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Towards the mechanical characterization of abdominal wall by inverse analysis

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ABSTRACT

The aim of this study is to characterize the passive mechanical behaviour of abdominal wall *in vivo* in an animal model using only external cameras and numerical analysis. The main objective lies in defining a methodology that provides *in vivo* information of a specific patient without altering mechanical properties. It is demonstrated in the mechanical study of abdomen for hernia purposes. Mechanical tests consisted on pneumoperitoneum tests performed on New Zealand rabbits, where inner pressure was varied from 0 mmHg to 12 mmHg. Changes in the external abdominal surface were recorded and several points were tracked. Based on their coordinates we reconstructed a 3D finite element model of the abdominal wall, considering an incompressible hyperelastic material model defined by two parameters. The spatial distributions of these parameters (shear modulus and non linear parameter) were calculated by inverse analysis, using two different types of regularization: Total Variation Diminishing (TVD) and Tikhonov (H^1). After solving the inverse problem, the distribution of the material parameters were obtained along the abdominal surface. Accuracy of the results was evaluated for the last level of pressure.

Results revealed a higher value of the shear modulus in a wide stripe along the craneo-caudal direction, associated with the presence of linea alba in conjunction with fascias and rectus abdominis. Non linear parameter distribution was smoother and the location of higher values varied with the regularization type. Both regularizations proved to yield in an accurate predicted displacement field, but H^1 obtained a smoother material parameter distribution while TVD included some discontinuities. The methodology here presented was able to characterize *in vivo* the passive non linear mechanical response of the abdominal wall.

1. Introduction

The most common solution for severe hernia cases is implanting a surgical mesh to cover the zone where the hernia takes place. Since an abdominal hernia consists of an opening in the abdominal wall, this mesh has to replace the function of the muscle/fascia while it is healing, absorbing strain and stress in lieu of the tissue. This technique, known as the Lichtenstein's tension-free mesh procedure, has been widely applied since its introduction (Lichtenstein et al., 1989). However, some common complications are still frequently associated with this surgery, such as pain (Paajanen and Hemunen, 2004), inflammation (Klinge et al., 2002), hernia relapse or even mesh breakage (Cobb et al., 2005).

Previous studies have been focused on the mechanical behavior of the abdominal wall. Most of those authors have worked with *in vitro* tests, mainly uniaxial or biaxial experiments, either on animal models (Hernández et al., 2011; Lyons et al., 2014; Cooney and Moerman, 2015) or using human samples (Kirilova et al., 2011; Martins et al., 2012; Abdelounis et al., 2013). Other authors performed *ex* vivo tests on human tissues (Tran et al., 2014; Podwojewski et al., 2014), analysing the response of human abdomen when pressure is applied to the whole wall and to isolated layers. Few of the studies dealt with human abdomen in *in vivo* conditions. Song et al. (2006) and Szymczak et al. (2012) both estimated strain values in specific directions when the patient was subjected to usual activities: expiration, bending and torsion of the abdomen, (Szymczak et al., 2012) and during a surgery when a pneumoperitoneum was induced (Song et al., 2006). More recently, Tran et al. (2016) also performed measurements of the elasticity and local stiffness of abdominal wall by shear wave elastography, determining the active and passive linear elastic mechan-

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ical response of the wall under physiological activities.

The main benefit of an *in vivo* test lies in the possibility of measuring a living tissue without altering its natural response, in a non-invasive way. Moreover, this type of test provides information about a specific specimen, which can be very useful for the patient-specific treatment. Over the last two decades, great strides have been made to enable the *in vivo* measurement of tissue deformation, via techniques referred to as "elastography" (Ophir et al., 1991; Rivaz et al., 2013; Chauvet et al., 2015; Tran et al., 2016). This fact, combined with the parallel advance in efficient algorithms, has made possible the *in vivo* mechanical characterization of several soft tissues by inverse analysis: human liver (Nava et al., 2008), breast tissue (Goenezen et al., 2012) and thyroid gland (Kybic and Smutek, 2005). With few exceptions (*e.g.* (Goenezen et al., 2012)) most work in this area has focused on linear elastic, small strain tissue characterization.

In this work we present an estimation of both linear and nonlinear elastic properties of the abdominal wall measured under *in vivo* conditions. Taking inflation tests performed on an animal model as a starting point, displacement of different points of the wall were measured by photogrammetry and the whole abdominal cavity was reconstructed. This methodology was previously introduced in Simón-Allué et al. (2015). The identification of the mechanical properties from the displacement field together with the inner pressure constitutes a nonlinear inverse problem. To solve it, we have employed an efficient algorithm that uses a gradient based quasi-Newton minimization strategy to seek those material parameter distribution whose numerical displacement field better match the measured displacement field (Gokhale et al., 2008; Goenezen et al., 2011).

The objective of this study is to establish a methodology able to characterize *in vivo* abdominal tissue only by the use of cameras and FE simulation of the mechanical response through a 3D model of the wall. A long term goal of this work is to enable patient specific mechanical property characterization to improve surgical treatment planning.

2. Material and methods

2.1. Experimental tests

Experimental tests were conducted on an animal model, specifically New Zealand White rabbits, frequently used as a model in hernia studies (Nilsson, 1982; Bellón, 2007; Hernández et al., 2011). This animal model presents the benefits of being easy to handle and biologically very sensitive to non-biocompatible materials. For this study 2 rabbits were subjected to several pneumoperitoneum tests, following the protocol described in (Simón-Allué et al., 2015).

Animals were obtained from the Animal Experimentation Service of the Research Support Services of the University of Zaragoza, with an average weight of 2.20 kg. Animals were healthy and free of clinically observable diseases. Prior to the procedure, they were kept under stable conditions of light and temperature following the recommendations given by the "Guide for the Care and Use of Laboratory Animals" (Guide for the care and use of laboratory animals,). All procedures were carried out under Project Licence 01/11 approved by the in-house Ethics Committee for Animal Experiments of the University of Zaragoza.

Before each experiment, animals were shaved from front to rear legs and placed face up on a surgical table, so that the abdominal surface remained well exposed. Thereafter, the skin was spotted with black dots situated in a grid pattern. These points were used as fiducial points in the post-processing. Concurrently, a synchronized stereo rig composed of two Prosilica GT1290 cameras was situated above the animal to record the deformation of the external abdomen during the pneumoperitoneum (see Fig. 1 (a)).

Subsequently, a Verres needle was inserted in the lower abdomen and connected to a Standard Karl Storz endoscope at the other end. A schematic diagram of the whole setup is shown in Fig. 1 (b). Gas (carbon dioxide) was introduced through this needle increasing the intra abdominal pressure (IPA) from 0 mmHg to 12 mmHg, in steps of 1 mmHg. Following each test, gas pressure was reduced back to zero. This procedure was repeated 4 times per specimen. The first test was excluded from the analysis to account for preconditioning. For the numerical postprocessing, 2 valid cycles were analyzed per animal. Images of the abdominal wall at the initial and final moment of the experiment can be seen in Fig. 2.

From the video recorded by the cameras, a pair of frames was extracted corresponding to each level of pressure. Frames were analyzed using the digital PhotoModeler (2013) Software, which allows us to determine the three dimensional coordinates of points shown in both images using photogrammetry. In this way the three dimensional coordinates of the black dots painted on the surface of the abdomen were determined as a function of the abdominal pressure. For this geometry and camera resolution an accuracy better than 1 mm can be assured (Simón-Allué et al., 2015).

2.2. Numerical analysis

The measured displacement of the black dots was used to determine the spatial distribution of the material properties of the abdomen. This inverse problem was solved by minimizing the difference between the measured and a predicted displacement field, where the latter was required to satisfy the equations of equilibrium for a nonlinear hyperelastic material. The spatial distribution of the material properties in this model was varied so as to yield a predicted displacement field that was optimally close to the measured displacement. A gradient-based optimization algorithm (LBFGS) (Zhu et al., 1997) was used to solve this problem, and the gradients were determined efficiently through the use of adjoint equations. At every step of the optimization algorithm one forward non linear elastic problem, and one adjoint elastic problem was solved.

In the following sections, we first describe the forward problem and then describe the inverse problem.

2.2.1. Nonlinear forward problem

Abdominal wall muscles are composed of individual components known as muscle fibres surrounded by connective tissue (ground substance, collagen and elastin fibres in different proportions) capable of absorbing the muscle lengthening. The connective tissue is largely responsible for transmitting forces. In this paper we consider only the passive properties of muscle tissue since it determines the response registered during the pneumoperitoneum with the rabbit anesthetized. The abdominal wall is subjected to large deformations with negligible volume changes, that is, only isochoric ($J \approx 1$) motions are possible. This response is modelled with an incompressible hyperelastic model. Due to the preferred directions of orientation of collagen and muscular fibers, the abdominal wall may display an anisotropic stress response when each muscle layer is modelled (Hernández et al., 2011). However, when the response of several layers working together is analysed, the level of anisotropy decreases significantly (Hernández et al., 2011). Therefore, we model the tissue using an incompressible, isotropic, and nonlinear elastic model depending on two parameters, whose spatial variation may provide different mechanical response of the tissue zones.

We characterize the hyperelastic response through the second Piola-Kirchhoff stress tensor given by

$$\mathbf{S} = Jp\mathbf{C}^{-1} + 2\frac{\partial \Psi(\overline{\mathbf{C}})}{\partial \mathbf{C}} \tag{1}$$

where J is the Jacobian of the deformation gradient ($\mathbf{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}}$), p the hydrostatic pressure associated with the additional volumetric constraint $J - 1 = 0$, $\mathbf{C}$ the right Cauchy-Green strain tensor ($\mathbf{C} = \mathbf{F}^T\mathbf{F}$) and $\overline{\mathbf{C}}$ the modified Cauchy-Green strain tensor defined as $\overline{\mathbf{C}} = J^{-\frac{2}{3}}\,\mathbf{C}$.