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Estimation of the elastic parameters of human liver biomechanical models by means of medical images and evolutionary computation

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ABSTRACT

This paper presents a method to computationally estimate the elastic parameters of two biomechanical models proposed for the human liver. The method is aimed at avoiding the invasive measurement of its mechanical response. The chosen models are a second order Mooney–Rivlin model and an Ogden model. A novel error function, the geometric similarity function (GSF), is formulated using similarity coefficients widely applied in the field of medical imaging (Jaccard coefficient and Hausdorff coefficient). This function is used to compare two 3D images. One of them corresponds to a reference deformation carried out over a finite element (FE) mesh of a human liver from a computer tomography image, whilst the other one corresponds to the FE simulation of that deformation in which variations in the values of the model parameters are introduced. Several search strategies, based on GSF as cost function, are developed to accurately find the elastics parameters of the models, namely: two evolutionary algorithms (scatter search and genetic algorithm) and an iterative local optimization. The results show that GSF is a very appropriate function to estimate the elastic parameters of the biomechanical models since the mean of the relative mean absolute errors committed by the three algorithms is lower than 4%.

1. Introduction

In the last decades, technological development has experienced a major breakthrough which has brought about awesome changes in medicine. In particular, computer-aided surgery (CAS) has experienced a significant progress mainly to real improvements in medical image processing software. In recent times, the tendency in surgery is to maximize the precision and to use less and less invasive methods. CAS is a less-invasive technique that assist surgeons during their interventions [1,2].

When surgical interventions are focused on organs, the inclusion in CAS of biomechanical models that simulate their

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mechanical response can considerably improve this technique [3]. In some hepatic interventions, the liver is deformed by the surgical instruments and/or the patients breathing [4,5]. For example, the liver is deformed due to the patient breathing during radiotherapy, which makes difficult locating the tumor at all times [6,7]. In these cases, knowing how the liver is deformed due to the interaction with the surgical instruments or due to the patient breathing is fundamental to accurately perform an intervention or accurately radiate the radiotherapy dose [8]. Therefore, a precise biomechanical model of the liver is essential in order to be used to help performing those interventions.

In biomechanical modeling of organs, the determination of the elastic parameters that describe the constitutive equations of the models is one of the most important issues to face. The current approach consists of performing physical experiments aiming at obtaining the mechanical response of the organ. Some of the researchers who studied the biomechanical behavior of the liver, measured its mechanical response by means of compression and/or tensile tests using *ex vivo* liver tissue samples [9–15]. However, the models obtained by these authors are not able to faithfully reproduce the liver behavior due to the mechanical differences between the *in vivo* and *ex vivo* tissue, which represent an increase of 17% in the stiffness for the *ex vivo* liver tissue [16]. Other authors [13,17–21] measured the mechanical response of the *in vivo* liver tissue by means of minimally invasive surgery or open surgery. In these cases, the mechanical response of the organ was only measured on some specific points of the organ by indentation or aspiration as in the case of [21]. This way, the mechanical behavior obtained for these authors can only represent the mechanical behavior of these little narrow areas of the organ [15].

In this framework, the use of medical image techniques can play an important role to estimate the parameters of the biomechanical models proposed for the soft living tissues since they can be obtained through non-invasive methods. In this paper, a method to computationally estimate the elastic parameters of two biomechanical models proposed for the human liver is presented. The Jaccard and Hausdorff coefficients, commonly used for the validation of segmentation algorithms in medical image, are here used to compute a novel error function, the geometric similarity function (GSF), which compares two simulated deformations of a liver reconstructed from computer tomography (CT). Several optimization strategies, which use GSF as cost function, are proposed to accurately find the elastic parameters of the models. The method described in this paper quantifies the error committed by the simulation over the entire volume of the liver. In addition, this innovative method will allow to estimate the parameters of any biomechanical model avoiding any type of surgery.

2. Materials and methods

This section is divided in three subsections. Section 2.1 introduces the mathematical fundamentals of the biomechanical models proposed for the human liver as well as the methodology followed to obtain its geometry. Section 2.2 describes the method used to compute the geometric similarity function (GSF), which evaluates the similarity between two finite element (FE) meshes corresponding to two simulated deformations carried out over the liver. Finally, Section 2.3 deals with the optimization strategies carried out to find the optimal set of parameters of the proposed models.

2.1. *Biomechanical modeling of the human liver*

Two hyperelastic models were chosen to represent the biomechanical behavior of the liver in this work: a second-order Mooney–Rivlin (MR) model and an Ogden model. The choice of these models is based on a previous work [15] in which it was found that these models provided the best results for the elastic part in the simulation of the biomechanical behavior of the lamb liver. The results of the methodology described in the present paper will be extrapolated to other more complicate models as it is explained in Section (4).

2.1.1. *Mooney–Rivlin model*

The strain energy potential for the second-order Mooney–Rivlin (MR) model, W_{MR}, is defined as Eq. (1) indicates:

$$W_{MR} = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + \frac{K_0}{2}(J - 1)^2 \quad (1)$$

where C_{10} and C_{01} stand for the material elastic parameters, K_0 stands for the bulk modulus and $\bar{I}_1$ and $\bar{I}_2$ denote the first and second deviatoric strain invariant, respectively.

2.1.2. *Ogden model*

The strain energy potential, W_O, is defined as shown in Eq. (2):

$$W_O = \frac{\mu}{\alpha}(\bar{\lambda}_1^{\alpha} + \bar{\lambda}_2^{\alpha} + \bar{\lambda}_3^{\alpha} - 3) + \frac{K_0}{2}(J - 1)^2 \quad (2)$$

where μ and α stand for the material elastic parameters, and where $\bar{\lambda}_1$, $\bar{\lambda}_2$, and $\bar{\lambda}_3$ denote the deviatoric stretches.

An *ex vivo* human liver was supplied by the *Unidad de Cirugía Hepatobiliopancreática y Trasplante Hepático of the Hospital Universitari i Politècnic La Fe* from an anonymous donor. The liver was placed in a box that simulates the human torso surrounded by a foam to get a similar shape to that the liver keeps inside the body (Fig. 1). The liver was scanned with the *Brillance iCT* from Philips®. The scan parameters were 80 kVp and 100 mA s. CT images of the liver were acquired in DICOM format with a size of 323 × 125 × 289 pixels. The voxel size was 1.085 mm × 1.085 mm × 0.80 mm. The DICOM images were processed in order to obtain a finite element (FE) mesh as it is shown in Fig. 2. The commercial software Simpleware 4.2® was used to segment the liver and generate a 3D model. A smoothing Gaussian filter was used to get a more realistic and continuous model. Finally, Simpleware 4.2 was also used to obtain the FE mesh, which was exported to the commercial FE package ANSYS 13.0®.

Breathing process can be separated in two stages: inhalation and exhalation. During inhalation, the diaphragm is contracted and flattened about 15 mm pushing the liver towards the rest of abdominal organs [22]. A deformation similar to this, i.e., similar to the compression that the liver suffers during the inhalation process was chosen aimed at testing the method proposed in this paper. A displacement of 15 mm was