The 'Virtual Population': Detailed, Whole-Body Anatomical Models Based On Medical Image Data

Esra Neufeld[1], Marie-C. Gosselin[1,2], Dominik Szczerba[1], Marcel Zefferer[1], Niels Kuster[1,2]
[1]*IT'IS Foundation for Research on Information Technologies in Society, Switzerland,* [2]*Swiss Federal Institute of Technology (ETHZ)*

Correspondece: neufeld@itis.ethz.ch, 0041 44 2459698, Zeughausstrasse 43, 8004 Zurich, CH

Introduction

Numerical simulations involving anatomical models are increasingly employed to develop and optimize medical devices and treatments as well as to assess their safety and efficacy. To model the physical interactions and biological processes occurring in the human body, the model geometry, tissue properties and boundary conditions have to be known. Furthermore, it is often crucial to investigate the impact of anatomical differences between individuals in order to evaluate the resulting variations across a given population. For this, a wide range of representative, detailed and accurate models as well as the tools to manipulate these models (e.g., posing, morphing, voxeling/meshing) are required. A first set of anatomical models (the 'Virtual Family' [1]) has previously been developed jointly with the FDA, primarily for exposure assessment to EM waves. The development of a second generation of anatomical models is presented here in combination with a series of advanced tools that provide additional functionalities and are specifically designed to make use of the capabilities of those enhanced models. The improved set of anatomical models considerably extends the possibilities offered by the first generation and is generalized for a wider user community and a broader range of modeling tasks.

Methods

Image acquisition and segmentation: A series of healthy volunteers of average height and built were selected such that typical adults of both genders and children of different age classes (5-14 years old) are represented. Additionally, an obese and an elderly male were also included. MR images of the ten volunteers were acquired according to an optimized protocol to obtain an in-slice resolution better than 1mm, slice thicknesses smaller than 2mm, a good contrast (incl. special scans for vasculature) and acceptable noise. The image data were segmented, distinguishing between 80 and 200 different tissues and organs. For this a dedicated software was developed that allows coupling highly automated (e.g., improved k-means-based clustering, competitive fuzzy connectedness) with highly interactive (e.g., live wire, interactive watershed transformation, brush) segmentation methods, and that offers filters for noise reduction, hole and island removal, interpolation, etc. Dedicated routines for vasculature tree extraction from contrast-enhanced CT have been developed but the reconstruction of vessel walls still needs to be improved.

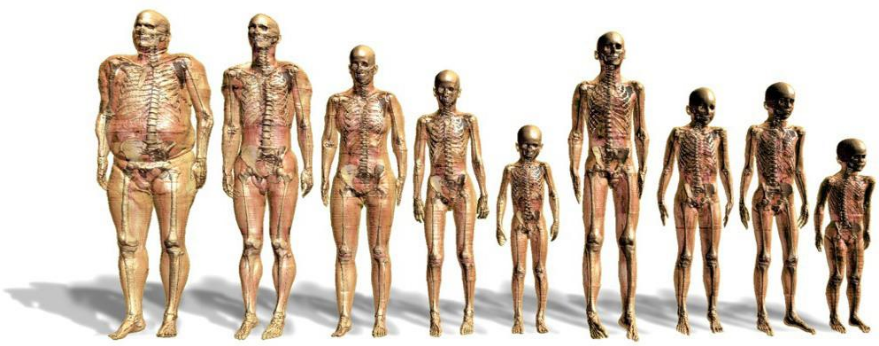

Figure 1: A selection of the Virtual Population models.

In addition to these models, pregnant women models at different gestational stages (3/7/9 months) were generated by incorporating available image data from fetuses into a modified version of the female adult model. Various non-human models were created as well (pig, dog, rats, mice).

Surface extraction: Routines were developed to extract triangle surfaces from the segmented image data, and to apply feature-preserving smoothing and surface simplification while maintaining topological compatibility (e.g., neighboring volumes share the same triangles on the interface) and avoiding self-intersecting surfaces. This resulted in 3D triangle-surface models of high fidelity.

Discretization: Routines allowing the discretization of the models for various numerical methods were developed. Those routines include homogeneous voxeling, voxeling on arbitrary rectilinear meshes (incl. conformal correction), and the generation of high-quality tetrahedral meshes. For the latter, two methods were implemented: an advancing front (with optimization) and a cut-cell octree (incl. smoothing) based method.

Morphing: To further parameterize the models with regard to BMI and thus extend the population coverage, a mechanical simulation-based approach was developed. FEM simulations were performed where the bones were treated as rigid, the fatty tissue was assigned a growing or shrinking force, and the remaining soft tissues were passively deforming. Meshes in the order of 100'000'000 elements were required to maintain the model quality, and high performance computing-enabled solvers capable of handling such problems had to be developed. In addition to this physics-based morphing approach, an interactive interpolation-based approach was implemented, where the user can move control points of various widgets to interactively define a deformation field.

Posing: To pose the models in different postures, two approaches were implemented: The first method uses a volume-preserving, skeleton- and influence-region-based approach from the field of computer graphics. This method allows articulating the models and real-time posing. The second approach uses mechanical simulations (similar to the previously described physics-based morphing) with actively prescribed bone movement and passively deforming soft tissue.

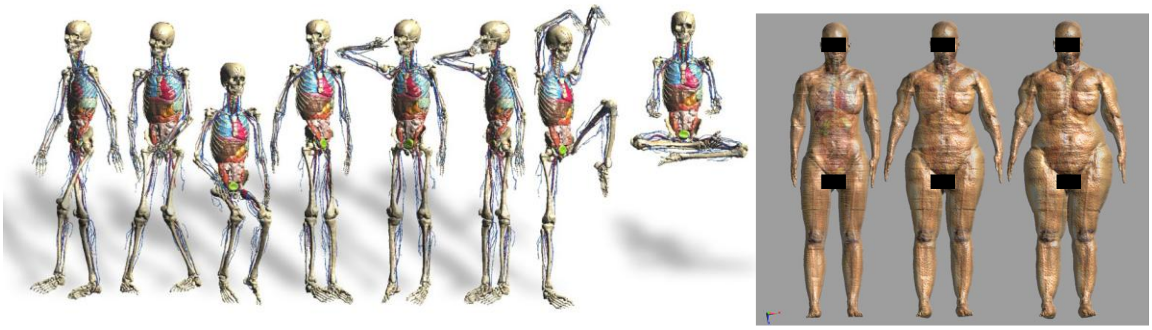

Figure 2: Interactive posture changing and physics-based morphing

Material properties: To provide the scientific community with the best possible tool, a literature-based public tissue parameters database was assembled. At the moment, only density, perfusion, dielectric and thermal properties are available (incl. information about spread of reported values in literature), but it is planned to compile data on mechanical and acoustic properties. An online user forum was established to discuss these properties and dynamically extend the database.

Results

The anatomical models have been used by a large number of groups for a wide range of applications. This includes for example the assessment of MRI safety in the presence and absence of active and passive implants, the development of novel therapies and applicators (e.g., for hyperthermia treatment of cancer, focused ultrasound, and RF ablation), the simulation of blood flow-induced surface potential changes in strong magnetic fields, the study of bone tumor resection and resulting mechanical stress, the improvement of imaging techniques (travelling wave and multi-transmit MRI), and the investigation of worker exposure. The models are one of the central components of the Sim4Life multiphysics simulation platform (see separate abstract) which allows simulating a wide range of physical and physiological phenomena involving the human anatomy. The Sim4Life platform permits multi-scale simulations, e.g., of blood flow (coupling of continuum models of perfusion with discrete pseudo-1D vessels, pipeline networks and full 3D CFD simulations).

Conclusions

A large number of high-resolution, detailed anatomical models are available, which have already been used for multiple relevant applications by over 250 groups worldwide. Methodologies have been developed that allow morphing, posing and BMI changes as well as discretization for various numerical methods. A continuously developing material database is publicly available. In addition, the project aims at collecting information on tissue inhomogeneity (e.g., perfusion and density maps) and boundary conditions (e.g., by coupling to lumped flow network models to obtain physiological inlet and outlet conditions for CFD). While new models are being segmented, the existing models are also subject to continuous improvement. Currently, the resolution and surface smoothness is being improved, the vasculature is being resegmented (to improve connectivity, resolution and shape), and refined models of specific sub-regions are being prepared. The goal is to extend the usefulness of the models beyond the current primary areas (EM, temperature, acoustics, ultrasound) to other physics applications (CFD, mechanics) and to enrich the models with a functional level (e.g., inclusion of neuron dynamics models, blood flow network). In the future, these models might be adapted to or enhanced with patient-specific data.

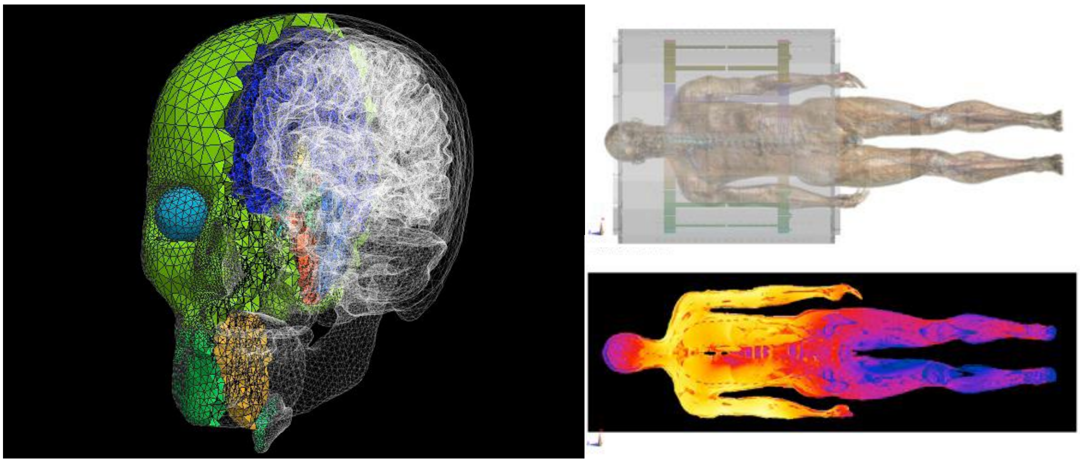

Figure 3: High-quality tetrahedral mesh for FEM simulations and voxel-based FDTD simulation (MRI exposure)

Acknowledgement:

Various components of this work have been supported by different organizations: CTI/EUREKA, MMF/GSMA, BfS, SNRP57, ZonMw. Various groups have contributed to the development: FDA, University of Houston, FAU, Siemens Medical Solutions, Erasmus MC, University of Zurich, ETHZ, AIT, SPEAG, ZMT.

References

1. Andreas Christ et al, 2010. The Virtual Family—development of surface-based anatomical models of two adults and two children for dosimetric simulations. Phys. Med. Biol., 55:N23.