Global sensitivity analysis of membrane model of abdominal wall with surgical mesh

K. Szepietowska & I. Lubowiecka
Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Gdańsk, Poland

B. Magnain & E. Florentin
INSA-CVL, Laboratoire PRISME, Bourges, France

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ABSTRACT: The paper addresses the issue of ventral hernia repair. Finite Element simulations can be helpful in the optimization of hernia parameters. A membrane abdominal wall model is proposed in two variants: a healthy one and including hernia defect repaired by implant. The models include many uncertainties, e.g. due to variability of abdominal wall, intraabdominal pressure value etc. Measuring mechanical properties with high accuracy is a challenging task in the case of living patients. The main aim of the study is to analyse sensitivity of uncertainties on the difference between the behaviour of a healthy and repaired abdominal wall with a surgical mesh implanted. Global sensitivity analysis is performed and Sobol' indices are calculated throughout the research. Regression-based polynomial chaos expansion is employed to reduce the number of required simulations. These outcomes will be used in efficient planning of further experimental and numerical studies.

1 INTRODUCTION

Ventral hernia occurs commonly as a postoperative complication after abdominal surgeries (Gillion et al. 2016). It can be treated by implantation of a surgical mesh. The study addresses the issues of laparoscopic ventral hernia repair. Recurrences or an excessive mesh bulging still happen, the consensus on the best properties of implant is still searched.

Abdominal wall mechanics is crucial in the context of ventral hernia repair (Junge et al. 2001). Therefore, abdominal wall and its components mechanics have been investigated (Hernández et al. 2011, among others). However, most of experiments presented in the literature were performed *ex vivo*. A few studies exist to identify these mechanical properties *in vivo* in humans (Song et al. 2006, Tran et al. 2016).

Song et al. (2006) proposed a method to identify the abdominal wall properties *in vivo* by measuring displacement of chosen points of patient's abdominal wall. The experiment was performed during laparoscopic repair, when in the course of inflation process the pressure in the abdominal cavity is known. Young's modulus of abdominal wall was calculated using radii of abdominal wall curvature of in two planes. Simón-Allué et al. (2017) developed this idea on an animal example to identify the spatially distributed parameters of a hyperelastic material model. They assumed that abdominal wall, although composed of layers with different orientation of fibers, can be regarded as isotropic. However, other literature results indicated anisotropy of an abdominal wall (Junge et al. 2001, Song et al. 2006).

Hernández-Gascón et al. (2013) proposed the Finite Element (FE) model of the abdominal wall with properties taken from *ex vivo* study on animal samples. The model geometry is based on MRI images of human. This model was later used by (Simón-Allué et al. 2016) to compare behaviour of different meshes in context of their compatibility with the abdominal wall. Pachera et al. (2016) proposed a model based on CT images including properties of abdominal wall components identified on samples harvested from human cadavers. However, in the model used in FE inverse analysis by Simón-Allué et al. (2017) the layers were not distinguished and the geometry was based on external surface information. This model was composed of 3D tetrahedral elements (3 elements per thickness of an abdominal wall). In this application, due to small thickness, a shell or membrane model seems to be reasonable. Such model was proposed by (Lubowiecka et al. 2017).

There occurs a high variability of abdominal wall properties and value of intraabdominal pressure (Cobb et al. 2005). What is more, there are additional difficulties with their accurate measurement. In the paper we investigate the influence of uncertainty of abdominal wall properties on the variance of compatibility of a chosen implant with the abdominal wall. In the study, differences are investigated between the displacement in the middle of the implant and the displacement of a corresponding point in healthy abdominal model.

2 UNCERTAINTY PROPAGATION METHODS

Since abdominal wall models are created in a "blackbox" commercial system MSC.Marc, non-intrusive probabilistic models are used within this study. The Monte Carlo (MC) method is an easily applicable and widely used method, but it requires huge number of model realizations. Polynomial Chaos (PC) method (Ghanem and Spanos 1991) can help to reduce number of computations. It is based on creating a metamodel. The computational model $\mathcal{M}$ is approximated by a series of multivariate polynomials:

$$\mathcal{M}(\boldsymbol{\xi}) \approx \sum_{\boldsymbol{\alpha}\in\mathcal{A}} a_{\boldsymbol{\alpha}} \Psi_{\boldsymbol{\alpha}}(\boldsymbol{\xi}), \quad (1)$$

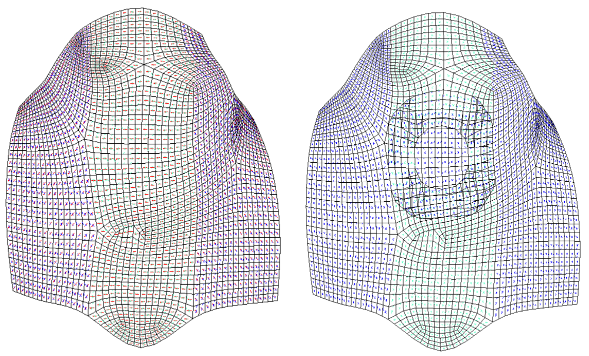
where $\boldsymbol{\xi}$ is an M dimensional random variable, $\Psi_{\boldsymbol{\alpha}}(\boldsymbol{\xi})$ is a multivariable polynomial basis, $\mathcal{A}$ is a truncation set of $\boldsymbol{\alpha}$ corresponding to polynomials of degrees smaller or equal to degree p. Since random variables are uniformly distributed , Legendre polynomials are employed. The regression-based approach (Berveiller et al. 2006) is one of the non-intrusive methods to calculate the coefficients $a_{\boldsymbol{\alpha}}$. This type of non-intrusive simulation can be controlled, see e.g. Chamoin et al. (2012).

Global sensitivity analysis enables the study of global effect of uncertain input on the output. The widely-used measures are Sobol's indices (Sobol 2001), which are based on ANOVA (ANalysis Of VAriance) decomposition. Sudret (2008) showed that Sobol's indices can be calculated using PC coefficients, which helps to highly reduce the computational cost of performing global sensitivity analysis.

In a non-intrusive method the choice of sampling points affects the accuracy. In the study a quasi-random approach was employed, the Sobol sequence points were taken into account. A polynomial order $p = 3$ and a number of 224 sampling points were assumed here.

3 MODELS

The models are created in a commercial FE software, MSC. Marc. They are composed of quadrilateral 4-node membrane elements of 3 translational degrees of freedom per node. Geometry of a healthy abdominal wall (Figure 1(a)) has been taken from the previous study (Szymczak et al. 2012). This refers to external surface of real human geometry. It is subjected to intraabdominal pressure p with a value appearing



(a) healthy (b) with hernia and implant

Figure 1: FE membrane models of abdominal wall

Table 1: Assumed limits of uniform distribution $\mathcal{U}(a,b)$.

Variable	E_1 [Pa]	E_2 [Pa]	G_{12} [Pa]	p [Pa]	α_{aw}
a	22000	16000	3000	4800	0
b	64000	29000	40000	18625	π

during cough. It is supported in the entire edge of the model.

The following results presented by Song et al. (2006) imply the material model assumed orthotropic. The material parameters are the same, but orientation is different. The abdominal wall model has been divided into 2 areas: central part corresponding to area of rectus abdominis muscle and linea alba with rectus sheath. In this area material direction corresponding to $E_1$is assumed to be in transverse direction. Lateral part corresponds to composite of lateral muscles and their fascias. Elasticity E_1, E_2 and G_{12}, pressure p and orientation of lateral part α_{aw} are assumed to be uniformly distributed random variables (Table 1).

The second model detected hernia defect, the abdominal wall was covered by a surgical mesh (Figure 1(b)). Orthotropic, bilinear elastic material parameters (Lubowiecka et al. 2016) correspond to DynaMesh implant. The implant stiffer direction is a transverse direction of the abdominal wall.

The quantity of interest is $u_i - u_{aw}$, where u_i is the displacement of the middle of the implant and u_{aw} is the displacement of the corresponding point on healthy abdominal wall model.

4 RESULTS

4.1 *Deterministic single case simulations*

Figure 2 shows displacement of a healthy abdominal wall. Figure 3 presents displacement of the model with an implant. Both figures are made for single deterministic cases (the same values of parameters for both pictures). Figure 4 shows displacements, when the implant stiffer direction is oriented parallel to the cranio-caudal direction. In the latter case, the mesh bulges over the abdominal wall. However, bigger dis-

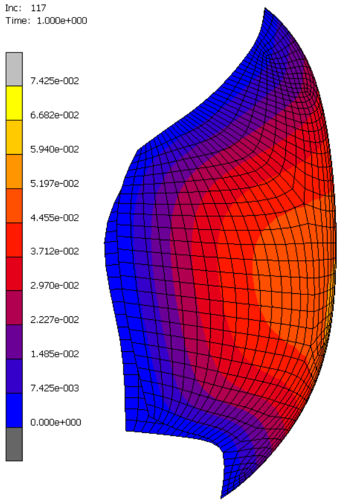


Figure 2: Displacement [m] of healthy abdominal wall

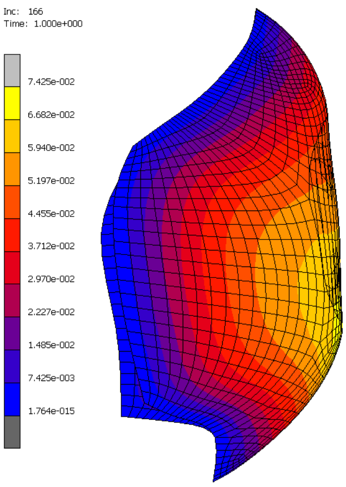


Figure 3: Displacement [m] of abdominal wall with implant with stiffer direction in transverse direction

placement in the entire model (in abdominal wall) appears in the first case of implant orientation.

4.2 *Uncertainty propagation and sensitivity analysis*

The histogram of quantity of interest is shown in Figure 5. For the point selected in the study (center of the implant) the differences even in high percentile levels are relatively low (the maximum obtained value is 0.0145m).

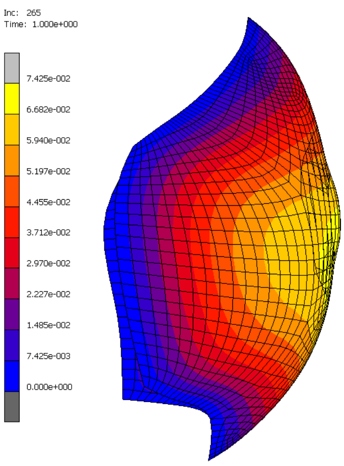


Figure 4: Displacement [m] of abdominal wall with implant with stiffer direction in cranio-cadual direction

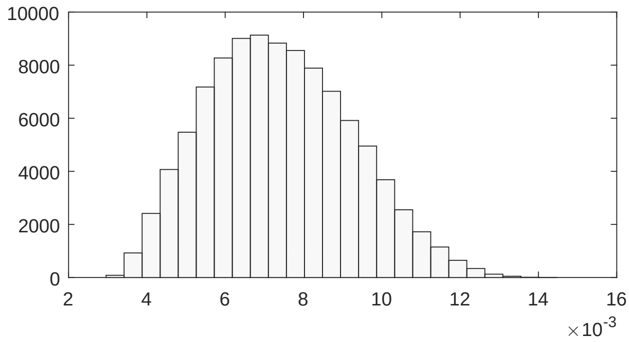


Figure 5: Histogram of $u_{aw} - u_i$ [m]

Table 2: Total Sobol's indices

Variable i	E_1	E_2	G_{12}	p	α_{aw}
S_i^{Tot}	0.5565	0.0519	0.027	0.3265	0.0821

Total Sobol indices S_i^{Tot} are collected in Table 2. It can be noted that E_1 has the highest contribution in the variation of the quantity of interest. Other material parameters influence is much smaller.

The abdominal wall is composed of layers with different fiber orientation. The orientation of the lateral part of the model is not clear. However, in the case of the investigated model, this orientation is not important compared to the most significant factors.

5 CONCLUSIONS

The global sensitivity analysis has been applied to global, membrane model of abdominal wall with an implant. Biomechanical studies are usually conducted on a small number of samples, so the distribution of variables are not well-known. Identification *in vivo* is challenging. The study shows that detailed identification of E_1 and the value of pressure are the most important. For the studied location of hernia, the orientation of lateral part of abdominal wall is not so important. However, similar analysis should be conducted for different quantities of interest.

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