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A Quantitative Approach for the Assessment of the Pelvic Dynamics

Une approche quantitative pour l'évaluation de la modélisation de la dynamique pelvienne

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Abstract

Pelvic organ modeling is a main goal towards a better pathophysiological comprehension, and further could help for the preoperative planning. However, modeling faces the problem of determining the soft tissue biomechanical parameters. In the context of pelvic floor diseases, a patient-specific modeling of the pelvic organ dynamics has been performed. The model achieved mainly reproduces the pelvic organ behavior during a strain. In order to correct the organ models used, we propose a methodology to quantitatively assess the accuracy of the simulation. The approach relies on the comparison of the simulated organ behaviors to the corresponding organ behaviors observed on a dynamic MRI sequence obtained from the same patient. For this purpose, complementary criteria are presented, they summarize the movements and deformations undergone by the pelvic organs during a strain.

Keywords: Pelvic dynamics, modeling, assessment, dynamic MRI, shape descriptors.

Résumé

La modélisation des organes pelviens est au cœur d'applications qui permettent une meilleure compréhension de la physiopathologie pelvienne. Elle permet également d'envisager une planification pré-opératoire. La modélisation se heurte néanmoins au problème de la détermination des paramètres biomécaniques des tissus mous. Dans l'étude des troubles de la statique pelvienne, une modélisation patiente-spécifique de la dynamique des organes pelviens a été réalisée. Le modèle obtenu reproduit globalement le comportement des organes lors d'un effort de poussée. Afin d'améliorer cette modélisation, nous proposons une méthodologie pour l'évaluation quantitative de la précision de la simulation, en comparant les comportements simulés des organes à ceux observés sur une séquence IRM dynamique de la même patiente. Des critères de comparaison sont présentés. Ils caractérisent les mouvements et les déformations subis par les organes pelviens.

Mots clés: Dynamique pelvienne, modélisation, évaluation, IRM dynamique, descripteurs de forme.

1. Introduction

Organ dynamics modeling is the heart of the biomedical simulation applications, which provide a better understanding of the pathophysiology of pelvic floor disorders. These simulators can be integrated into the preoperative planning, in order to assist the surgical handling and to avoid potential complications and recidivisms. A review has been presented in [1] within this

context. Also, advances in medical imaging by magnetic resonance imaging (MRI) techniques have permitted to obtain patient-specific organ models, instead of generic ones. Indeed, starting from the MRI acquisitions of a patient, the geometric model of the studied organ is built, the organ behavior is then simulated thanks to a physical model. The choice of a well-suited biomechanical model and its parameters is an open issue, even more crucial in the case of a patient-specific modeling. Some solutions have been proposed through *in vivo* and *ex vivo* local rheological measurements [2], but determining the models of all tissues is still a major challenge.

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Beyond this question, the modeling precision and realism are the crucial criteria in respect to the simulator validity. Indeed, the organ simulated behavior should conform to the real one, thus it is necessary to define an evaluation methodology. Within the context of the study of the pelvic floor disorders, we have been interested in modeling the main organs of the female pelvis. The feasibility of this task has been shown in [3], the simulation produced a behavior of the pelvic organs qualitatively validated. But the remaining question is how to verify the precision of this modeling. We try to answer to this question in this paper, by proposing a quantitative approach which compares the simulation sequence to the dynamic MRI of a same patient. Comparison criteria have been specifically designed to quantify the organ deformations and movements along a sequence by using shape descriptors and anatomical references approximation. They would provide some clues about the correction to be applied to the physical model parameters. We introduce in section 2 the proposed approach for the modeling assessment where the defined criteria are detailed. Some results are discussed in section 3. Section 4 concludes the paper.

2. Pelvic Dynamics Modeling Assessment

2.1. Clinical Context

The pelvic floor disorders are characterized by large organ deformations and abnormal organ descents during the strain. Although significant research has been performed, the pelvipereineal physiology remains poorly understood, and the different treatment ways of these complex disorders are subject to controversy. The pelvic viscera (bladder, uterus, vagina, rectum) are located between the pubic symphysis in front, and the sacrum in behind. They are linked with musculo-aponeurotic structures such as the levator ani, whose role is essential in the pelvic floor. Radiologists assume that the most relevant observation of the pelvic organ dynamics is done within the median sagittal plane, it constitutes a ground truth available in clinical routine. The movements in the coronal and transverse planes are limited and can be considered as negligible. We use a $2D + t$ MRI strain image acquisition in DICOM format, performed with 1.5T PHILIPS Gyroscan on the sagittal plane, by using an ultrafast T2-weighted pulse sequence ($tr = 3.6ms$, $te = 1.8ms$, $thickness = 10mm$, $FOV = 24cm$).

2.2. Approach

The figure 1 depicts the patient-specific modeling process developed in [3]. The block named "Characterization" compares the pelvic dynamic MRI with the

simulation computed. The aim is to quantify the differences between the two modalities in order to achieve an efficient model correction based on objective parameters. The simulation provides a time sequence of 3D organ volumes, the mid-sagittal plane analogous to the dynamic MRI plane is extracted. Hence both modalities (MRI, simulation) provide planar images which are then segmented, in order to build for each main organ a sequence of contours. The comparison criteria are introduced in the next subsection, then, the comparison methodology will be presented.

2.2.1. Deformation Criteria

The organ deformation is quantified by measuring the morphological variations of its contours along a time sequence, the shape descriptors (SD) are used. This choice is motivated by the fact that the studied organs are non-rigid which undergo large deformations, specially the bladder which does not have a determinate shape. SD are numerical attributes representing the shape aspect, they are widely used in pattern recognition, a review is proposed in [4]. An adaptation of SD was proposed in [5], where the organ deformation at a given time is the distance between the organ SD coefficients at that time and the organ SD coefficients at the rest-state ($t = 0$). Several SD have been experimented, such as the shape signature, or the Zernike moments, we used for this study the Fourier Descriptors (FD). We used Fourier Descriptors (FD) in this study, we have shown that the results of different descriptors are equivalent in [5]. FD characterize a 2D closed contour in frequency domain by considering this boundary as a periodic function :

$$FD_i = \frac{1}{N} \sum_{k=0}^{N-1} r_k \exp^{-j2\pi ik/N} \quad (1)$$

Where r_k is the radius between the shape barycenter and the k^{th} sampled point. Each contour is sampled into equidistant points and we have considered 100 points in our experiments. Then, each frame provides a magnitude vector ($\|FD_0\|, \|FD_1\|, \dots$) for one organ.

2.2.2. Movement Criteria

A simple way to characterize an organ movements is to compute its center of mass on each sequence frame, the barycenter trajectory will summarize the displacement. The clinical evaluation of the pelvic dynamics and the pelvic floor disorders is done from the observation of anatomical landmarks and the measurements of different quantitative parameters. We automatically determine the anatomical structures compatible with this

practice. The anorectal angle is the junction of the rectum with the anus, this angle is computed from the rectum boundary by exploiting the curvature properties of the rectum medial axis, as depicted in figure 2-b, the three angle points $p1, p2, p3$ are determined so that these points have the maximal curvature. The uterovaginal angle represents the uterus declination compared with the vagina, we have followed the same process as the one proposed for the anorectal angle approximation. As the bladder does not have a characteristic shape, we have assumed that the bladder neck is the lowest point of the bladder contour.

2.2.3. Sequence Comparison

We define the relative distance measure (rd) between the simulation and the real sequence, it depends on organ motion or deformation estimators. For a given organ org of two sequences s_1, s_2 :

$$rd(org, s_1, s_2) = \frac{|X(org, s_1) - X(org, s_2)|}{X(org, s_1) + X(org, s_2)}.100 \quad (2)$$

Where $X \in \{\delta x, \delta y, ang, def\}$ is an organ behavior estimator. def represents mean deformation magnitude. The movements are quantified by the maximum displacement of the organ ($\delta x, \delta y$).

3. Results and Discussion

The quantitative evaluation was applied to the modeling of several patients. We present in this section the results of the modeling evaluation of a patient, the calculated simulation was deemed satisfactory by clinicians. Figure 3 summarizes the trajectories of each organ barycenter and its specific landmark on a 2D plane. The rd computed from the trajectories are reported in Table 1. Figure 4-d depicts the evolution of the anatomical angles during the simulation (blue), and the real strain on the dynamic MRI (red). We observe that the barycenter trajectories of the three organs are almost identical, which corroborates the qualitative evaluation of the clinician about the overall organ movement. Same observation for the anatomical angles measured (figure 4-d), where the angle evolution on both modalities is similar. The correlation of the uterovaginal angle vertex trajectories on the model and the MRI is excellent. This correlation is also excellent for the bladder neck and the anorectal angle vertex at the beginning of the abdominal strain, but quite poor at the end of the strain. The computed relative distances confirm those observations. The discrepancy is linked to the organ deformation dynamics on the simulation, which correspond to a beha-

avior law. Furthermore, figures 4-a, 4-b and 4-c show results of the deformations on the simulation (blue) and the dynamic MRI (red), by using Fourier descriptors applied on the three pelvic organs. We observe that the bladder overall deformations during the simulation are small compared to the deformations undergone by the bladder on the MRI sequence. With regard to the uterus and rectum, the deformations magnitudes are close to those measured on the ground-truth. We note also that the deformations during the simulation are linear, while the real behavior is characterized by a significant deformation magnitude at the beginning of the strain. This bias is the result of the mechanical model selected in this experiment, the deformations linearity measured on the simulation may correspond to the mass-spring model effect. On the whole, the quantitative criteria have corroborated the visual assessment made by the clinician. They bring more details about the organ dynamics objectively. They are complementary, as they describe distinct organs behaviors (movements, deformations) and handle different organ references.

4. Conclusion

The validation of the organ dynamics modeling is an open issue, due to the inaccessibility to the biomechanical properties of soft tissues. The originality of this work lies in the use of the dynamic MRI as ground truth, and the determination of the appropriate criteria for the pelvic organs modeling assessment. The modeling approach focuses on the overall reproduction of the organs behavior rather than on the precision of the mechanical properties of soft-tissues which are currently inaccessible in vivo.

In order to quantify the accuracy of the modeling, we have defined criteria which compare the organs dynamic on MRI sequences and simulated ones. These criteria compute from the organs contours the deformations and the movements undergone by these organs during a strain. The approach is twofold : the organ deformation estimation based on the shape descriptors has presented satisfactory results regarding stability and complexity, it has also overcome the registration issue of the non-rigid organs handled. Also, organ movements are characterized by clinically meaningful points and angles whose evolution constitute the motion estimators.

Furthermore, this assessment approach has the advantage to be independent from the physical model choice, so that it can be considered as a basis for the comparison between different physical models which will be developed in the future. The quantitative evaluation allows

Organ	Barycenter		anat. pts.			Def
	δx	δy	δx	δy	ang	
Bladder	35%	12%	37%	44%		39%
Uterus	12%	7%	19%	21%	11%	22%
Rectum	32%	5%	29%	14%	3%	33%

TABLE 1: Relative distance computed on deformations and displacements.

us an empirical revision of the physical model parameters whatever the physical model kind. It would be interesting to automate the correction process by using an inverse method, associated with an optimization process for the biomechanical parameters setting. And, in order to have a full automated process the automatic segmentation of the pelvic organs on MRI is currently a work in progress.

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Conflicts of Interest

None.

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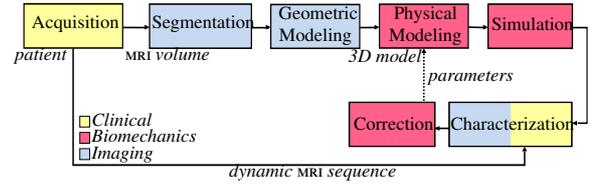
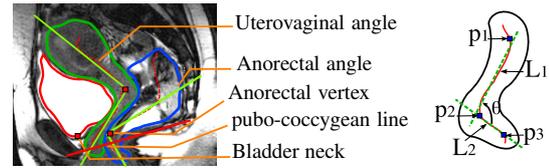


FIGURE 1: Pelvic organ modeling flowchart



(a) Computed landmarks. (b) Angle approximation.

FIGURE 2: Approximation of the anatomical references.

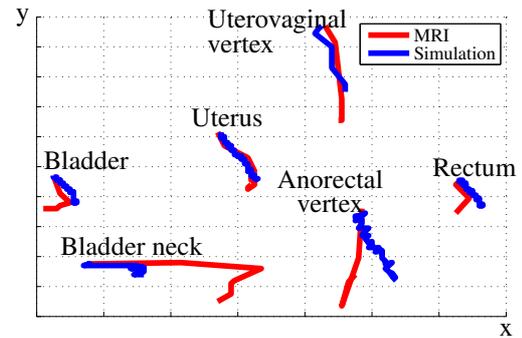


FIGURE 3: Trajectories of the barycenters and anatomical points.

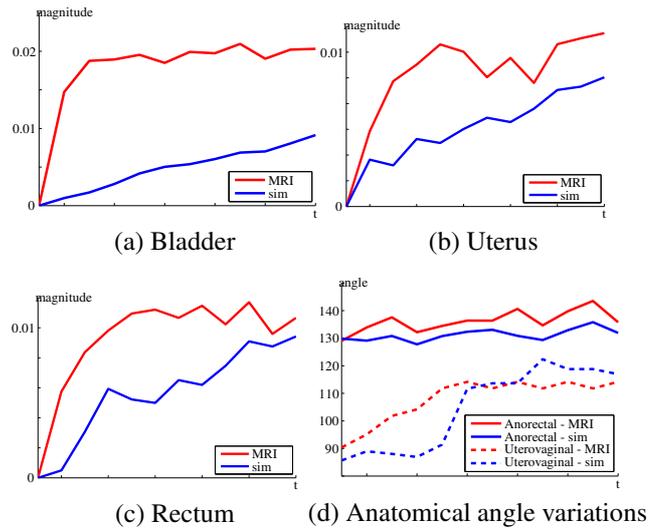


FIGURE 4: Organ evolution on the simulation and the dynamic MRI.