FEMONUM: A Framework for Whole Body Pregnant Woman Modeling from Ante-Natal Imaging Data

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Abstract

Anatomical models of pregnant women can be used in several applications such as numerical dosimetry to assess the potential effects of electromagnetic fields on biological tissues, or medical simulations for delivery planning. Recent advances in medical imaging have enabled the generation of realistic and detailed models of human beings. This paper describes FEMONUM, a complete methodological framework for the construction of pregnant woman models based on medical images and their segmentation. FEMONUM combines several computer graphics methods, such as surface reconstruction and physics-based computer animation to model and deform pregnant women abdomens, to simulate different fetal positions and sizes and also different morphologies of the mother, represented with a synthetic woman body envelope. A set of 16 models, anatomically validated by clinical experts, is presented and is made available online to the scientific community. These models include detailed information on the utero-fetal units and cover different gestational stages with various fetal positions.

1. Introduction

Any digital simulation requires at least two models to run: a *physical* model describing the simulated phenomenon and a *geometrical* model representing the object onto which the phenomenon happens. For instance, in the particular case of digital dosimetry in human tissues, the physical model is an electromagnetic field propagation simulation and the geometrical model is a human body. Generating the latter can be done from real world bodies by the means of 3D medical images. In order to explore the various parameters of a simulation, physicists and other users need a segmented model, with different labels for different organs, and the ability to change the pose of the input digital body, i.e. animating it intuitively. They also need smooth models due to the various artifacts that arise during simulation on strong geometrical differential singularities and noisy areas, and may even require an adaptively re-sampled model to keep computation tractable. Ultimately, generating new bodies out of existing models or hybrid bodies, constructed from both virtual and real data, is what computer graphics can offer to develop further the repository of models to simulate and study uncertainty and variability of such simulations. To some extent, we demonstrate how computer graphics techniques – most particularly digital geometry processing and computer animation – can bridge the gap between medical images and physics applications. Moreover a number of technical elements have been reflected to medical applications, based on both our models and the resulting simulations (e.g. volume computations, interactive visualization).

Our work takes place in the context of medical imaging for digital modeling and focuses on the case of digital dosimetry for pregnant woman models to help physics discovering the real impact of radio waves onto humans. This paper summarizes our work to produce a set of pregnant woman models in standing position created using FEMONUM, a new modeling framework based on variational segmentation of medical images, 3D surface sampling and reconstruction as well as interactive physically-based computer animation for fetus and pregnant woman modeling. One of the key aspects of FEMONUM is its ability to convert data to different representations according to the task: while segmentation is performed on (anisotropic) 3D images, surface reconstruction from their sampling and mesh formats are generated automatically to enable affine transformations and non-rigid deformations based on interactive physics models or animation skeletons. The resulting mesh model may then be directly used for FEM simulation or converted to a discrete volumetric representation for FDTD methods.

FEMONUM combines interactive and automated steps, depending on the modeling task. The most important feature of this framework lies in the simulation of the intrinsic anatomical variability to generate a larger set of pregnant woman models, performing realistic deformations on an existing set. Our contribution – validated by obstetricians † – participates in the build up of deeper clinical knowledge of fetal morphology, anatomy and development of potential pathologies. These models were used in digital dosimetry studies performed by Orange Labs scientists ‡, measuring the fetus exposure to different types of electromagnetic fields and helped to establish a basis for answering large scale public health questions §.

† Hospitals: St Vincent de Paul, Port-Royal and Beaujon, Paris

‡ Orange Labs, http://www.orange.com/fr_FR/innovation

§ http://www.who.int/peh-emf/research/rf_research_agenda_2006.pdf (WHO Report)

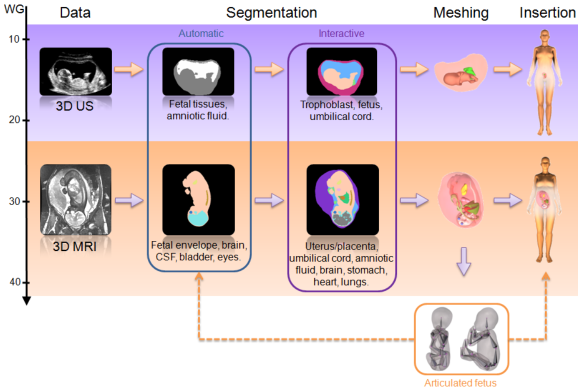


Figure 1: *Overview of the FEMONUM methodology. WG stands for weeks of gestation.*

2. A pregnant woman modeling framework

In this section we briefly describe the methodology used to create our set of pregnant woman models. This methodology can be mainly decomposed into four steps (Figure 1). Firstly, from medical images, a segmentation of different visible organs in the utero-fetal unit (UFU) is performed using automated or interactive tools. Secondly, in order to enable spatial transformations and non-rigid deformations, organ contours are extracted from the segmentations and represented as smooth meshed surfaces (by mesh reconstruction) avoiding undesirable singularities caused by "staircase" effects of naive direct meshing approaches. Thirdly, a fetal bone armature is modeled to enable arbitrary positioning of the fetus. Finally, physics-based deformations are applied to automatically insert the UFU inside a generic non-pregnant woman body in standing position, taking into account the variability of the muscle and the fat layers of the mother's body (variable for different morphologies). We refer the reader to [BAd*10] for a detailed description of this framework.

Utero-fetal unit segmentation To create realistic models of the UFU, we used medical images acquired with two modalities used in routine pregnancy follow-up: 3-D ultrasound (3-DUS) and magnetic resonance imaging (MRI) These two types of medical imaging modalities allow us to cover the three trimesters of pregnancy. Depending on the type of image, up to eleven uterofetal structures can be segmented (see Figure 2). The segmentation methods exploit in an original way prior knowledge about the two types imaging modalities and about the fetal anatomy, which is merged with image information. Details can be found in [AAB08, ABAB10, BAd*10]. A special attention is paid to the generation of topologically correct segmentations, which is important for the subsequent modeling steps.

3D surface mesh modeling For non ionizing dosimetry studies, the Finite Difference Time Domain method [TH00] is frequently used for numerical simulations on a regular spatial grid, with labeled anthropomorphic models which need to be smooth to avoid simulation bias on singularities. Naive direct meshing approaches generate "staircase" effects on the surface models, especially when MRI images with anisotropic resolution are considered. We derived a dedicated method for generating high quality triangular meshes from pre-segmented volumes of interest [ABB*09]. We adopt a generic approach by first extracting unorganized sets of points from the segmented volume data and then generating meshes by sampling smooth surfaces which approximate these point sets. The entire process is performed in a few seconds. The mesh reconstruction algorithm is composed of three main steps, illustrated in Figure 3. With this algorithm, a mesh of arbitrary resolution can be extracted from an arbitrary sparse point set. Consequently, the system enables to produce dense surface sampling and accurate subsequent deformations of the objects as well as robust rasterization within the original volume domain. As a result, we obtain a triangular mesh $\mathcal{M}$ sampled at arbitrary precision (controlled by the marching cube grid size), and a smooth surface defined from the input boundary samples extracted from the volume image data (Figure 4). Surface meshes for all segmented organs in Figure 2 were generated with our method. These mesh models can then be used for further interactive articulation, deformation and visualization.

Articulation of the fetus Articulating the fetus is desirable to change its position inside the maternal uterus and study the impact of the fetal position in dosimetry studies for example. In order to simulate various fetal positions, we propose to build a hierarchical armature for the fetus mesh. Similarly to a skeleton, it is composed of pseudo-bones placed inside the mesh, via registration of landmark points identified on the images, such as articulations, and associated to each vertex. We use inverse kinematic (IK) to easily define precise positioning of hands and feet. Moreover, it allows us to automatically limit the rotation of the limbs.

All the positions were validated under the control of medical experts. The articulated fetus armature was created using Blender [ble], based on the detailed segmentation of a particular MRI dataset.

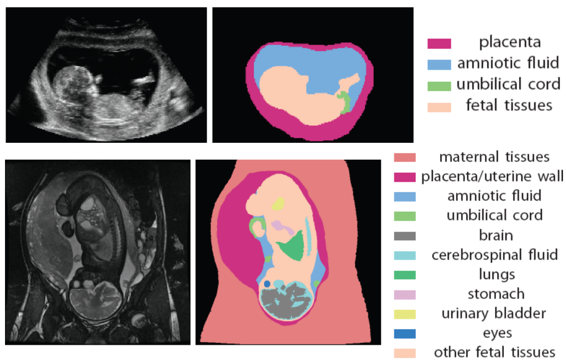


Figure 2: ***Top**: Slice of a 3D US volume of a fetus aged of 11 WG and its corresponding segmentation results. **Bottom**: Slice of a 3D MRI volume of a fetus aged of 33 WG and its corresponding segmentation results.*

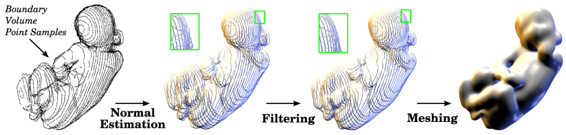


Figure 3: *Illustration on a fetus body during the modeling pipeline.*

UFU insertion and woman morphology modeling The field of view of the medical images used to extract the UFU includes only a part of the maternal body and the whole pregnant woman body cannot be generated from them. To overcome this limitation, we chose to use the virtual woman body called Victoria distributed by DAZ 3D Studio (`http://www.daz3d.com`). The Victoria model only represents a body envelope. Recognizing the difficulty to represent the displacement of organs within the maternal body during pregnancy, we have not included them yet. On the other hand, pregnant women differ in morphology, while carrying fetuses with similar sizes and weights. We focused on the representation of this intrinsic population variability by modeling the maternal fat and muscle layers as single homogeneous abdominal tissues, around the UFU. Figure 5 illustrates the muscle and fat layers representations. We also include a partial skeleton of the mother pelvis region, pre-segmented from a subject having the same height as Victoria (see Figure 6).

We have proposed an automated insertion method [dBA*10] of the UFU inside Victoria's body envelope to create generic pregnant woman models, not specific to an individual patient. To register the UFU inside Victoria, a rigid transformation is computed to minimize the distance between three landmark points (at the femoral heads and between the L3 and L4 lumbar vertebrae) identified in the images and pre-defined inside Victoria. Then, we have derived an interactive GUI to allow the user to deform the muscle and fat layers of the model. Both tissues are tetrahedrized, using state-of-the-art variational 3D meshing methods from CGAL [cga], during the interactive sculpting process to apply Finite Element Method based physical deformations. Finally, the UFU is inserted in the non-pregnant model, scaled down, rotated by 20° in order to simulate the standing position, and progressively scaled up to simulate the fetal growth with respect to the mother body envelope deformations. Collision detection between the UFU and the muscle layer is computed to control the physical deformations of the mother abdomen. All the physics constraints applied on the models are computed with the help of the open source medical simulation framework SOFA [ACF*07].

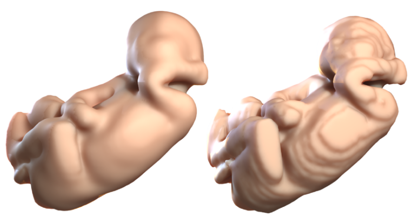
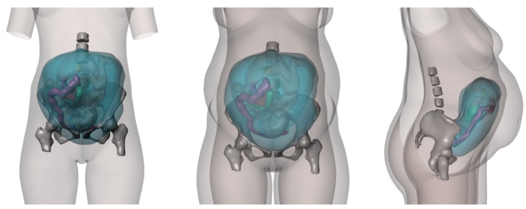


Figure 4: *Illustration on a fetus body of the proposed surface reconstruction (left) versus direct meshing from image segmentation (right).*

Figure 5: *Coronal and sagittal views of the muscle and fat layers represented, respectively, by brown and yellow tetrahedra.*

3. Results and validation

Sixteen pregnant woman models were generated at various stages of gestation and in supine/standing positions of the mother, using the proposed method. Four were built from 3DUS images (6, 7, 8 and 11 WG) and twelve from MRI images (from 24 to 33 WG). The 3DUS image datasets enabled us to create the first published pregnant woman models with embryo/fetus models built from medical images, acquired during the first trimester of pregnancy. Fetus models in cephalic, breech and transverse presentations were built from MRI images, thus covering the main configurations among the large variability of fetal positions [GCF*06]. Besides, different implantations of the placenta were also represented, since its location within the uterus varies greatly [KIN*07]. Finally, the first pregnant woman model embedding a UFU with twins was built. These different factors of variability are of particular interest since they have an influence on the distance separating the fetus from the maternal body outer envelope, and hence the sensitivity of the fetus to non-ionizing dosimetry. Two models are illustrated in Figure 6. All the models are described in detail on the web page of the project: `http://www.tsi.enst.fr/femonum`. They



(a) (b) (c)

Figure 6: *Views of two different pregnant woman models created using the same detailed UFU (33 WG), automatically inserted. (a) Coronal view without fat addition. (b) (c) Coronal and sagittal view with fat addition.*

are made available to the scientific community and can be freely downloaded for research purpose.

The models were anatomically validated by our clinical collaborators, who provided routine image data used to precisely measure fetal growth of individual organs. Regarding the segmentation, validation was performed by visual inspection on a number of representative images (for both US and MRI imaging modalities), showing a satisfying accuracy. This type of validation was considered sufficient for applications such as dosimetry studies, where the main goal is to achieve a good realism of the derived models.

4. Medical applications and conclusion

As discussed with our clinical collaborators, their are several applications for the generated pregnant woman models. They have already been exploited in different numerical dosimetry studies [BAH*09, HCA*10], performed by Orange Labs, to study the dose absorbed by body tissues from exposures to ionizing and non-ionizing radiations (see Figure 7). The results concluded that the fetus' exposure (always below the official norms) depends on the fetus morphology, stage of pregnancy and position. The composition of the mother's model, heterogeneous or homogeneous, and her position also induce an important difference on the whole body SAR (Specific Absorption Rate) in the fetus. These results have led our current research to focus on physics-based mother positioning and the insertion of higher details for the different tissues of the mother.

Echography training is another field to explore. A trainer system capable to change at will the UFU configuration and the woman's morphology, to simulate complex placenta positioning and fetal pathologies is of great interest. It can in particular enable students to get a more extensive training on the variety of cases that can be encountered in clinical practice. Finally, our models can be also used for delivery procedure simulation and planning. Obstetricians can visualize, in an easy and intuitive manner, complex image data which can be useful for visual inspection of potential pathologies and malformations, or incompatibilities with natural delivery. As confirmed by obstetricians, it also enables measurements of the fetus volume for more precise weight estimations, or of the size of the placenta to avoid any complication at the stage of birth.

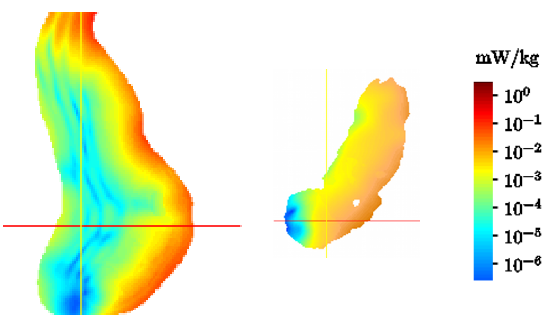


Figure 7: *Numerical dosimetry results showing the SAR repartition in the mother and the fetus bodies, for a particular exposure to an EM field.*

In conclusion, we have described the FEMONUM framework for whole body pregnant woman modeling from antenatal imaging data and we refer the reader to the dedicated webpage (http://www.tsi.enst.fr/femonum) for all related resources, including papers and models.

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