# ORTHOTROPIC MEMBRANE AS A MECHANICAL MODEL OF SURGICAL IMPLANT IN ABDOMINAL HERNIA REPAIR

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**Abstract:** Even though the incisional hernia repair surgery is a well known procedure, mechanical properties of the tissue-implant system are unknown, so the implantation of the repairing mesh is quite intuitive, and recurrences of the condition continue to occur.

The main objective of the study is to define a model of repaired hernia that can be used for surgery planning and assessment of the repair durability. The load applied to the structure corresponds to this widely accepted model as the one that can cause hernia recurrence. In the proposed solution, the reaction forces calculated when the extreme abdominal pressure acts on the model are considered as the crucial factors in the repair planning and the connection strength evaluation. These reactions representing the tissue-implant junction forces cannot exceed the limit value experimentally obtained for the synthetic mesh and porcine tissue connection described in literature.

The achieved finite element simulations results are compared with the experiments and the proposed solution shows good accuracy.

**Keywords:** biomechanics, membrane, incisional hernia, finite element modelling, orthotropic implant

## 1. Introduction

Hernia is an opening or weakness in the wall of a muscle, tissue, or membrane that normally holds an organ in place. A hernia occurs when a part of an internal organ protrudes through a weak area of a muscle. The most common hernia occurs in the abdomen, when a weakness in the abdominal wall develops into a localised opening, through which adipose tissue, or abdominal organs covered with peritoneum, may protrude.

Most abdominal hernias can be surgically repaired. The minimally invasive operation, laparoscopy, most commonly used today allows a reduction in the time needed for recovery after treatment. In modern muscle reinforcement techniques, a synthetic mesh prosthesis that prevents overstretching of the weakened tissue is applied. The mesh is placed over the defect using staples (tacks) to keep the mesh in place (stapling technique). These mesh repair methods, called *tension free*, prevent muscles from pulling together under tension (Figure 1).

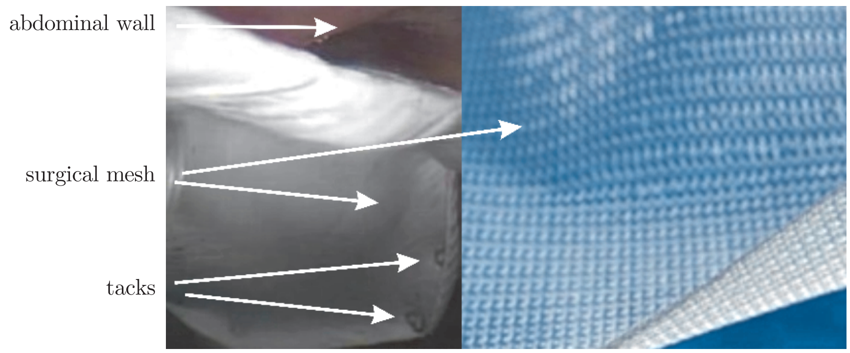


**Figure 1.** Surgical mesh implanted in abdomen

Although the ventral hernia repair surgery is a well recognised practice, the mechanical properties of the tissue-implant system are unknown and difficult to estimate. Therefore, the repairing mesh implantation is quite intuitive, hence the number of tacks required for holding the implanted mesh correctly and their optimal position on the mesh surface are unknown. This often results in hernia recurrences (see *e.g.* [1]). Since an increase in the number of the implanted tacks can cause pain by affecting human nerves and damaging blood vessels, their number should be reduced to a minimum, but at the same time it should assure the repair durability. A large abdominal wall hernia defects have been shown to have recurrence rates of between 25 to 52% when primarily repaired [2]. Those rates can be significantly reduced when using synthetic implants as a tension-free repair system. The mechanical modelling of the tissue-implant system can support the surgical knowledge in resolving this complex matter and in the development of a better, mechanic based hernia repair practice.

The main objective of the study is to define a simple repaired human hernia model that can be used to assess the repair strength. In this study, the author proposes a solution based on the finite element method, where the synthetic implant is modelled as an orthotropic membrane and the zone of its interaction with the tissue is approximated by elastic supports. The simulations of the dynamics of such a system represent the behaviour of a hernia repaired with the use of a surgical mesh undergoing intraabdominal pressure. This pressure corresponds to a postoperative cough or jumping which are identified as the main cause of hernia recurrence [3, 4]. In addition to the statistical data about hernia recurrences, no specific procedure for the repair assessment is available in the mechanical and medical literature. Some preliminary hernia repair models have been proposed and analysed by the author's research group before, as *e.g.*

the cable and membrane implants previously studied and outlined in [5, 6]. A membrane model for the herniated rabbit abdominal wall has been also proposed [7] where the postoperative behaviour of the implanted mesh and abdomen due to the stiffness changes is discussed.

In the proposed solution, the abdomen is not modelled since its mechanical properties are not really known and the study is based on the implant model reaction forces. This approach does not require the abdomen model definition. The reactions calculated when the extreme abdominal pressure act on the model, are considered as the crucial factors to be considered in the repair planning and evaluation. These forces cannot exceed the limit value experimentally obtained for the connection of the implant and porcine tissue described in [8].

The finite element simulation is compared with some experimental results provided by the research group and achieved within Project HAL2010 supported by the EU, as part of the Innovative Economy Operational Programme. The analyses were performed for two configurations of the fixing system for a hernia 5 cm in diameter, as the experimental results were available. The geometry of the two simulated models with 10 joints every 4 and 3 cm corresponded to the clinic recommendation for hernia surgery.

## 2. Material properties of surgical mesh

The Dyna Mesh® synthetic implant was applied to the model. The material properties of the analysed surgical mesh were identified on the basis of one dimensional tensile tests on the machine Zwick Roel Z020 as presented in [6, 9]. The experiments results revealed orthotropy of the implant [10] with different bilinear elastic moduli in two orthogonal directions, $E_1 = 6.41\,\mathrm{N/mm}$ and $E_2 = 0.34\,\mathrm{N/mm}$, when the strain $\varepsilon \leq 0.15$ and $E_1 = 13.78\,\mathrm{N/mm}$ and $E_2 = 3.73\,\mathrm{N/mm}$ when $\varepsilon > 0.15$ following the tensile tests. Poisson's ratio was estimated as $v_{12} = 0.35$, the mass density was identified as $368\,\mathrm{kg/m^3}$ and the mesh thickness $t = 0.45\,\mathrm{mm}$. The orthogonal directions 1 and 2 refer to the mesh structure and thus to the orthotropy. As presented in [11], the material parameters have to satisfy the formula $E_2 v_{12} = E_1 v_{21}$, on the basis of which, the mechanical model of the implant is built. Similar anisotropic behaviour of hernia implants has been observed for other kind of meshes as presented in *e.g.* [12, 13] even if there are more sophisticated material models for the technical fabrics developed and applied in the structural analysis, see *e.g.* [14].

## 3. Mechanical hernia repair model

The implant is considered here as an orthotropic membrane structure [8] with elastic supports representing the tissue-implant interaction zone [6, 15]. In the studied cases, 10 connection points in a semi-circular order were assumed (Figure 2). The membrane represents a surgical mesh acting in the hernia orifice. The assumed opening diameter is equal to 0.05 m. The points of tack introduction are connected with the hernia orifice edge by elastic springs. The model geometry corresponds to the samples used in the experiment.

It is only a few studies that refer to experiments on the abdominal wall stiffness, including [16, 17], where the author has applied an approximate procedure to identify the stiffness of the elastic supports.

In this approximation, the fascia and the implant membrane were considered as 2 springs connected in a serie. The fascia stiffness of about 2 N/mm, as presented in [18], was taken for the connection modelling. Hence, the resultant spring stiffness per one tack was assumed as 1.5 N/mm.

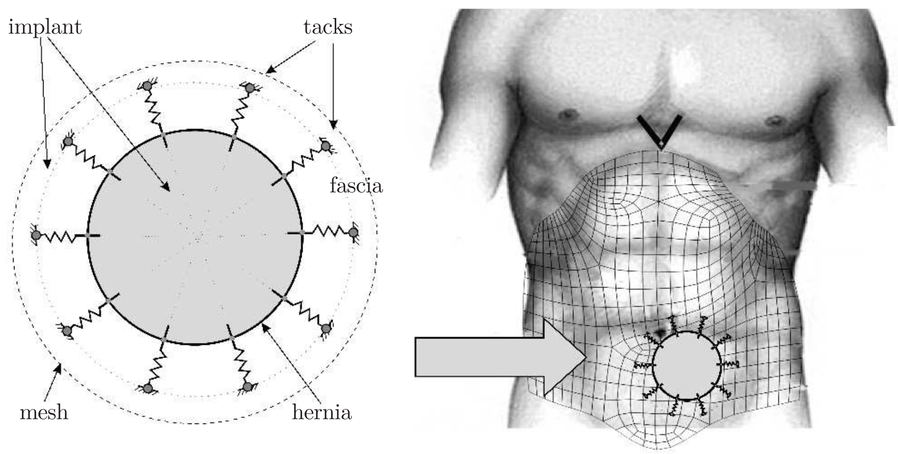


**Figure 2.** Mechanical hernia model

The extreme load acting in the human abdomen that can damage the implant connections and result in recurrence of the condition is an internal pressure that can reach the value of 270 mm Hg [3, 4]. This load can commonly appear during postoperative cough or jumping. Therefore, this type of load was applied to the system within the dynamic analysis of the proposed model and considered in the repair strength estimation.

## 4. Finite element simulation of the dynamic behaviour of implanted mesh and experimental results

### *4.1. Finite element modelling of implanted surgical mesh*

The nonlinear dynamic analysis of both hernia models was performed by means of the MSC.Marc system. A 4-node finite membrane elements of type 18 (MSC.Marc) containing 3 translational degrees of freedom in each node were applied, see *e.g.* [19]. 356 membrane elements and 30 springs (3 per joint) were used to define the finite element model (Figure 3).

The dynamic analysis was performed on the finite element model and the obtained results were compared with the experiments to evaluate the model accuracy. The study representing experiments carried out in a specially prepared

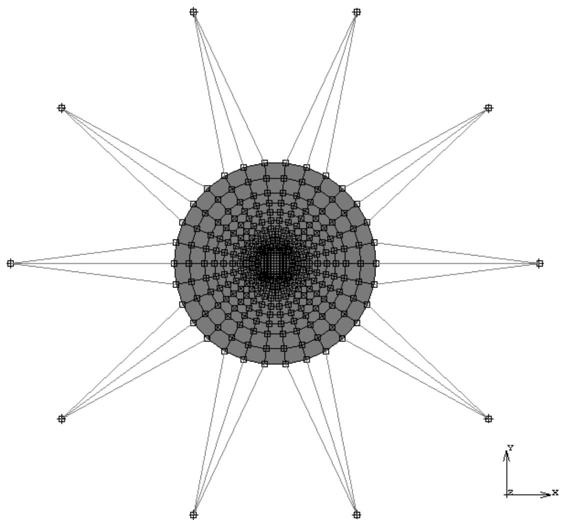

**Figure 3.** Finite element model

pressure chamber on operated porcine hernias (Figure 4) is described in [9]. The experiments details are not within the scope of the paper and it is only their results that are presented here to compare with the simulations.

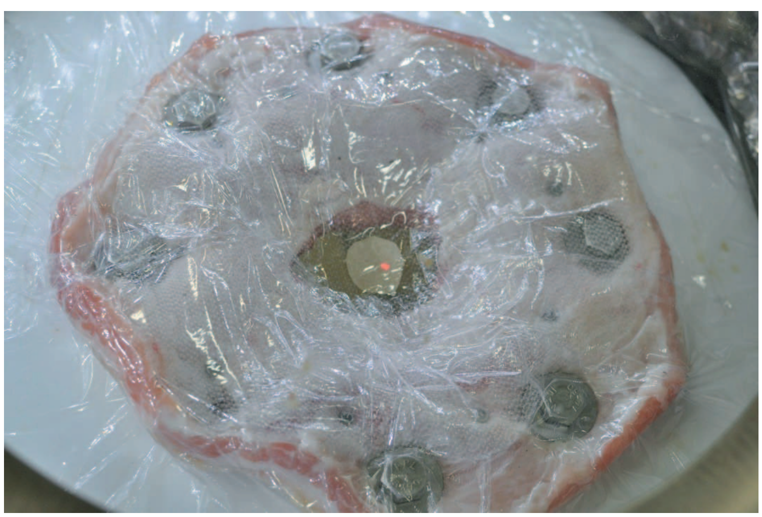

**Figure 4.** Porcine specimen comply with hernia repaired by a synthetic implant

The same synthetic implants were applied in the experiments and the calculations. The applied load was represented by a triangular function the values of which were increasing until the maximum during 0.1 s and then decreasing to 0 during the next 0.1 s. The whole analysis was performed during 2 s. The sample displacements were measured by laser sensors and provided for a comparative analysis for the model accuracy checking.

### 4.2. Simulation results

The models were loaded by an air impact simulating the postoperative cough. The implant maximum deflection as well as the displacement of the hernia edge undergoing the abdominal pressure was calculated and compared with the experiments as shown in Figure 5. The displacements of tacks in the mesh plane identified during the experiment were also included in the model. The results presented a relatively good accordance of the simulations within the experiments. That means that the mechanical models accurately represented the dynamic behaviour of the tissue-implant system. The experiment showed the tissue-implant system viscoelasticity, which was not considered in the modelling. Since the short moment of the load acting is crucial in the analysis, it was only the elastic material behaviour of the model that was assumed, hence the membrane deflection decreased significantly while unloading. However, as the fundamental danger results only from the highest abdominal pressure, it is only the extreme values of implant displacement and hence the junction forces that were considered. The model accuracy in this area was satisfactory.

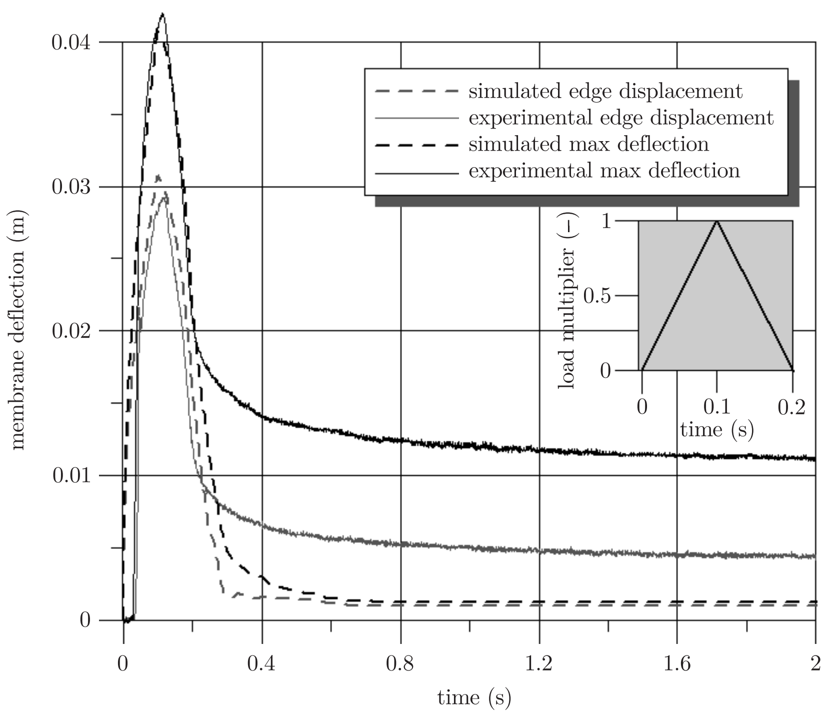


**Figure 5.** Finite element simulation results for 5 cm diameter hernia repaired by Dyna Mesh synthetic implant with 10 joints every 4 cm

The dynamic analysis demonstrates relatively strong damping in the tissue-implant system, therefore the Rayleigh damping parameters were introduced also to the mechanical model. The mass and stiffness damping parameters were estimated on the basis of modal analysis according to the formula:

$$\xi_i = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2} \tag{1}$$

where $\alpha$ and $\beta$ are the mass and stiffness damping, respectively and $\omega_i$ represents $i^{\mathrm{th}}$ natural frequency of the system [20]. These two coefficients were estimated as $\alpha = 0.9$ and $\beta = 0.02$, for which the simulation best fits to the experimental results.

The second repair model with tacks placed every 3 cm was also analysed. The same damping parameters were applied in the simulation and accurate results were achieved (Figure 6).

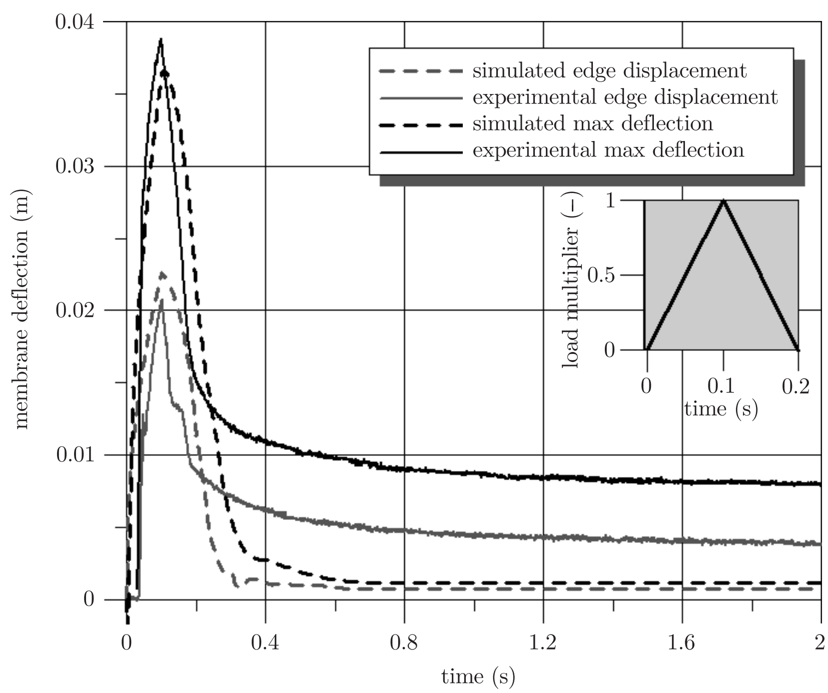


**Figure 6.** Finite element simulation results for 5 cm diameter hernia repaired by Dyna Mesh synthetic implant with 10 joints every 3 cm

The accuracy of the simulations in relation to the experimental results for both the considered variants of the operated hernia model indicates the correctness of the proposed solutions.

### *4.3. Assessment of repair durability*

An important issue in the analysis is the value of the junction force represented by the reaction forces of both systems under pressure. The maximum value of the reactions should not exceed $H = 9.05\,\mathrm{N}$, which is the value of the fascia-implant connection strength identified on the basis of the one dimensional

**Table 1.** Extreme reaction forces in analysed hernia repairs simulations

| Fastening system | $R_{\max}$ [N] | $R_{\min}$ [N] |
|---|---|---|
| Dyna Mesh, 10 joints every 4 cm | 8.11 | 7.33 |
| Dyna Mesh, 10 joints every 3 cm | 6.44 | 5.95 |

tensile test presented in [5]. Hence, this term can be applied to the assessment of the repair durability. The extreme reaction forces in both orthogonal directions for the analysed models are shown in Table 1.

The maximum reaction acts in the direction corresponding to the direction of the maximum elastic modulus of the implant. For the analysed systems this force does not exceed the limit what means that the connection will not be broken under the pressure load of 270 mm Hg. This is also confirmed by the experiments where no damage of the repair was observed.

## 5. Conclusions

In the study the author proposed and analysed a mechanical model of hernia repaired by a synthetic implant. The hernia size and fixing system corresponds to a clinical case. The proposed model of implanted surgical mesh represents accurately the dynamic behaviour of the tissue-implant system as presented in the comparison of the simulation with the experimental results.

The reaction forces of the model represent the junction forces in the implant and tissue connections. Since no specific procedure for hernia repair assessment exists and all the surgeries are made on the basis of the intuition and experience of doctors, the forces obtained in the analysis can be used in the evaluation of the repair durability. As shown in the simulation results, the forces achieved from the proposed model do not exceed the limit value identified and presented in literature. This fact corresponds to the experimental results of the same cases of operated hernias where no damage is observed under the extreme pressure load.

The values of the minimum and maximum reaction forces reflect clearly the implant orthotropy. This means that also the mesh orientation should be taken into consideration when operating hernia due to the anisotropic properties of the human abdomen [21] and highly different strains range identified in different parts of the torso due to the human physiological activity [22, 23].

The proposed tissue-implant model of repaired hernia can be used for both the repair strength estimation and the mesh placement analysis. This will result in important clinical advice for the planning of hernia surgeries.

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The calculations were performed at the Academic Computer Center in Gdansk, Poland.

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