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Statistical model for simulation of deformable elastic endometrial tissue shapes

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ABSTRACT

Statistical shape analysis plays a key role in various medical imaging applications. Such methods provide tools for registering, deforming, comparing, averaging, and modeling anatomical shapes. In this work, we focus on the application of a recent method for statistical shape analysis of parameterized surfaces to simulation of endometrial tissue shapes. The clinical data contains magnetic resonance imaging (MRI) endometrial tissue surfaces, which are used to learn a generative shape model. We generate random tissue shapes from this model, and apply elastic semi-synthetic deformations to them. This provides two types of simulated data: (1) MRI-type (without deformation) and (2) transvaginal ultrasound (TVUS)-type, which undergo an additional deformation due to the transducer's pressure. The proposed models can be used for validation of automatic, multimodal image registration, which is a crucial step in diagnosing endometriosis.

1. Introduction

Endometriosis is a complex gynecological disease in which endometrial cells appear outside their usual locations in the uterine cavity [1]. The main symptoms depend on the site of active endometriosis and are influenced by hormonal changes. This disease affects approximately 10% of women in the reproductive age group and may cause chronic pelvic pain, severe dysmenorrhea, infertility, rectal bleeding and digestive problems. Currently there is no etiologic cure for endometriosis, but it can be treated in a variety of ways including pain medication, hormonal treatments, and laparoscopic surgery in severe cases.

Diagnosis and surgery planning in endometriosis are often improved by analyzing shapes of organs and tissues. Recent advances in medical imaging offer increasingly detailed information on typical anatomical structures. However, there is a lack of validation techniques for automatic image registration strategies, especially for multimodal images. In many medical applications, real data can only be extracted manually by an expert, and then used to validate image processing algorithms. Indeed, scarcity of data for evaluation results in restricted studies. In this paper, we present a new statistical framework to generate realistic data that can be used as ground truth when dealing with deformability of endometrial cells. Standard methods to assess an accurate diagnosis use multiple modalities including transvaginal ultrasound (TVUS) and magnetic resonance imaging (MRI). However, some limitations due to non-localized endometrial lesions or their infiltration in other organs cannot be directly avoided. An interesting solution is to statistically analyze shapes of real clinical data and provide enough simulated (random) samples to validate the TVUS to MRI registration step; registration of these two modalities is key for fusing complementary information for diagnostic purposes [2,3].

There are many approaches to generate synthetic data for validation of medical image processing methods [5,6]. First, one can use physical image phantoms with known shapes. However, phantoms are limited to specific information with restricted variability and are very costly if adapted to complex medical cases. Second, virtual organs can be simulated using controlled numerical models. These approaches are usually based on parametric models with good approximations and computational cost. But, they are limited to controlled deformations governed by the model. Thus, ignoring the variability of anatomical structures limits their realism. Finally, one can utilize tools from shape analysis to characterize large amounts of natural variability. Several methods have been proposed to model 3D anatomical shapes (see e.g. [7–9] and references therein) with different advantages and disadvantages. In this paper, we adopt a versatile Riemannian framework of Jermyn et al. [10] based on the square-root normal field (SRNF) representation of cylindrical surfaces to provide a set of tools, including parallel transport, exponential map, and geodesics, needed for

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principled statistical analysis of endometrial tissue shapes. Other applications of these methods for *spherical surfaces*, including disease classification and graphics, have been previously considered in [10–12].

Clinical data and contributions: This study was carried out using real data from ten patients who have small endometrial implants in the pelvic area. For each patient, MRI was used to examine their pelvic organs. First, MRI slices which include both the endometrial implant and its neighboring organs were selected for each patient. MR images used for these experiments had an average size of $400 \times 400 \times 5\ \text{mm}^3$ with a voxel resolution of $0.5 \times 0.5 \times 5\ \text{mm}^3$. Second, soft tissue organs (i.e. bladder, uterus, ovary, rectum) and the implant were segmented by an expert. Finally, the endometrial tissue data was represented using a cylindrical surface parameterization, which was constructed from a set of 2D MR contours (Fig. 1(a)). The corresponding 2D TVUS images were also segmented to provide deformed endometrial tissue curves. All of the surfaces in our dataset, reconstructed using a basis defined in the following section, are shown in Fig. 1(b) (the original data is shown in [4]). There is a lot of variation in this data, and thus, parsimonious shape models are very important in this application.

Some preliminary results of this study were presented in a recent conference paper [4]. The novel contributions of the present paper are (1) random sampling from a Gaussian model using the exponential map instead of a linear approximation and (2) simulation of semi-synthetically deformed endometrial tissue shapes. The first contribution is theoretical in nature, although it can also have practical implications (see Fig. 2). In particular, we extend the tools proposed in [11] to apply to cylindrical surfaces and use shooting geodesics to develop random sampling from a Gaussian endometrial tissue shape model. The second contribution allows for simulation of TVUS-type, *deformed* endometrial tissue shapes via parallel transport on the shape space of cylindrical surfaces. The rest of this paper is organized as follows. Section 2 defines a mathematical framework for shape analysis of cylindrical surfaces. Section 3 describes tools for statistical modeling of endometrial tissue shapes along with a thorough quantitative and clinical evaluation of the proposed model. Section 4 provides a brief summary.

2. Mathematical framework

Let $\mathcal{F}$ be the space of all smooth embeddings of a cylinder in $\mathbb{R}^3$, where each such embedding defines a parameterized surface $f: \mathbf{S}^1 \times [0,1] \to \mathbb{R}^3$. Let Γ be the set of all boundary-preserving diffeomorphisms of $\mathbf{S}^1 \times [\mathbf{0},\mathbf{1}]$. For an endometrial tissue surface $f \in \mathcal{F}$, $f \circ \gamma$ represents its re-parameterization. As shown in previous work, it is inappropriate to use the $\mathbb{L}^2$ metric for statistical shape analysis of parameterized surfaces, because Γ does not act on $\mathcal{F}$ by isometries [10]. Thus, we utilize the square-root normal field (SRNF) representation of surfaces and the corresponding Riemannian metric proposed in [10]; additional tools for statistical analysis were given in [11]. However, most of the previous work was limited to spherical surfaces. Thus, in the following, we provide a

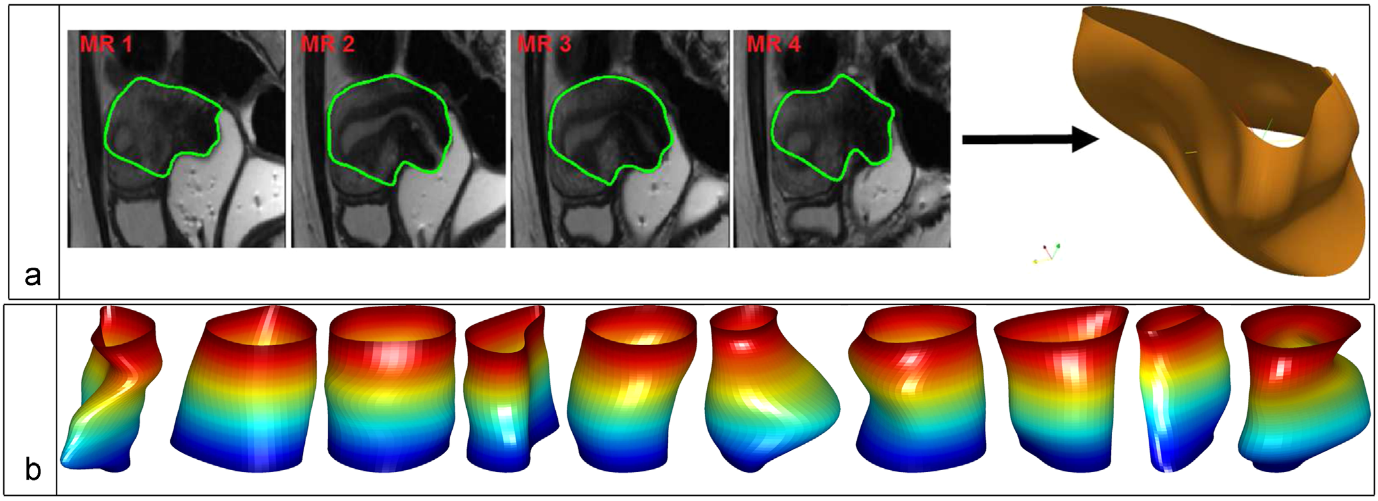

Fig. 1. (a) An example of constructing a cylindrical surface using MR image slices. (b) Endometrial tissue surface data from [4] reconstructed using the basis $\mathcal{B}$.

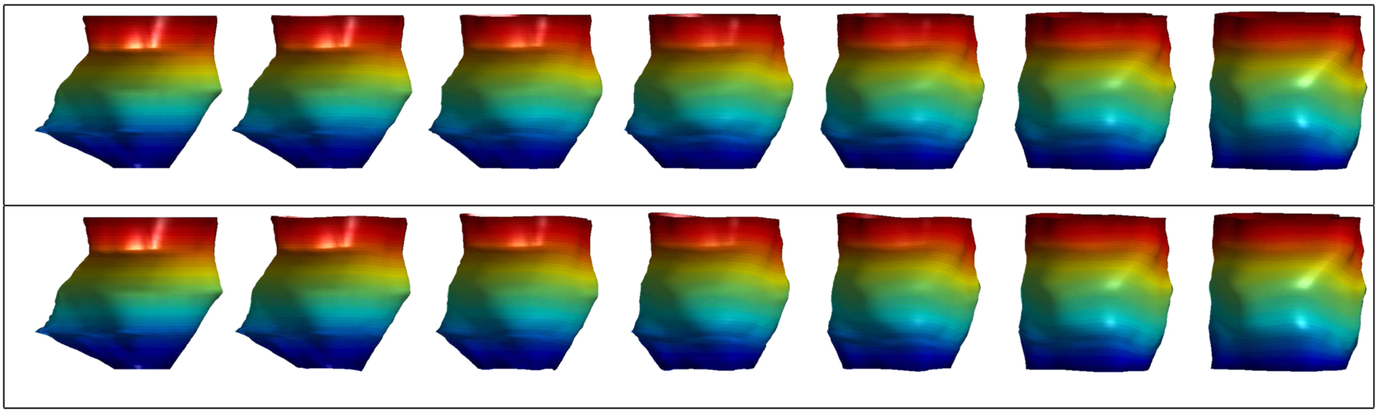

Fig. 2. A linear interpolation (top, $E(F^*) = 0.7831$) and a geodesic path (bottom, $E(F^*) = 0.6144$) between endometrial tissue shapes.