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Chap 15: Uterus - Biomechanical modeling of uterus. Application to a childbirth simulation

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Abstract

This chapter focuses on the uterus, a major organ of the female reproductive tract. The uterus is a complex organ due to the evolution of its mechanical properties during the life. These modifications are due to the age, the hormonal changes, the number of pregnancies, and the fact that during any gestation, the size of the uterus is multiplied by more than four. The route of delivery (*i.e.* vaginal delivery *versus* cesarean section) may also impact the uterus mechanical properties. All these modifications make that the same woman will have different wombs during her life. Thus, the mechanical properties of the uterus are complex which involves some difficulties to propose an accurate simulation of its mechanical behavior.

In this context, we present in this chapter some researches made to simulate the mechanical behavior of the uterus. One of the interest of simulating its mechanical behavior is to improve the knowledge of its attachment system (*i.e.* ligaments binding the uterus to the pelvis wall). In particular, in this case, the goal is to evaluate damages that could occur during vaginal delivery in order to prevent or to improve treatment of uterine prolapse. The simulation of the mechanical behavior of the uterus could also lead to preventive strategies in order to prevent preterm birth caused by a short cervix. In this case, we have to understand which kind of anatomical changes lead to a cervical shortening.

We present two approaches to realize such a numerical simulation of the uterus: the first approach focuses only on the uterus (without considering others organs); the second approach simulates in real-time a vaginal delivery. This latter technique considers all the organs interacting during a childbirth but with a lot of

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simplifications. The aim is to obtain a correct global behavior and not necessarily an accurate simulation of each organ involved. These two approaches are complementary to achieve realist simulations and to understand the role of each tissue in the pelvic system.

Keywords: Uterus, vaginal delivery, 3D reconstruction, measurements of mechanical properties, Finite Element model, biomechanical simulation.

1. Introduction

In this chapter, we focus on the uterus which is a major organ of the female reproductive tract. In the literature, work has been presented to improve the knowledge of its anatomy and mechanical properties. In particular, the aim is to study the ligaments which bind the uterus into the pelvis. The idea is to evaluate their damages during vaginal delivery in order to prevent uterine prolapse or to propose adequate medical treatments if necessary. An other interest is to prevent preterm birth by a better understanding of the causes and the consequences of cervical shortening. One of the main difficulty remains the fact that the mechanical properties of the uterus vary according to age, hormonal changes, number of pregnancies and the fact that during any gestation the size of the uterus is multiplied by more than four. The route of delivery (*i.e.* vaginal delivery *versus* cesarean section) may also impact the uterus mechanical properties.

In the following, we will present two approaches to model and simulate the mechanical behavior of the uterus.

- To obtain an accurate simulation of the uterus behavior, some work [1, 2, 3] focused only on the uterus without considering the organs around it.
- We also present our work about a biomechanical simulation of a real-time childbirth delivery. In this work, the aim is to couple a numerical simulation to a physical interface in order to propose a complete simulator for medical training. Thus, our numerical simulation concerns the principal organs involved in a childbirth including naturally the uterus, organs of the reproductive tract and the fetus. The numerical simulation includes some simplifications in the modeling of each organ to obtain a realist global behavior that could be used to teach vaginal instrumental delivery.

These two approaches of work seem completely opposite, but they are complementary to obtain a realist simulation and for evaluating the pertinence of each

part of the model (for example to evaluate the role of each ligament connected to the uterus). In both case, the usual pipeline is used to realize such a biomechanical simulation. First of all, we have to extract the organ from medical images to create its geometrical representation (for example a mesh). We also have to measure its mechanical properties (like stiffness parameters) and to determine its constitutive law using experimentations. Then, a more or less complex physical model (usually based on the Finite Element method) is defined to reproduce its mechanical behavior according to experimental results obtained and determined boundary conditions.

For the following of this chapter, section 2 presents the anatomical and functional description of the uterus. Section 3 presents previous work proposed: (i) to reconstruct a geometrical model of the uterus from medical images, (ii) to measure its mechanical properties, and (iii) to simulate its mechanical behavior and connections to ligaments. We also present in this section some work performed to improve laparoscopic uterine surgery by adding on the laparoscopic images the hidden structures. Section 4 focuses on our work to simulate the descent of the fetus during a childbirth delivery in real-time. Then, to finish this chapter, section 5 gives a conclusion about the work proposed in the study of the uterus.

2. Anatomical and functional description of the uterus

Fig. 1 illustrates the position of the uterus: it is inside the pelvis, dorsal of the urinary bladder, and ventral of the rectum.

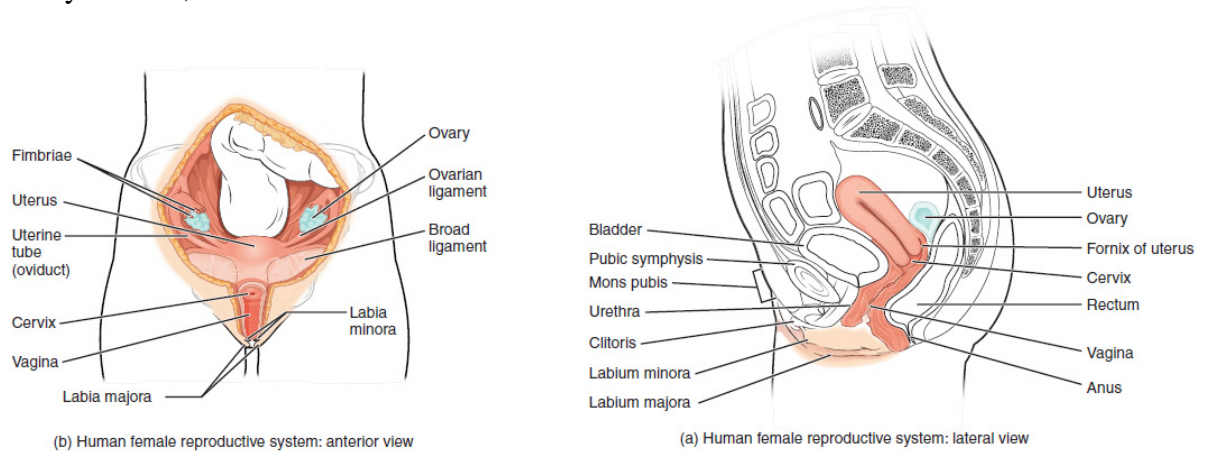


Figure 1: Structures present around the human uterus and relating to the human uterus [4].

Anatomical description of the uterus. The uterus is a fibro-muscular organ of the female reproductive system. It can be seen as a thin closed membrane in which the fetus develops during pregnancy. It is pear-shaped and it is about 7.6 cm long, 4.5 cm broad (side to side) and 3.0 cm thick. During the pregnancy, the size of the uterus will increase from 8 cm long to 35 cm. The uterus can be anatomically divided into two parts: the corpus or body and the cervix. The two opposite parts of the uterus are connected to the others organs: the cervix opens into the vagina, while the other part of the uterus is connected to the Fallopian tubes.

A complex structure of ligaments to fix the uterus to the pelvis. The uterus is a mobile organ which moves posteriorly under the pressure of a full bladder, or anteriorly under the pressure of a full rectum. The mobility is conferred to it by musculo-fibrous apparatus that consists of suspensory and sustentacular part. The ligaments that attach the uterus to the pelvic wall is a complex structure. The fundus is attached on each side (right and left) to a tripod structure: namely from anterior to posterior the round ligament, the Fallopian tube and the utero ovarian ligament. From a mechanical point of view, the Fallopian tube is a mobile structure and does not seem to interact significantly. The two others ligaments, round ligament and utero ovarian ligament, play a significant mechanical role.

When one follows the side of the uterus fundus, we find the peritoneal flap that does not seem to play any significant role. Lower, we find on each side the Mackenrodt ligament that goes around the uterine artery and the ureter. This ligament is a complex 3D structure. By going deeper in the pelvis one reaches the cervix and finds posteriorly the utero sacral ligament and anteriorly the vaginal cuff. Finally, the vaginal cuff is itself attached to the pelvic wall by the levator ani muscles and perineal floor muscles.

Modification of the uterus during pregnancy. Before pregnancy and during the first trimester of the pregnancy, the uterus is a two segments organ: the lower part being the cervix and the higher part being the uterine body. Both part are separated by a virtual border named the uterine "isthmus". Then, at 32 weeks of pregnancy the lower segment appears. This segment is between the cervix and the uterine body. At term, it will be a 10 cm high new part of the uterus. Thus, at the end of the pregnancy, the uterus will no longer be a two parts organ but a three parts organ (with the uterine body, the lower segment and the cervix).

3. The previous work published in the literature about the uterus

Several studies have been proposed to study the uterus during these last years [5, 6, 7, 8]. The final aims of these studies are not necessary the same, but it can be interesting to combine them to achieve a more accurate simulation of the mechanical behavior of the uterus. To discuss this previous work, we follow the classical pipeline which permits to create a biomechanical simulation. We also point out in this section, specific work performed to add hidden structures on laparoscopic images for assisting and improving laparoscopic uterine surgery.

3.1. Generation of the geometrical models

The first step to realize a biomechanical simulation is to construct the geometrical models for the considered organs.

Extraction from MRI data. Classically, the meshes of the organs are obtained after the segmentation of MRI (Magnetic Resonance Imaging) images. Then, as some important discontinuities can appear due to the resolution of medical images, the surface meshes need to be smoothed to obtain regular meshes which are needed for the computation of the numerical simulations. These two steps are performed using appropriate softwares.

Quality of the geometrical model. The level of details of the geometrical model varies according to the aim of the simulation. For a teaching tool for which the interactive time is an important matter, a simple geometrical model is chosen (*i.e.* it does not consider the suspensory ligaments of the uterus for example) with a limited number of nodes to decrease the computational time of the simulation. Fig. 2-3 present the geometrical model of the uterus proposed in [5, 6] respectively. Fig. 4 presents the FE models proposed in [9] to simulate a vaginal delivery.

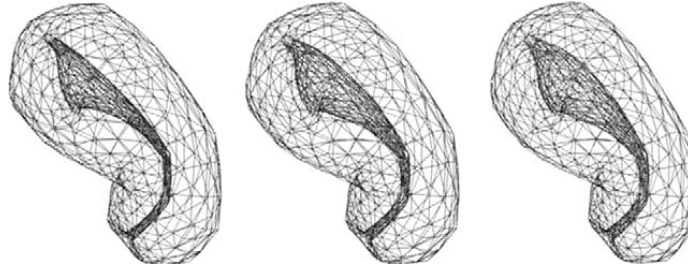


Figure 2: Geometrical model of the uterus used in [5] for real-time models.

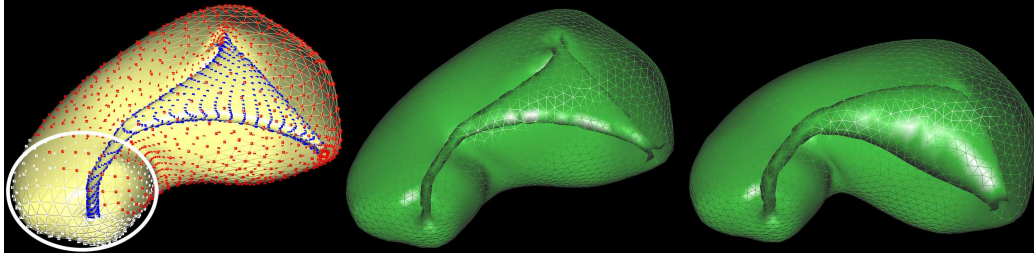


Figure 3: Geometrical model of the uterus proposed in [6].

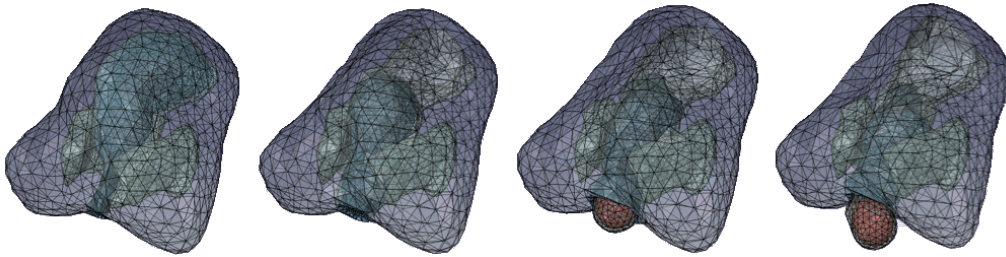


Figure 4: FE model of a vaginal delivery at different steps of the simulation. Images from [9].

For a simulation which focuses on the role of the different structures of the pelvic floor (in particular to investigate the role of the different structures on pelvic statics dysfunctions), a more complete anatomical model including all the structures is naturally requested. Fig. 5 presents the pelvic floor proposed in [10].

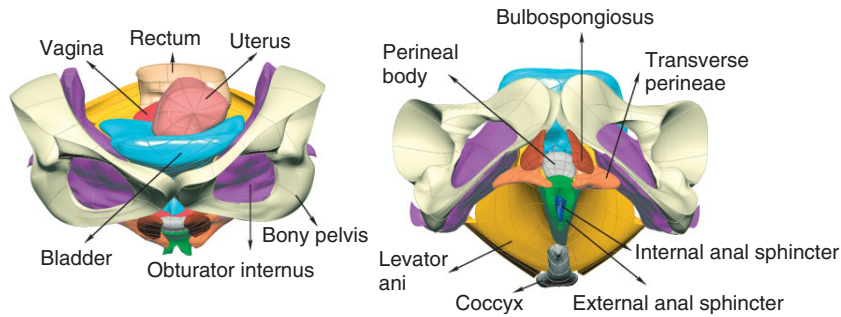


Figure 5: The pelvic floor model presented in [10] to simulate vaginal delivery.

For a numerical simulation that only focuses on the uterus, we need a complete geometrical model of the uterus with a high number of nodes. Fig. 6 presents a FE model of the uterus proposed in [5]. It has 20,000 elements.

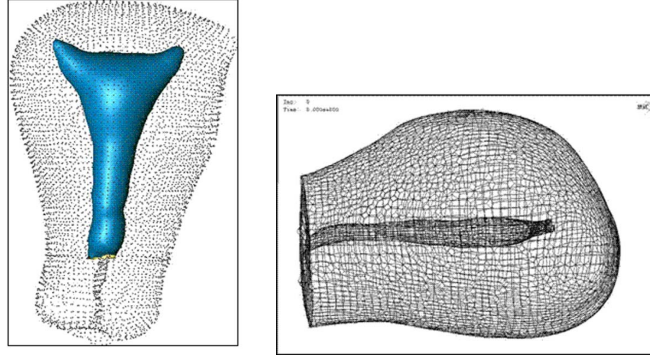


Figure 6: FE model of the uterus with 20,000 elements. It has been proposed in [5].

Manual reconstruction. The segmentation of the MRI data is still difficult for the pelvic system and it remains hard to extract all the details such as the ligaments connected to the uterus. In this case, the partial segmentations obtained from MRI data have to be completed using a manual reconstruction [11]. This step is performed according to anatomical descriptions. It concerns the vagina, the pelvic floor, floor muscles, ligaments (with some difficulties for some ligaments where there is no consensus) and the cervix (according to the considering dilatation step in the case of the realization of a childbirth simulation).

Variable anatomical models. The use of solid models to generate geometrical meshes facilitates the addition of elements (like ligaments) into these models. This is an important issue when all the structures are not visible in the medical images, or when we want to adjust the models according to educational criteria for a training simulator, or to better understand the role of each structure of the female pelvic system (which is illustrated in Fig. 1). For example, House [7] constructed geometrical models of the uterine fundus and cervix (which are presented in Fig. 7) to understand the deformation mechanisms which lead to cervical shortening during pregnancy. The construction of the geometrical models was performed in two steps. Firstly, solid models have been generated from MRI data using a solid modeling software. Secondly, the numerical models (appropriate for the simulation) have been generated by exporting the solid models in a finite element software. A 3D ultrasound technique applied on pregnant volunteer patients was also used to obtain imaging volumes.

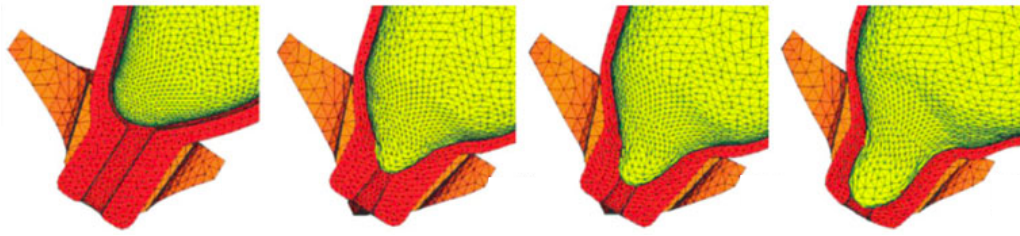


Figure 7: FE models proposed in [7] for numerical simulations of cervical function.

In the context of the development of a medical training simulator, an other challenge is to propose a wide variety of scenarios. These scenarios are based on models for healthy organs or pathological organs. For this purpose, in order to realize a training hysteroscopic simulator (which permits to visualize the inner surface of the uterus), Sierra presented a framework to generate variable models of the uterus anatomy [12, 13]. The method was based on a statistical description. The parameters of the geometrical model of the uterus concerned for example the dimension of the fundus, the dimension of the cervix and the length of the corpus (see Fig. 8). This work was completed by a method to generate pathologies found in the uterine cavity (such as leiomyomas and polyps) and a method to incorporate these pathologies into the model of the healthy uterus [14, 15].

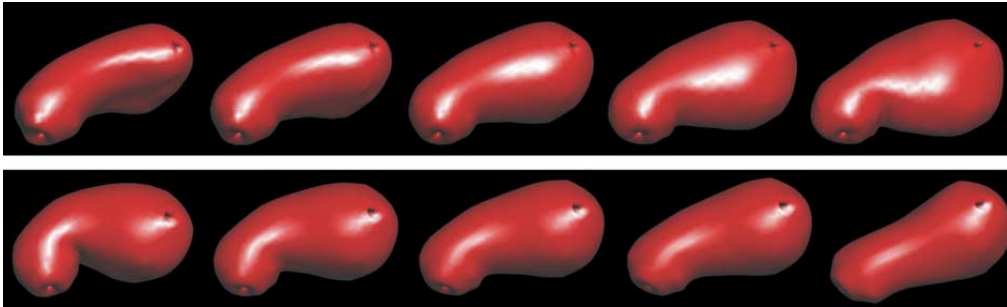


Figure 8: Generation of variable anatomical models proposed in [13].

3.2. Study of the uterus in laparoscopic images

In recent years, searchers have developed software for assisting and improving laparoscopic uterine surgery [16, 17, 18, 19]. The goal is to provide real-time Augmented Reality (AR), which allows the surgeon to see where important hidden

structures are located, such as the uterine canal, major blood vessels and myomas (see Fig. 9). This works by aligning (or *registering*) a pre-operative radiological image such as MRI or CT with the real-time laparoscopic video. Once done, anatomical structures from the pre-operative image are overlaid with the laparoscopic video in real-time. Currently AR has been developed for the treatment of myomas (also called uterine fibroids) using pre-operative T2 weighted MRI images [17]. A preliminary study of the clinical impact was published in [20]. To achieve this AR, three technical challenges were solved.

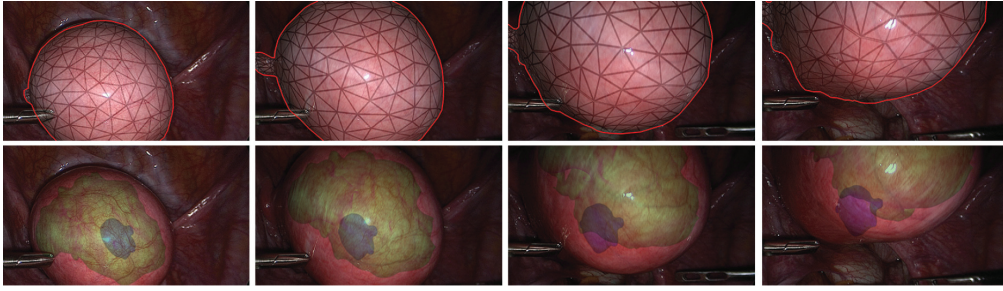


Figure 9: Registration between the uterus in a pre-operative MRI to intra-operative laparoscopic images (top), and visual augmentation (bottom) of two hidden myomas. Images from [17].

Reconstruction of the 3D model. The first challenge is to reconstruct a 3D model of the uterus and myomas from the MRI data (commonly known as *segmentation* or *delineation*). Because the pre-operative image is taken before surgery (typically several weeks before), this process does not need to be solved in real-time, and was performed semi-automatically with the aid of a human operator using open-source segmentation software [21].

Initial registration. The second challenge is to determine the change of shape of the uterus between the uterus in the pre-operative image and at the start of surgery (referred to as the *initial registration*). This is necessary to correctly register the pre-operative models with the laparoscopic video to account for soft-tissue deformation. For non-pregnant patients, soft-tissue deformation is caused by a number of factors including the patient’s lying position and rate of abdominal insufflation. The initial registration was solved as follows. We record a short laparoscopic video of the uterus from different angles (the *exploratory video*), by having a surgical assistant move the uterus with a cannula. From the exploratory video, the

3D shape of the uterus was reconstructed using a process called *Structure-from-Motion*. The registration was achieved using three complementary visual cues. The first cue was the 3D reconstruction: specifically, that the surface of the visible region of the pre-operative uterus model should align closely to the 3D reconstruction. The second cue was manually-annotated registration landmarks. A "registration landmark" is a point on the uterus that can be found in both the pre-operative MRI and the laparoscopic images. The junctions between the Fallopian tubes and the fundus were used, as these could be clearly found in both modalities. The third cue was the boundary contours of the uterus. Specifically, the uterus' boundary was manually annotated in the exploratory video, and the registration was made to align the pre-operative model's boundaries with the manually-annotated boundaries. Registration was achieved with a so-called *energy minimisation* approach. This involves encoding the registration cues as energy terms, and numerically minimizing the energy to obtain the correct registration. To achieve this, a model of deformation must be used. Here an approximate model was used (a 3D affine model), which is not a complex deformation model. However, a compromise had to be made between using a more complex model and being able to determine the model's parameters. The affine model was shown to provide a good approximation and its parameters could be determined reliably. Note that research has continued to make the initial registration fully automatic. In [19] a method to automatically detect the uterus and the Fallopian tube junctions in laparoscopic images was proposed. In [18] a method to automatically segment the uterus in laparoscopic images was proposed. The segmentation gives the boundary contours of the uterus, which saves considerable time for a human annotator.

Alignment of the pre-operative images with the laparoscopic video. The third technical challenge to achieve AR is to update the initial registration for each new laparoscopic image and to overlay the myomas onto the laparoscopic image. Unlike the first and second challenges, this one needs to be real-time. A simplifying assumption was made, which was that the update could be modeled with a 3D rigid transform. This transform can account for changes of the laparoscopes position and global changes of the uterus' position, but it cannot account for significant soft tissue deformation. This was acceptable by instructing the surgeons to not significantly deform the uterus with surgical tools whilst AR was active. A robust, automatic solution was found that worked reliably for long durations (5 minutes or more) [16]. This operated at approximately 20 frames per second on a standard workstation PC and could handle occlusions from instruments and the uterus going out of the field-of-view. For each laparoscopic image, the registration

was used to give the 3D position of the myomas in the laparoscopes field-of-view. The myomas surfaces were then rendered from the laparoscope's viewpoint, and the render was blended with the real laparoscopic image. The blend was done to give the impression that the uterus was semi-transparent and the myomas could be seen inside. Fig. 10 presents the registered models obtained in [16].

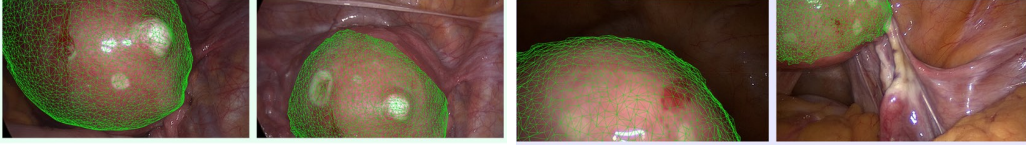


Figure 10: The registered models obtained using WBMTR (Wide-Baseline Multi-Texturemap Registration). Images from [16].

The several techniques proposed in these papers may be used in the context of MRI data of pregnant patients to improve the extraction and the reconstruction of the uterus and the others tissues around it.

3.3. Assessment of the biomechanical properties of the uterus

To simulate the mechanical behavior of an organ, we also have to perform some experiments *in vivo* or *in vitro* on the tissues to determine its stress-strain relationship, that is a specific force per unit area (stress) *versus* a specific displacement from initial length (strain). This relation is the constitutive law of the organ. It characterizes the mechanical behavior of the deformable object. This mechanical behavior can be linear, non linear, isotropic, anisotropic, heterogeneous, viscoelastic or viscoplastic. We also need to determine the mechanical parameters associated to the constitutive law. Their exact values are extremely difficult to determine and they may vary by one or several order of magnitude, depending on the protocol used for their estimation. Moreover, the values obtained *in vitro* are usually inappropriate, and it is often difficult to perform the experiments *in vivo*.

Several techniques to perform the measurements. In 2014, Mazza [8] presented a review on research made to characterize the biomechanical and microstructural properties of the cervix during pregnancy. This kind of research is made in order to prevent preterm delivery, with an established correlation between the stiffness of the cervix and the risk of preterm delivery. Three methods were privileged for these measurements. The first method, called elastography, consists to assess the deformation of the organ by measuring its displacement when a force is applied

on it. The corresponding displacement of the organ is quantified by tracking the position of a large number of points of the organ during the motion. We obtain an elastogram corresponding to a color map indicating the difference between soft regions (*i.e.* with large displacements of the points) and hard regions (*i.e.* with very small displacements of the points) of the deformed organ. The second method consists to compress the tissue using ultrasound until no further deformation can be observed to determine its "maximum deformability". The third method consists to use an aspiration device to determine *in vivo* the stress-strain curve of the tissue.

Impact of the protocol used. In 2008, Myers [22] proposed a study to establish a stringent protocol to collect data in order to measure the mechanical properties of cervical tissue under different loading modes (for example, in tension, confined compression, unconfined compression). The study was performed for non-pregnant and pregnant patients. To briefly sum up, a non linear behavior was observed for the cervical stroma. Moreover, one of the interest of this paper is to draw attention on the large discrepancies in the results presented in the literature. Thus, a lot of precautions are necessary to ensure the repeatability of the measurements performed on a tissue to obtain useful values for the numerical simulation and to characterize with accuracy the mechanical properties of the tissue.

Results obtained from an aspiration device. In 2006, Mazza [23] presented a study performed with an aspiration device to characterize the mechanical properties of the human uterine cervix *in vivo*. The average values of the stiffness parameter vary from 0.095 to 0.24 bar/mm. The experiments have been performed on eight patients, aged from 47 to 69 years and having had 1 to 4 births. As during the pregnancy, the uterus undergoes significant changes [24], Bauer [25] presented another study in 2009 performed with the same device but on pregnant women (between 21 and 36 weeks' gestation). Stiffness values varied between 0.013 and 0.068 bar/mm. We can note that the tissue of non-pregnant patient is significantly stiffer than tissue of pregnant women. These results remained the same for both tension and compression experiments. In 2013, Badir [26] presented a novel procedure for the realization of measurement on the cervix during gestation. This procedure was also based on the pipette aspiration technique. As the measurement is fast and it does not caused any pain, it can be used as routine control during the pregnancy. Thus, it permits to obtain a large amount of measurements and it permits to follow the evolution of the biomechanical properties during the gestation.

To sum up, a lot of studies have been performed on the cervix biomechanical properties. Obviously, this part of the uterus was studied because of the estimated relation between cervical stiffness and the risk of preterm. The techniques and protocols of measurement used are more and more precise and aim to ensure the repeatability of the measurements. But it seems still difficult to assess with high accuracy the biomechanical properties of the tissues. Indeed, the measurements naturally depend on many parameters such as localization of the assessment, degree of cervix lubrication, type of protocol used to move the tissue (mainly by applying a force on it), maternal age, number of pregnancies, or term of pregnancies.

3.4. The Finite Element models proposed to simulate the behavior of the uterus

Once the geometrical models of the organs created and their mechanical properties studied, we can create the corresponding physical model in order to perform the numerical simulation. This physical model is more or less complex according to the aim of the numerical simulation. To achieve an accurate simulation, a Finite Element model is generally chosen with a constitutive law in agreement with that of the organ (classically hyper-elastic and anisotropic for tissues). To reduce the computational time, a simpler law can be selected but at the expense of precision. We also have to define the boundary conditions of the organs involved in the simulation as well as their interactions.

Electrophysiological and molecular mechanism of uterus. Sharp [27] proposed a review on the computer models published to study the uterine activation during labor. The models were divided in three categories: (i) models of uterine electrophysiology and propagation, (ii) models of the molecular mechanisms that initiate the labor, (iii) and biomechanical models of labor. Then, the review focused only on electrophysiological and molecular mechanisms activating labor. This kind of research seems distant from work on biomechanics models but it can be interesting to follow the results obtained with this approach.

Modeling of the uterine pressure. In 2010, Li [28] proposed a review on finite element models developed to simulate mechanics of vaginal delivery. The described models concerned in particular the modeling of the pelvic floor (including the levator ani muscles) and the fetal head. The aim is to be able to simulate both the deformation of the head and the pelvic floor. The most challenging aspect of childbirth modeling is to take into account all the forces applied on the organs: the expelling forces induced by the uterus and the abdominal muscles. Those forces

were approximated by applying kinematic boundary constraints on the fetal head. This strategy avoids to explicitly simulate the complex mechanism of the uterus which is not the primary aim of those simulations.

Finite Element models of a pregnant woman. Some papers focused on the modeling of the pregnant woman to study injury mechanisms in car crashes [29, 30]. The aim is to propose a specific safety system to decrease the risk of fetal loss. A simulation based on a Finite Element model was performed. The geometrical model of the uterus was extracted from MRI data of a pregnant woman at nine month of pregnancy. Then, the gravid uterus has been incorporated into the HUMOS (HUMAN MOdel For Safety) model which is a Finite Element model of a complete human body in driving position. The mechanical behavior of the uterus was modeled as a hyper-elastic Ogden material and the amniotic fluid was represented using a Euler model. Thus, the anisotropic behavior of the uterus was not considered in this study. For the validation of the simulations, the PMHS (Post Mortem Human Subjects) approach has been improved by inserting an artificial uterus made in silicon into a woman body. Four belt loading tests were realized and compared to the numerical response of the model in similar conditions. Preliminary results obtained were in agreement with the experimental curves. In these tests of car crash, the uterus did not sustain high strain.

Recently, a biomechanical model of the pregnant pelvic system has been proposed in [11]. The aim was to study the constraints applied on the pelvic components during childbirth to improve the knowledge about uterine prolapse. The pelvic system proposed (see Fig. 11) included the muscles, ligaments and pelvic organs. The geometrical models have been constructed from MRI data with a manual reconstruction of non visible structures. These manual reconstructions have been made according to anatomical descriptions. The ligaments were also added to the geometrical models with some difficulties for ones for which no consensus is established. Moreover, several models of the fetal head and uterus have been used to simulate the vaginal delivery. Thus, the volume of the geometrical models have been changed in order to measure their corresponding impacts on the ligaments. The properties of the tissues were based on previous work performed by the same team [31, 32, 33, 34] and the tissues were modeled with an elastic linear behavior using the shell finite elements. As boundary conditions, the pelvic bone and uterine fundus were fixed; the muscle floor was fixed to the pelvic bone. Then, the simulation of childbirth was performed by imposing a trajectory of the fetal head during its descent. The simulations enabled to measure the deformation of the uterosacral ligaments during the vaginal delivery. Some improvements

have to be made in order to consider the hyper-elastic and anisotropic behavior of the tissues. Nevertheless, we can note that this pregnant pelvic system is the most complete proposed in the literature. Thus, we can hope that, once the improvements performed, this pelvic system (which includes the ligaments connecting the uterus to the pelvis) could improve our knowledge of damages sustained during a vaginal delivery.

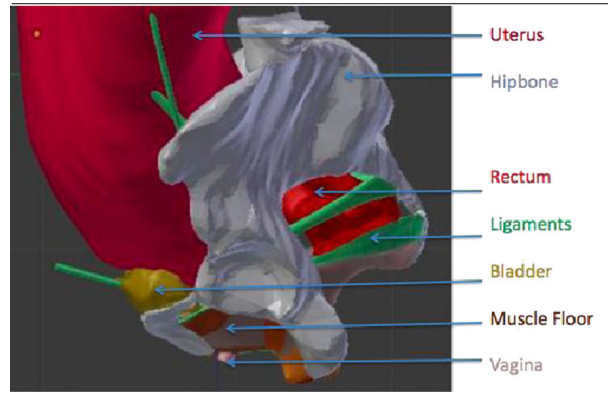


Figure 11: The geometrical model of pelvic system (proposed in [11]) of a pregnant woman.

Finite Element models of the uterus. In 1975, Mizrahi and Karni [1] have presented a mechanical model of the uterus. As the thickness of the uterus is small in comparison to its two others dimensions, they modeled the uterus as a thin closed shell. They also treated the constraints involved by the ligaments attachments and the cervix. For the definition of the shell model, they considered that the uterine muscle has no rigidity in bending and that the single stiffener is the cervix acting as a tensile anchoring ring. Moreover, the displacements of the cervix have been put to zero for a single contraction and constant during the second stage of labor when the cervix is fully dilated. They also assumed that the volume bounded by the uterus is constant during the deformation due to the incompressibility of the inter-uterine fluid. In [2], they presented a study to improve the anisotropic behavior of the uterine muscle. It is difficult to evaluate the results obtained as there is no comparison between the results obtained by simulations and real *in vivo* experimentations.

More recently, an other Finite Element model (FEM) of the uterus was proposed in [3] to reproduce realistic mechanical and physiologic behaviors of hysteroscopy. The corresponding surgical procedure consists to distend the uterus

with the accumulation of watery fluid in order to easily access and to well visualize the uterine cavity and fallopian tube. The volumetric mesh used for the hysteroscopic simulations was composed of tetrahedra with a total of 56,000 nodes. The mechanical behavior defined was based on a polynomial strain-energy function proposed by Kauer [35]. Moreover, as boundary conditions, the cervix was fixed at the beginning of the hysteroscopy. Then, a pressure of 20 kPa was applied into the uterine cavity. But due to a lack of experimental data, it was difficult to prove the accuracy of the model for various loading situations. We can note that these simulations required about 17 hours of CPU time.

Real-time simulations of the uterus. Some work focused on the implementation of mechanical models of the uterus that run in real-time [36, 37, 38, 12, 6, 5]. The idea is to propose training simulators for hysteroscopic or laparoscopic surgery. The challenge is to make adequate simplifications of mechanical models to develop pertinent simulators reproducing realistic simulations. In this context of real-time simulation, the accurate FEM proposed in [3] was combined to a Free-Form Deformation (FFD) technique [6]. The idea is to register accurate responses of the tissue model to different fluid pressures in order to use these results during the real-time simulation. For this, some hypothesis were made to simplify the model: the interactions made on the uterus with the simulator were restricted to the fundus of the uterus; the boundary conditions of the uterus did not change during the intervention; the cavity of the uterus should not endure extreme modifications (*i.e.* the topology of the uterus was supposed not to change). Thus, the FEM [3] was first executed as precomputations. Then, during the use of the simulator, the results of the FEM simulation were loaded and used to compute in real-time the response of the tissue according to the interaction applied. For this purpose, a simple linear interpolation was performed to compute the new positions of the mesh. Furthermore, a fluid simulation (based on the Navier-Stokes equations) was also performed to simulate the fluid flow in the cavity in order to increase the simulator realism. In future work, the authors will plan to use the GPU to simulate the fluid with an higher accuracy. Moreover, the FEM simulation used for the computations will be improved to simulate the non-linear and anisotropic behavior of the myometrium.

4. Our childbirth simulation in real-time

Our work focused on a childbirth simulator for training of medical gestures during vaginal delivery. In this context, we proposed a biomechanical simulation

of the descent of the fetus during the second step of the labor. The challenge was to obtain a real-time simulation. This was achieved by making a lot of simplifications in the modeling of each organ involved, since it is not possible to combine an accurate simulation of each organ. Thus, our aim was to obtain a realist trajectory of the fetus induced by the interaction of each organ despite their simplifications. All the details of this work can be found in [9].

The simulation was composed of the fetus, uterus, pelvis and abdomen of the parturient woman. During the childbirth process, the uterus is one of the most important organs of the pelvic system since it supports all the efforts applied by others organs. Thus, the uterine contractions associated to the voluntary efforts of the parturient woman induce a pressure on the fetus, pushing it into the birth canal. Throughout the descent of the fetus, the inner walls of the uterus are flattened against the fetal body, decreasing the uterine volume progressively. The height of the uterus at the end of the childbirth process is approximately one third of its height before the beginning of the labor.

4.1. Generation of the geometrical models

The geometrical models of the organs have been generated from MRI data for soft tissues and CT-scan data for the bony parts of the parturient. For this, the ITK SNAP software has been used for the segmentation of the medical images. Then, the ReMESH software has been used to simplify the dense mesh of each organ obtained after the segmentation. Finally, the volume mesh of each organ has been generated by importing the surface mesh in the Abaqus Finite Element software. The 3D mesh has been generated thanks to the use of the tetrahedralization algorithm based on the Delaunay technique.

Fig. 12 presents the geometrical model of the uterus used in the simulation. At the left, the figure presents the initial model obtained from MRI data. It was composed of 42,811 nodes. At the middle and the right, we can see the final 3D model of the uterus obtained after smoothing the initial model. It includes the uterus body, the cervix and the vaginal canal. The cervix has been manually constructed from anatomical description. This final 3D model of the uterus was composed of 7,489 tetrahedra.

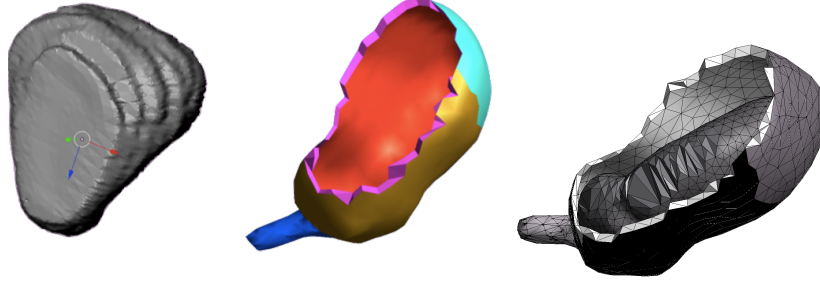


Figure 12: The geometrical model of the uterus. At the left, the data (with 42,811 nodes) generated from MRI data. At the middle and the right, the 3D model (with 7,489 tetrahedra) generated after smoothing. The cervix has been manually constructed.

4.2. Biomechanical modeling of the uterus and forces

FE model of the uterus. For the biomechanical modeling of the uterus, the work of Mizrahi [2] showed that the behavior of uterine muscles changes during the childbirth, with an isotropic behavior in the early stages of childbirth and an anisotropic behavior at the end of the labor. To simplify our model, we considered only an anisotropic behavior for the uterine membrane and we modeled the uterus as a Neo-Hookean material. The strain energy per unit of reference volume is then defined by:

$$W = C_{10} (\bar{I}_1 - 3),$$

with $C_{10} = G/2$ where $G = E/(2(1 + \nu))$ is the shear modulus, E is the Young modulus, ν the Poisson ratio, and \bar{I}_1 the first deviatoric strain invariant defined as $\bar{I}_1 = \bar{\lambda}_1^2 + \bar{\lambda}_2^2 + \bar{\lambda}_3^2$ with $\bar{\lambda}_i$ the deviatoric stretches defined by $\bar{\lambda}_i = J^{-\frac{1}{3}} \lambda_i$, where J is the total volume ratio and λ_i are the principal stretches. For our model, we chose a density of 950 kg/m³ and $C_{10} = 30$ kPa [23, 25].

Modeling of the uterine contractions and expulsion forces. Instead of modeling the muscle behavior of the uterus, we modeled its consequences which are the uterine contractions. These forces are applied on the uterus during labor and are involuntary. They occur 3 or 4 times every ten minutes (which corresponds to one period). The average duration of a contraction is 90 seconds and its amplitude varies between the "base tonus" (pressure prevailing in the uterus caused by strong deformation) and the intensity of the uterine contractions. The difference between these two amplitudes (called "true intensity") corresponds to the effective thrust forces of the uterine contractions applied on the uterus during the delivery [39]. Fig. 13 illustrates these uterine contraction forces.

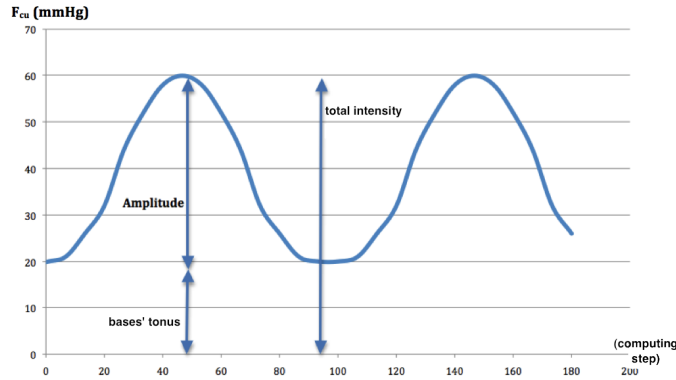


Figure 13: Uterine contraction forces (mmHg) *versus* time.

This thrust is insufficient to make the fetal delivery by deleting the effect of the pelvic muscles which retain the fetus. Therefore, during the second stage of labor, the parturient woman must voluntarily produce a series of significant abdominal thrusts (called "expulsion forces"). These expulsion forces are caused by the contraction of the abdominal muscles (which are normally located in the lower abdomen, but lifted by the presence of the fetus) and the diaphragm. Although, these expulsion forces are about 4 times higher than the uterine contractions, they have to be synchronized with the uterine contractions. Fig. 14 illustrates this fact: to exceed the threshold necessary to overcome pelvic floor resistance the addition of these two forces are necessary.

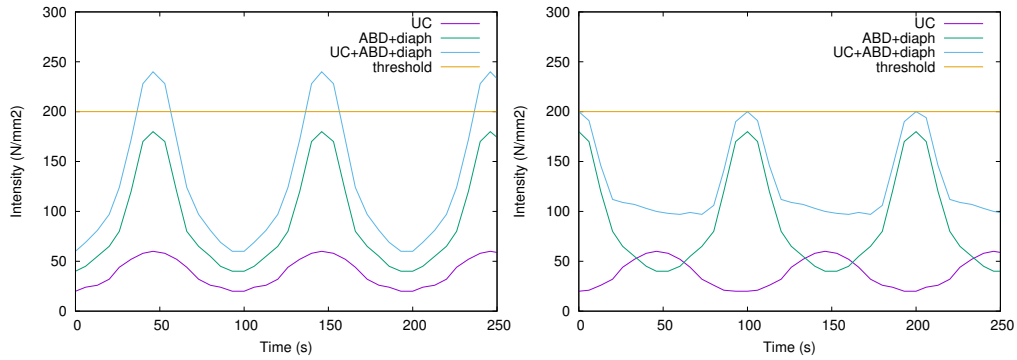


Figure 14: Evolution of the uterine forces: synchronized forces (left) and unsynchronized forces (right). The line corresponds to the threshold for the expulsion of the fetus. *UC*: uterine contraction; *ABD*: abdominal forces; *diaph*: diaphragm forces.

Thus, the combination of the uterine forces and the expulsion forces applied

on the uterus shrink the uterine walls. This fact causes a force that expels the fetus into the vaginal canal. Consequently, in our simulation, we applied periodically the uterine contraction forces and the expulsion forces on the uterus to simulate this behavior.

For the boundary conditions of the uterus, we limited the displacements of the vaginal canal in the transverse plane (allowing the opening and closing of the vaginal canal while avoiding the descent of the organs) and we connected the displacement field in the lower part of the uterus to the pelvis (instead of modeling all the ligaments connected the uterus to the pelvis). Fig. 15 presents an illustration of the boundary conditions and the parts of the uterus where were applied the forces: in gray, the part of the uterus on which the uterine contractions were applied; in green, the part of the uterus on which the uterine contractions and the maternal expulsion forces were applied; in red the part of the uterus fixed to the pelvis.

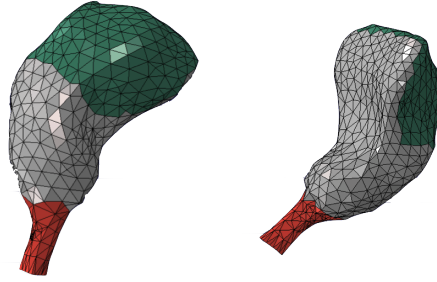


Figure 15: The parts of the uterus where were applied the forces and the boundary conditions used for the simulation: the uterine contractions (green); the uterine contractions and expulsion maternal forces (gray); the part of the uterus fixed to the pelvis (red).

4.3. *Contacts between the uterus and the others organs involved in the simulation*

In our simulation, the uterus is the interface between the maternal abdomen and the fetus. Consequently, the thrust and the fetal movement were performed through the uterus. To model the contacts between the uterus and the others organs involved, we considered as a frictionless contact, the interactions between the uterus and the fetus (due to the fact that the amniotic fluid has lubricated the internal walls of the uterus). We also considered as a frictionless contact, the interactions between the uterus and the maternal abdomen (due to the viscous contact provided by the peritoneal fluid between all the organs within the great

peritoneal cavity). Fig. 16 presents the boundary conditions of the organs modeled in our simulation of vaginal delivery.

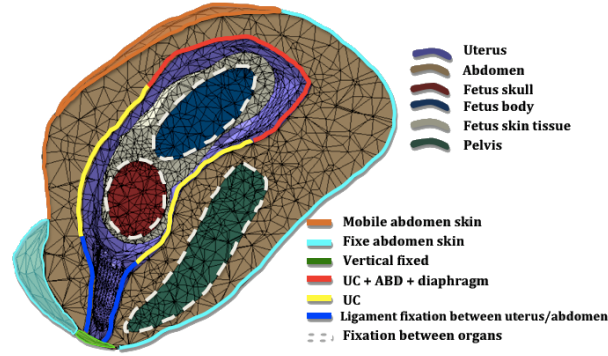


Figure 16: The modeled organs and their boundary conditions. *ABD*: abdominal forces.

4.4. Mechanical behavior of the uterus during the simulation

The simulation was performed by using the Abaqus FE software developed by Dassault Systems. We used the Euler explicit scheme, with 250 time steps. The duration of our birth simulation was 32 minutes, requiring 8 contractions to expel the fetus (with an average fetal head velocity of 0.09 mm/s). The execution time was 45 minutes on an Intel PC Core duo, 2.4GHz, 6 GB RAM.

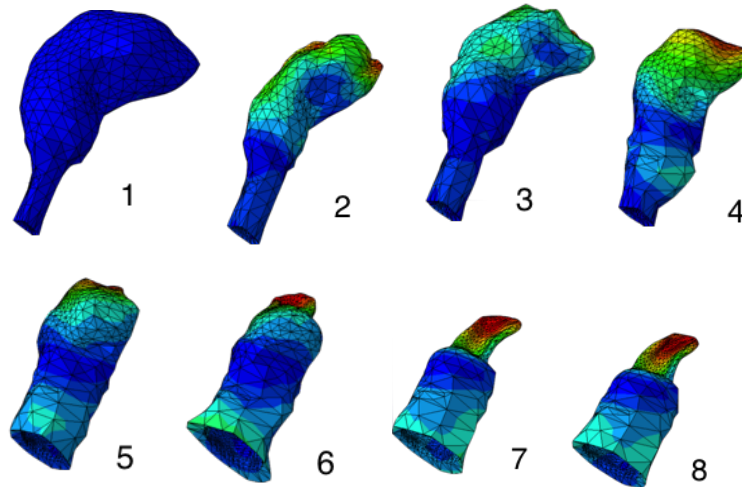


Figure 17: Behavior of the uterus at different stages during the simulation of the fetus' descent.

Fig. 17 presents some pictures made at different stages of the simulation. These pictures show the evolution of the shape of the uterus during the simulation of the descent of the fetus. We can see the decreasing size of the uterus during the simulation. To evaluate this reduction, we tracked the front-sagittal trajectory of a point at the top of the uterus (noted u_i^{pt1}). We compared this point to a point on the lower part of the uterus (noted u_i^{pt2}). As shown in Fig. 18, the distance between these two points was 230 mm at the beginning of the labor phase and it was 80 mm at the fetus delivery. Consequently, the size of the uterus has been decreased of about 2/3 which is consistent with reality.

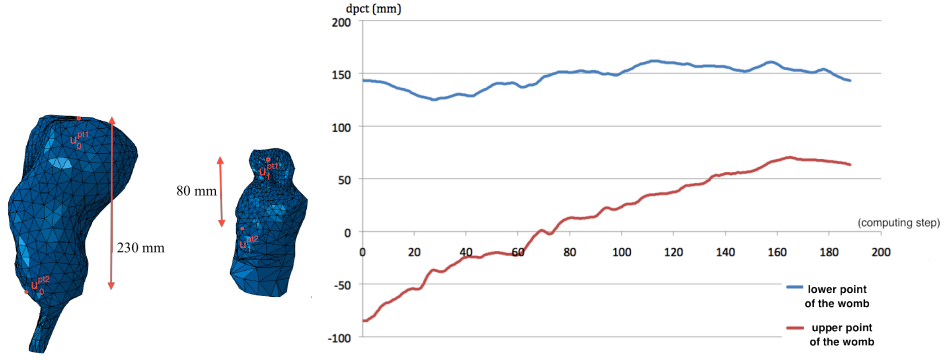


Figure 18: Evolution during the simulation of the trajectory of a front-sagittal point of the uterus.

We also followed two points chosen in the transversal plane of the uterus. Fig. 19 shows the movement of these points along the coronal/transversal axis.

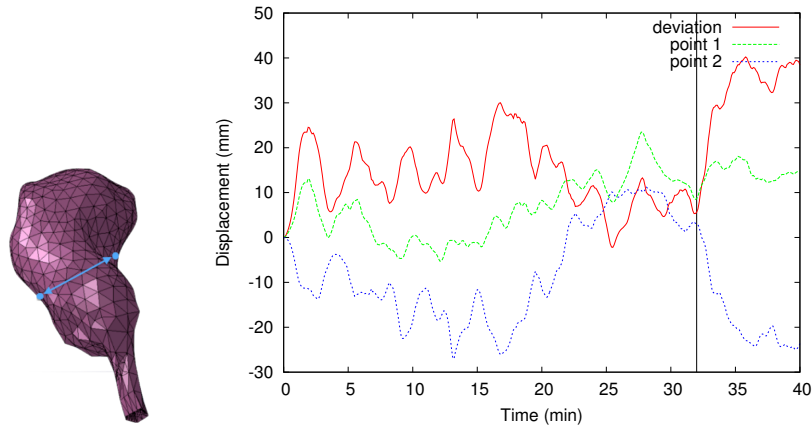


Figure 19: Displacement of two points chosen in the transversal plane of the uterus.

As expected, their displacements followed opposite directions, as the behavior of the uterus corresponds to the periodic behavior of the uterine contractions.

4.5. Discussion about our real-time simulation of vaginal delivery

We managed to simulate the descent of the fetus during the vaginal childbirth. The trajectory of the fetus was only induced by the interactions between the considered organs in the simulation and the expulsion forces applied on the uterus. The uterus was simulated with an anisotropic behavior. In agreement with reality, its size decreased during the vaginal delivery. In the future, we will consider a more precise simulation of the mechanical behavior of the uterus in order to increase the simulation accuracy of the cervix during the vaginal delivery. But the challenge will remain, *i.e.* a compromise between the precision of the simulation and its computational time, in order to couple our simulation to a haptic device.

5. Conclusion

We presented in this chapter, researches that focused on the study of the uterus. This work was mainly performed to improve the knowledge about this organ. To analyse this work, we followed the classical pipeline which enables to realize a biomechanical simulation of an organ.

It is still difficult to directly extract from medical MRI images all details of the uterus anatomy and geometry in particular all the ligaments that connect the uterus to the pelvis. Thus, a manual reconstruction of unseen structures is still required. We also reviewed advances that were made to measure organs mechanical properties (in particular performed on the cervix due to its direct impact into the risk of preterm childbirth). Recent procedures and protocols improve the measures repeatability and enable to better understand their limitations. Then, we provided a presentation of some finite element models used to simulate the mechanical behavior of the uterus for pregnant or non-pregnant uterus. These models are more or less accurate according to their purpose.

More specific research dealing with Augmented Reality used during laparoscopic uterine surgery are presented. This work can be used in the context of biomechanical simulation of the uterus and pelvic system.

Finally, we presented our work on real-time simulation of the fetus descent, in order to develop a training simulator of medical gestures performed during vaginal delivery. Despite the simplifications performed to obtain a real-time simulation, the deformation of the uterus is in agreement with the reality, with a decrease of

its size during the childbirth.

The next challenge is to propose a patient specific simulation, which integrates the measurement of the mechanical properties of the cervix performed on the patient. The idea is to be able to quantify the risk of preterm of the patient or to prevent the uterine prolapse by quantifying the damages induced by a vaginal delivery onto the ligaments of the patients.

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