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A geometrical model of the pelvic system for patient-specific childbirth simulations

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Résumé — The aim of this work is to construct a geometrical model, suitable for personalized childbirth simulation with the finite element method. Linked to medical imaging data, the developed algorithms allow us to represent the main muscles and ligaments of the pelvic region in a semi-automatic manner. The model is parametric, from which patient-specific geometries can easily be instantiated, allowing to quickly launch simulations on new patients. We show the advantages of this model to existing workflows, and validate it with simulations.
Mots clés — Pelvic system, parametrized geometry, patient-specific modeling

1 Introduction

The advancement of medical imaging techniques and the availability of powerful computers make it possible today to obtain patient-specific information and to develop more and more complex numerical models, which allows approximating reality and anatomical complexity while having reasonable computation times. The mature techniques now allow to tackle a major societal issue : the risks associated with childbirth. In Europe, there are 5.1 million births per year [1]. About 20 % of births result in chronic pain, 5 % in urinary or fecal incontinence and almost 20 % in postpartum depression [1].

The patient-specific approach is more and more common in healthcare in order to permit a better understanding of physiology, to allow a personalized diagnosis of pathology or to help doctors in their medical decision. The numerical models on which this approach is based on are highly related to the specificities of the patient. Thus, certain models were parametrized by the characteristics of the patient [2, 3]. This way, they offer, on a case-by-case basis, truly adapted results. They also enable to take into account the influence of certain parameters, such as the size of the head of the fetus or the different birth scenarios. The study presented here focuses on the pelvic system and aims to develop models suitable for numerical simulation (smooth surfaces) and able to represent the geometry of a patient and particularly the pelvic muscle system.

Previous works on pelvic organ prolapse and childbirth, such as [4], [5] or [6] considered only the levator ani muscle (LAM) and the surrounding ligaments. These models focus on the deformations of the pelvic system in order to evaluate the risk of complications during delivery and require advanced and personalized anatomical models to predict tears [7].

A difficulty that arises during the reconstruction of the surfaces from MRI data is that on the images the muscles of the pelvic system are difficult to identify [8]. Hence, it is difficult to obtain an anatomically representative geometry of the levator ani and perineal muscles. Moreover, the manual segmentation of the muscles produces uneven surfaces, which need to be smoothed before being usable for analysis. By creating a representative geometry, we avoid the need of identifying the hardly visible muscles.

Our objective is to propose a highly automated workflow, which enables personalized childbirth simulations to be carried out quickly, acting as a risk-prevention tool. To reach this goal, a patient-specific geometry is constructed based on MRI images as a first step. The two main novelties of our work are i) the complete modeling of the perineum with all the muscles, and ii) the creation of a geometry, which is directly suitable for simulation.

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2 The geometrical model

The authors in [9] relied on point cloud measurement data to reconstruct the surface of the LAM. On the contrary, we build the geometry ourselves, which provides some advantages. On the one hand, we are able to generate a high-quality mesh, which is important for the solution of nonlinear problems. On the other hand, having an explicit geometrical description at our disposal, we have control over the mesh generation procedure (e.g. mesh adaptation). We are interested in modeling the urogenital and anal triangles. This geometric description is based on the work of our team in model reconstruction [2, 7]. The classical process by segmentation method allows to create a representative 3D model with nine anatomical structures (Fig. 1).

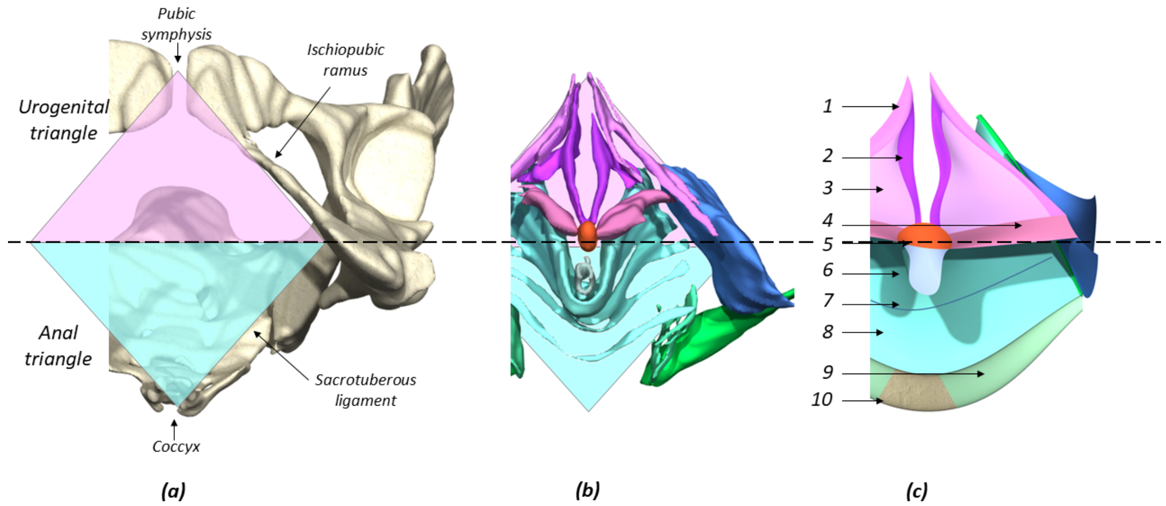

FIGURE 1 – Reconstruction of the pelvic region of a female patient based on MRI. (a) sketch of the urogenital triangle of the perineum and the anal triangles of the LAM, (b) illustration of the structures manually segmented by 3D Slicer (c) Representative surface model, where 1 – ischiocavernosus, 2 – bulbospogiosus, 3 – deep perineal muscle, 4 – transverse perineal muscles, 5 – perineal body, 6 – LAM/puborectalis muscle, 7 – LAM/pubococcygeus muscle, 8 – LAM/iliococcygeus muscle, 9 – coccygeus muscle, 10 – coccyx

Figure 2 shows our model, where several simplifications were made (cf. Fig. 1). This model allows the representation of the different heads of the perineum muscles and the LAM. The main results of the literature present more simplified models for the simulation of childbirth. To our knowledge, this is the most complete muscular model for the simulation of childbirth.

2.1 Parametric geometry

Our model is fully parametric, which provides high degree of automation : the geometry can be recreated in a matter of seconds for a new patient.

Another salient feature of our model is that it contains few variables and parameters. By variables, we mean inputs that the user can change based on some characteristic points of the anatomy of a specific patient. These variables are thus defined on the urogenital triangle with four points for the perineum in connection with anatomical zones, easily detectable on the images such as the bottom part of the pubis, left and right ascending ischiopubis ramus and the perineal body. For the anal triangle and LAM, the five variables are located at a higher level and are characterized by left and right superior pubic ramus, ischial spine and sacrum/coccyx joint. These nine control points allow us to identify the muscle attachment zones that will define the anatomical extrema of our model.

Parameters, on the other hand, are internal to the model, and they only depend on the variables.

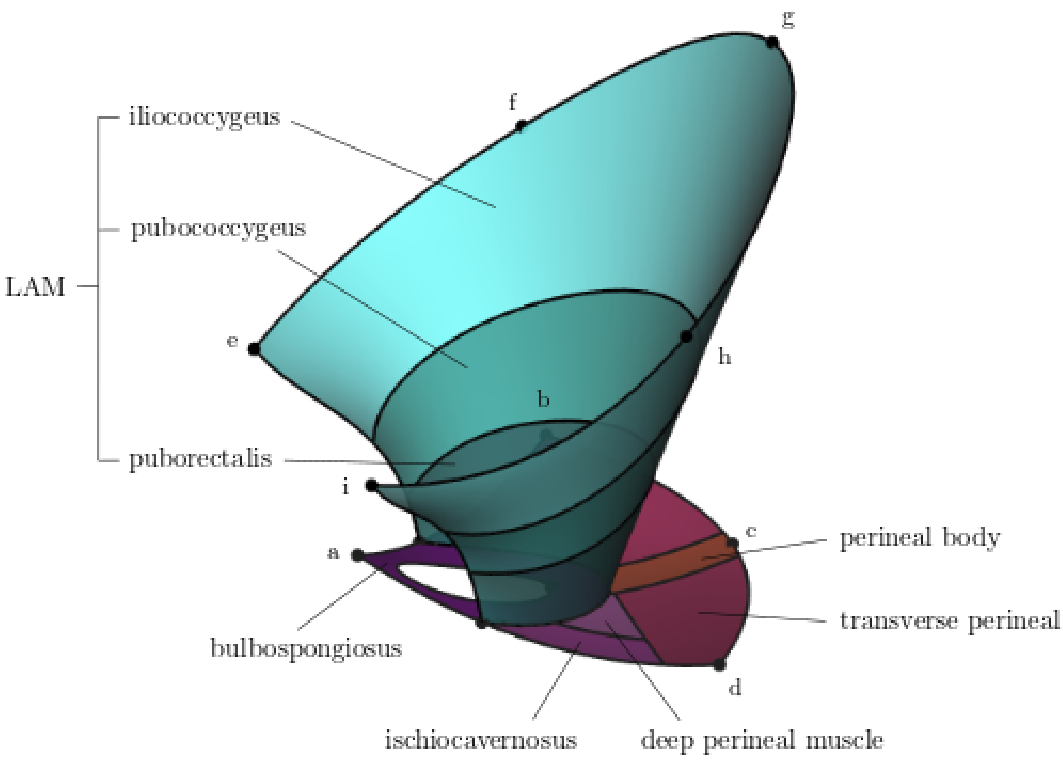

FIGURE 2 – Simplified geometrical model with the major muscles. The nine input variables denote the following : a – pubic symphysis, b, d – ascending ischiopubic ramus, c – perineal body, e, i – superior pubic ramus, f, h – ischial spine, g – coccyx

As a first step, the base surfaces of the perineum and the LAM were created. Next, the muscles were individualized to represent a whole structure, as it appears in Fig. 2.

Our model is hierarchic : the program first generates the perineum and its muscles, then the muscles of the levator ani, finally other muscles and ligaments that surround the LAM.

2.2 Parameter calibration

To be admissible, the parameters must satisfy certain geometrical constraints. However, these constraints still leave much freedom to the range in which the parameters can vary. To find appropriate values for the parameters, we calibrate them on patient-specific data. MRI images were taken of the pelvic region of ten females. The intensity values of the grayscale images (tomography slices) allows one to delineate the muscles of that region. However, tomography images consist of slices parallel to the axial anatomical plane, while the characteristic muscles are not easily identifiable in these planes. Moreover, if the distance between two consecutive slices is relatively large, tiny features are not visible. To alleviate these two issues, a tool has been written, which allows the definition of a cutting plane. This plane intersects the MRI slices, interpolating the grayscale values. In scientific visualization, this technique is referred to as volume slicing. We found two applications for this utility.

Comparing Fig. 1 with Fig. 2, it becomes evident that the bulbospongiosus muscle is not a shell-like structure but it has significant extension normal to the axial plane. By taking parallel slices normal to the base surface of the perineum, we can verify how good our simplification is.

Superimposing custom MRI cutting planes and the geometry helps in calibrating the parameters. An example is shown in Fig 3, where the cutting plane is created to pass through points a-b-d of the geometry.

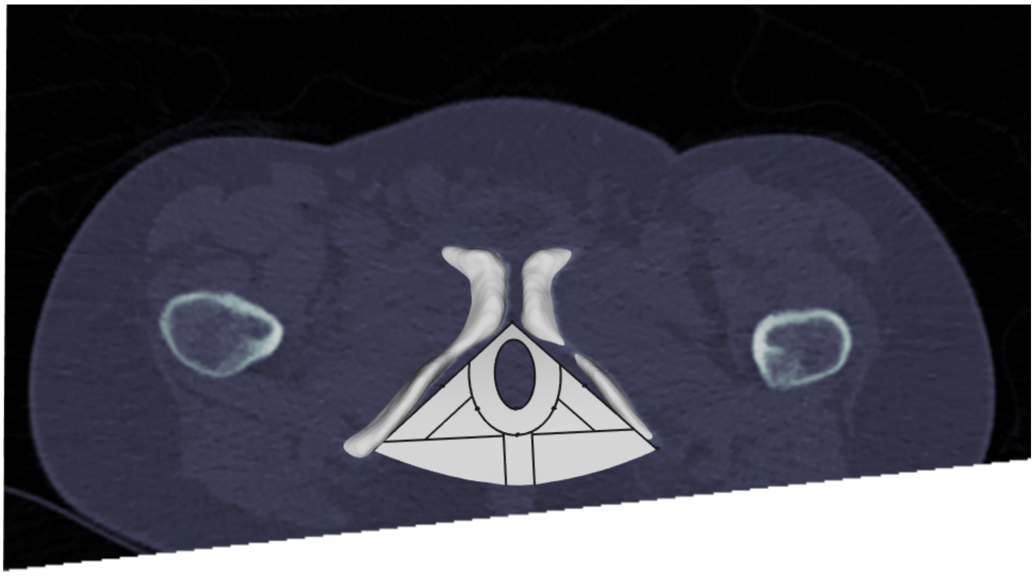

FIGURE 3 – Geometry of the perineum and the tomography data interpolated on a plane, shown in the same scene

3 Implementation

Our tools exclusively rely on open-source software. The geometry has been created without user intervention by harnessing the Python interface to FreeCAD, a cross-platform 3D parametric modeller. The tomography data, available as DICOM files, is handled by SimpleITK [10]. We integrated the MRI image slicing utility into FreeCAD, as shown in Fig. 3.

4 Discussion and future work

A parametrized geometry has been proposed to describe the female pelvic region. Our approach does not require the segmentation of the anatomical structures of the pelvic region. As a result, we do not need to cope with the difficult identification of the muscles. The parametric geometrical model decouples the geometry from actual patient-specific data and acts as a blueprint. By relying on a few variables, characteristic to a specific patient, this approach makes it easy to quickly instantiate patient-specific geometries. Finally, the explicitly defined geometry will allow other researchers to carry out computations for childbirth simulation.

It may turn out that the included muscles are not sufficient for the numerical model to appropriately capture the arising strains and stresses during childbirth. Due to the hierarchical build of the geometry and that the parameters are independent of each other, it is easy to add new elements (representing muscles and ligaments) to the existing geometry. To avoid the geometrical model being unnecessarily detailed compared to the simulation, or vice versa, enriching the geometrical and the numerical models should be done in tandem. This is an ongoing work.

In the future, if it turns out that muscles and ligaments are not sufficient, we can apply this parametric idea for bones as well. For the ten patients, the segmentation of the bones has already been performed, which resulted in a 3D model, stored as an STL file. Some extremities in this discrete geometry serve as input points for our simplified geometrical model. Using machine learning techniques to automatically extract the coordinates of these points from the MRI data would circumvent the manual segmentation step. This is a fruitful direction for further research, since it would make our workflow completely automatic.

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