Physically-based simulation of biological tissues

Anatomical models only provide a static geometrical representation of the patient anatomy and do not take into account the deformation of soft tissue that may occur before or during therapy [DPS*06]. To address this issue, it is necessary to add a biomechanical model that can estimate soft tissue deformations under the application of known forces or displacements.

Unlike most deformable models used in computer vision or computer graphics, physically realistic soft tissue deformation requires to model the relationship between deformations and forces based on continuum mechanics. In this framework, forces are represented as stress fields and deformations as strains. A mechanical model is characterized given a functional relationship between stress and strain. Most soft tissues exhibit complex mechanical phenomena such as viscoelasticity, hysteresis, material nonlinearity and anisotropy [DA04, Fun93]. Thus, there exist several mathematical constitutive models that describe stress-strain relations for soft tissue in a fairly realistic way. In this tutorial, we will only consider linear elastic materials and basic hyperelastic materials (such as St Venant Kirchoff [PDA03, JP99] and Neo-Hookean models). A difficult yet essential issue in biomechanical mechanics is to find the proper parameters of those mathematical models for a given tissue. Four methods for parameter estimation will be covered in this tutorial : elastography [MOD*01], *in vitro* indentation tests [CM96], *in vivo* indentation tests [NMK*03] and data assimilation.

Once a given mathematical soft tissue model is chosen with a relevant set of parameters, it is necessary to discretize such constitutive models on a computational mesh. To this end, we will overview the concept of finite element modeling focusing on a simple case : the Rayleigh-Ritz formulation [Bat82] on a tetrahedral mesh [DA04]. To guide the audience, a link between linear elasticity and spring mass models will be developed to show that such models have a similar complexity. The FEM formulation [OZ00] leads in the general case [Bat82] to a relation between displacement $\mathbf{U}$ and nodal forces $\mathbf{F}$: $\mathbf{F} = \mathbf{K}(\mathbf{U})$ where $\mathbf{K}$ is a (non constant) stiffness matrix. Different numerical approaches for solving these (non-linear) systems of equations including precomputation, dynamic implicit and explicit time integrations.

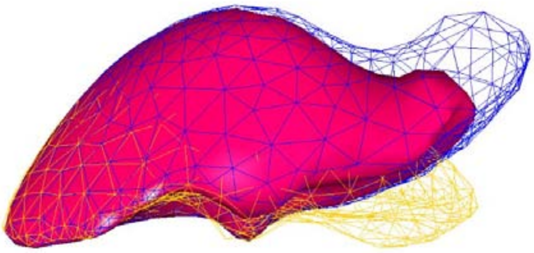

Figure 2: *Comparison between linear elasticity (blue wireframe) and St Venant Kirchoff (solid red) materials on a liver. The yellow wireframe mesh correspond to the rest position.*

Several examples of soft tissue deformation will be shown including liver surgery simulation [DA05], cardiac simulation [SDA06] and knee joint simulation. The SOFA platform [ACF*07] will be used to provide several interactive demonstrations of soft tissue deformation.

4. Medical visualization and applications

The large amount of data provided by the modern clinical modalities can give a lot of diagnostic information to radiologists and clinicians. Data usually encode maps of physical parameter values in 2D, 3D or 4D and it is not obvious in general, how to show them to the doctors allowing a clear understanding of organs morphology or functionality and eventually obtain quantitative diagnostic values. The simplest data analysis method, still widely applied by radiologists, consists of just showing 2D images (printed or on screen), acquired or resliced, using ad hoc color mapping and windowing to enhance the structures of interest.The intrinsic 3D or 4D nature of most of the data, however, suggests the necessity of finding effective ways of displaying the whole dataset in order to give an immediate interpretation of the organ morphology and functionality.

Standard Computer Graphics techniques, like volume rendering, surface extraction/rendering, can be applied to reach this goal, obtaining photo-realistic representation of organs in 3D. Several visualization enhancements can then be applied to give the physicians useful diagnostic information in addition to the simple morphology [GZ06]. The importance of medical data rendering is not, however, limited to a simple diagnostic use. 3D/4D visualizations can be applied in surgical planning, to increase the understanding of organs morphology and or to perform accurate measurements. All specific applications of 3D data visualization (pre-operative planning [RBBS06], augmented reality in operating rooms, surgical simulation, etc.) require not only the application of advanced visualization techniques, but also a careful design of the interaction in order to give the end user the possibility of easily navigating the scene [Bar05], selecting the views and performing qualitative and quantitative evaluation.

This part of the tutorial aims to review the main techniques and trends in medical visualization. Firstly, we focus on 3D visualization in radiology, by describing the state of the art of radiology workstations, and the current efforts aimed to overcome the limitations especially with respect to the complexity of the 3D interaction [CNC*05]. Secondly, we give an overview of recent medical volume rendering tecnhiques [BG07, GMI08] and we show how they can be exploited to drive new generation autostereoscopic light field displays [AGI*08].

For the realization of Virtual Humans and physical simulators, that is the main subject of the tutorial, it is expected that the complexity of the reconstructed models will grow relevantly in the future and the large size of the data sets will require specific solution for visualization. To this end, multi resolution schemes have been recently proposed to speed up the rendering of huge data sets on commodity hardware, either for triangular meshes [GM05] and for volume data [GMI08]. These kind of techniques, together with the usage of multiscopic visualization displays [AGI*08], represent a promising ground for deriving interactive and effective visualization methods of large and complex human models (see figure 3).

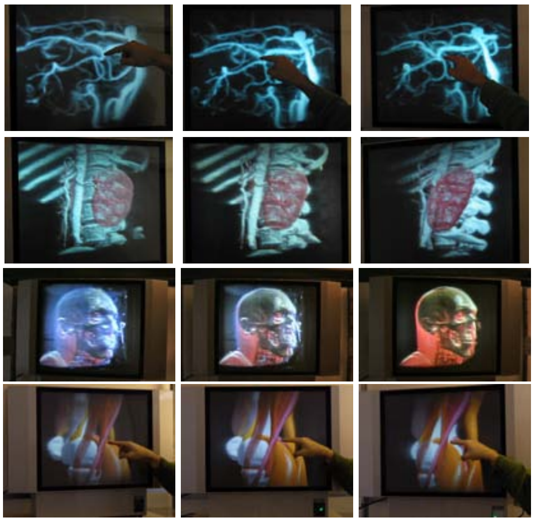

Figure 3: *Real-time inspection of medical volumetric models visualized with a lightfield display [AGI*08]. Pictures are taken with an hand-held camera at different viewing angles, in order to highlight the horizontal parallax of the light field display.*

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Tutorial syllabus

Introduction (12:00 - 12:15 (15 mn), Nadia Magnenat-Thalmann)

- Presentation of authors/institutions
- Tutorial overview
- Medical problems through medical projects presentation
- Main medical acquisition modalities: medical imaging, motion capture, 3D body scanner and acquisition of mechanical physiological parameters.

Anatomical modeling from medical data (12:15 - 13:05 (50 mn), Nadia Magnenat-Thalmann and Jérôme Schmid)

- Anatomical modeling review, comparison of musculoskeletal modeling approaches
- Medical image segmentation and registration techniques: from direct to knowledge- and physically-based segmentation, exploring approaches based on computer graphics techniques (e.g., deformable models, GPU-based approaches).
- Examples of musculoskeletal modeling: segmentation and multi-modal data fusion

Physically-based simulation of biological tissues (Part 1: 13:05 - 13:30 (25 mn), Part 2: 15:00 - 15:25 (25 mn), Hervé Delingette)

- Soft Tissue constitutive materials based on continuum mechanics.
- Overview of different discretisation techniques: finite elements, finite volumes, boundary elements, particle systems.
- Parameter Estimation of soft tissue models based on indentation tests, elastometry and inverse problems.
- Quasi static and dynamic evolution of soft tissues and numerical integration.
- Important issues in interactive soft-tissue simulation (haptics, topological changes,..).
- SOFA : a software platform for medical simulation.
- Example of medical simulation (knee joint, cardiac modelling, liver surgery, ...).

Medical visualization and applications (15:25 - 16:15 (50 mn), Marco Agus and José Antonio Iglèsias Guitiàn)

- Medical data rendering: techniques, applications and related problems
- Visualization in radiology: past, present and future
- Diagnostic use of 3D models and interaction techniques for medical applications
- Volume data rendering techniques
- Medical volume visualization on spatial light field displays

Conclusion and discussion (16:15 - 16:30 (15 mn), all speakers)

- What is still missing? what are the greatest challenges?
- Questions from audience
- Closing remarks

Resume of presenters

Prof. Nadia Magnenat-Thalmann has pioneered research into Virtual Humans over the last 25 years. She obtained several Bachelor's and Master's degrees in various disciplines (Psychology, Biology and Chemistry) and a PhD in Quantum Physics from the University of Geneva. From 1977 to 1989, she was a Professor at the University of Montreal where she founded the research lab MIRALab. She moved to Geneva in 1989 and recreated the Swiss MIRALab, an internationally interdisciplinary lab composed of about 25 researchers. She is presently taking part in more than a dozen of European and National Swiss research projects and is the coordinator of the European Research training network Marie Curie "3D ANATOMICAL HUMAN". She is also coordinating one major group within the Research Project COME, a Swiss National Project on simulating virtual surgery procedures. She has worked in the past on several EU projects on medical topics, particularly the successful EU project CHARM. She is editor-in-chief of the Visual Computer Journal published by Springer Verlag and co-editor-in-chief of the journal Computer Animation and Virtual Worlds published by Wiley

Dr. Hervé Delingette is currently a research director in the ASCLEPIOS research group at the INRIA research center in Sophia Antipolis and is leading the INRIA research action CardioSense3D on cardiac modelling. He received in 1989 a Master degree and in 1994 a PhD degree from the Ecole Centrale des Arts et Manufactures de Paris, (France) and was habilitated in 2006. From 1989 until 1992, he was a Visiting Scientist at the Robotics Institute of Carnegie Mellon University (CMU) and the Human Interface Laboratory of Nippon Telegraph and Telephone (NTT). His research interests are in the fields of medical image analysis, image segmentation, soft tissue modelling, surgery simulation and computational models of the human body. He is member of the Editorial Board of the Medical Image Analysis journal and he authored and co-authored more than 50 journal papers in those fields. He co-chaired the First Symposium on Surgery Simulation and Soft Tissue Modeling in 2003.

Dr. Marco Agus is a researcher of the Visual Computing (ViC) group at CRS4. He received a M.Sc. degree in Electronic Engineering (1999) and a Ph.D. degree in Mechanical Engineering (2004) from the University of Cagliari (UniCa). His main research interests are related to computer graphics and scientific visualization, haptic simulation, and physically based simulation, with strong focus on surgical simulation for training. Marco published in major international refereed journals and received awards for his contributions to haptic research, specifically in the derivation and calibration of physically-based models for surgical tasks involving hard tissues (bone deburring). He served as program committee member and reviewer for international conferences and journals.

Jose A. Iglesias Guitian is a Marie Curie Early Stage Researcher in the Visual Computing group of CRS4 (Center for Advanced Studies, Research and Development in Sardinia). He obtained his master degree in Computer Science in 2006 at the University of A Coruna (UDC), Spain, discussing a thesis on the integration of real time animated characters inside The Empty Museum virtual reality system. From October 2004 and prior to joining CRS4 he was also a researcher in the Visualization for Engineering Architecture and Urban Design Group (VideaLAB) at the School of Civil Engineering of the UDC, where he worked on several projects related to Virtual Reality and visualization. His research interests include virtual humans, character animation techniques, 3D modeling and terrain rendering.

Jérôme Schmid is currently Ph.D. candidate at MIRALab and working on medical imaging. He is an engineer in Computer Science specialized in imaging and virtual reality. He obtained his master degree in 2003 at the Superior National School of Computer Science and Applied Mathematics of Grenoble (ENSIMAG), France. He worked more than three years in the field of medical imaging, at IRCAD Institute, France and at the Minimally Invasive Surgical Skills Centre of the Prince Of Wales Hospital, Hong Kong. His interests include image processing, segmentation, registration and augmented reality.