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MODELING OF PHOTOCHEMICAL AND PHOTOTHERMAL EFFECTS IN SOFT TISSUE SUBJECTED TO LASER IRRADIATION

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A number of photochemical, photothermal, photoablative, and photoionization effects take place in the tissue exposed to the laser. These effects are used in various medical procedures. An example of a treatment that uses photochemical effects is photodynamic therapy (PDT) aimed at destroying cancer cells. Photosensitizer particles are introduced into the tumor area, which, when exposed to a specific wavelength of light, create conditions that are toxic to the diseased cells. The mechanism used here is the transformation of the standard triplet form of oxygen into its singlet form.

In addition to the photochemical changes in the tissue, there may be an increase in tissue temperature that can result in alteration of tissue parameters and, in extreme cases, thermal damage to the tissue.

The work concerns the numerical analysis of phenomena occurring in tissue subjected to laser irradiation. The task includes steps related to the modeling of laser energy deposition, temperature distribution, and photochemical reactions in tissue.

To determine the propagation of light in biological tissues, various approaches can be used. In typical soft biological tissue the scattering dominates over the absorption, so in this paper the steady-state optical diffusion equation is taken into account.

To describe the temperature field in the tissue, the Pennes bioheat transfer equation is used. These equations contain, among others, heat source functions related to metabolism, perfusion, and laser irradiation. Additionally, the perfusion coefficient is assumed to be dependent on thermal damage.

The model related to photochemical reactions contains a set of coupled, time-dependent differential equations of concentration for triplet oxygen, singlet oxygen and photosensitizer. In addition to the photochemical parameters directly related to the type of photosensitizer, the equations take into account the rates at which triplet oxygen is delivered to the surrounding tissue.

At the stage of numerical realization, for solving optical diffusion equation and set of concentration equations, the finite difference method is used, while for solving the Pennes bioheat equation, the boundary method is applied.

MODELING OF THE INFLUENCE OF ELEVATED TEMPERATURE ON OXYGEN DISTRIBUTION IN SOFT TISSUE

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As a result of an increase in the temperature of biological tissue, which may be the effect of an external heat impulse, the thermophysical parameters of the tissue may be altered. Special attention should be paid to the perfusion coefficient, which is often treated as an indicator of tissue thermal damage. It should also be noted that biological tissue contains blood vessels of various sizes: arteries, arterioles, capillaries, venules, and veins. The general description of the presence of blood in these vessels is described by the perfusion coefficient.
One of the most essential functions of blood is to transport oxygen from the lungs to the tissues. Gas exchange between blood and tissues takes place in the smallest blood vessels, the capillaries. An increase in tissue temperature also causes a change in the velocity of blood in the capillaries, which affects the transport of oxygen to the tissues and, as a consequence, can lead to hypoxia.
The work is concerned with the numerical analysis of the phenomena occurring in the 3D domain of a biological tissue subjected to an external thermal impulse. The analysis is based on the bioheat transport equation in Pennes form. Using the Arrhenius scheme, the degree of thermal damage to the tissue is estimated, and, tissue parameters are treated as temperature- or damage-dependent.
The thermal model is supplemented with an additional model in order to analyze changes in the partial pressure of oxygen in the capillary vessel and surrounding tissue. This model is based on the Krogh cylinder concept, and the problem is axisymmetric. The main equation that describes the distribution of partial oxygen pressure in the tissue subdomain includes a component related to oxygen consumption in the tissue, while the equation for the capillary subdomain takes into account blood saturation and its relationship to partial oxygen pressure. The oxygen distribution model is linked to the thermal model through the relationship between blood velocity in the capillary and the perfusion coefficient.
At the stage of numerical realization, mainly the finite difference method is used, and the analysis is concerned with the influence of the thermal model parameters on the temperature distribution and thermal damage of the tissue, and the impact of the oxygen distribution model parameters on the occurrence of hypoxia in the tissue surrounding the capillary.

COMPARATIVE ANALYSIS OF SLOW FREEZING AND VITRIFICATION METHODS USING INTERVAL ARITHMETIC

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The paper presents numerical simulations of heat transfer in the biological tissue during cryopreservation. We have considered the two-dimensional, homogenous, and cylindrical sample.
Cryopreservation is the process in which biological structures are frozen and stored at low temperatures. It can be performed in various ways. Slow freezing and vitrification are commonly used for that. These approaches differ mainly in cooling rate and cryoprotectant (CPA) concentration. Slow freezing has a low cooling rate and low CPA concentration, which can cause the formation of ice crystals to be a danger to tissue. Vitrification, in contrast, is characterized by high cooling rates and high CPA concentrations, which contributes to the chemical toxicity to the tissue. In the research, calculations have been conducted for both methods.
The mathematical model of thermal processes is described by the Pennes equation. It was supplemented by the boundary conditions of the second or third type that are associated with methods simulated (slow freezing or vitrification) and the initial condition. In addition, the governing equations contain the phase changes phenomena implemented by the procedure called the 'one domain method', also known as the 'fixed domain method'.
The numerical model is based on the finite difference method (FDM) applying the interval arithmetic rules. Note that the thermophysical parameters are introduced as interval numbers with perturbations +/- 5%. Thermophysical parameters depend on many circumstances. Therefore, it is not reasonable to use a deterministic approach with them with average values given, for example, in the literature. On the other hand, stochastic and randomized modelling can be introduced, which unfortunately is time-consuming. Interval arithmetic is a simplification of complex stochastic modelling and also introduces an element of randomness that is not present in deterministic models.
The final part of the paper includes a comparison of calculations achieved for two types of simulation, cryopreservation by slow freezing and vitrification. The results obtained are represented by the ranges that comprise the correct values of the temperature distribution.

INFLUENCE OF 3D PRINTING ON THE GEOMETRICAL AND MECHANICAL PROPERTIES OF MESH

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Scaffolding in the shape of mesh structures is commonly used in various medical implants (e.g intervertebral fusion cages) whose task is to ensure stable connection at the implant-bone interface. The use of 3D printing technology allows to control the filling density and create spatial structures characterized by mechanical properties favouring osseointegration with bone tissue [1].
The main goal of this study was to determine the impact of 3D printing technology on mechanical and geometrical properties of analysed mesh structures by experimental and numerical methods.
Our research was carried out on the geometry of meshes, where the construction of a single element was based on the connection of two six-armed pyramids described by the dimensions: width of the shoulder spacing (2mm and 1.8mm), height of the connection of the arms between the pyramids (0.2mm and 0.24mm), height of the elements corresponding to the distance between the two pyramid vertices (1.8mm and 1.6mm).
Mesh structures made of Ti6Al4V powder by the SLA method were subjected to the indentation test utilizing spherical indenter (5mm diameter). The test was carried out to damage of structure with a speed of 2mm/min. After test, microscopic analysis of the mesh structures was performed utilizing light microscope. Subsequently, indentation was recreated with finite element method to assess the stress and displacement of analysed structures. Furthermore, numerical analysis of a single element, loaded with force corresponding to the intradiscal pressure, was performed.
Both experimental and numerical analysis show a significant impact of connection height. Analysis of single element and experimental indentation test indicates lower values of stiffness for structures with 0.2mm connection height. The highest stiffness coefficient was equal to 2570N/mm (single element analysis) and 231 +/-6N/mm (experimental indentation test). Additionally, numerical recreation of indentation test and single element analysis show negative corelation between connection height and displacement, however experimental approach did not indicate this dependence. The highest value of maximal displacement was 1.75e-5mm (single element analysis) and 3.76mm (indentation recreation).
Both numerical analyses of segment and whole structure show dependence of stress and displacement distribution on element height, shoulder spacing width and connection point height. Stress distribution obtained as a result of numerical indentation recreation show areas of stress values exceeding mechanical strength of analysed structures. However, damages resulting from experimental indentation were observed in slightly different areas. Microscopic analysis shows that printed structures significantly vary from geometrical models - a possible cause of observed differences.

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BIORESORBABLE STENTS: DESIGN, SIMULATION AND EXPERIMENT CASE STUDY

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The paper focuses on bioresorbable stents made of PLLA. Stents of this type have significant advantages, among which full bioresorbability can be mentioned, but also disadvantages that cannot be ignored. The disadvantages include the lower radial support of stents made of bioresorbable materials compared to stents made of, for example, nitinol. For this reason, the geometry of the stent should be well thought out when designing the stent.

In the first stage of work, a stent was designed in CAD software, whose geometry allowed adequate radial support of the blood vessel to be provided, but at the same time did not cause disturbances in blood flow. In the next stage, the stent was fabricated using micro-injection moulding. The fabrication technique is important to ensure that the stent has adequate mechanical properties and functions properly both before and after being placed in the patient's body. The stent is manufactured in an open form and must be closed on the guide wire prior to insertion during the angioplasty procedure. Therefore, both the manufacturing technique and the design process must be well thought out. Therefore, several CAD models of the stent were made and numerically calculated before selecting the appropriate stent geometry for fabrication.

In the next step, the fabricated stent was subjected to experimental studies using the DIC technique. This technique is used due to the small size of the test piece. It allows us to obtain accurate results from a speckle pattern applied to the stent, whose deformation during strength tests is recorded by a camera. In this way, the strength properties were determined during basic tests, such as stent tension, compression, or bending. The results obtained experimentally were compared with the results of the same tests simulated numerically. This approach allowed the validation of the numerical models and valuable information from the experiment about the behavior of the stent in reality. On this basis, a material model was determined, which should be used during numerical simulations to make their results as reliable as possible.

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NUMERICAL MODELING OF LASER INDUCED HIGH-TEMPERATURE HYPERTHERMIA USING THE DUAL-PHASE LAG EQUATION

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High-temperature hyperthermia is an effective and safe method of tumor destruction. This method has a high success rate in the treatment of melanoma, sarcoma, lung, esophageal and liver tumors.
The paper presents a numerical simulation of heat transfer in the soft tissue containing the tumor during laser irradiation. The temperature distribution is described by the dual-phase lag (DPL) equation supplemented by appropriate boundary and initial conditions. The evaporation of water contained in the tissue is taken into account by defining the effective specific heat. The laser source function in the DPL equation contains the total light fluence rate, which is a sum of collimated part and diffuse part. To determine the diffuse fluence rate the steady-state optical diffusion equation supplemented by boundary conditions should be solved. The thermophysical and optical parameters of soft tissue occurring in the equations are assumed to be temperature dependent. The coupled non-linear problem is solved using implicit scheme of the finite difference method. Based on the temperature distribution the Arrhenius integral is calculated which is the measure of degree of tumor destruction.

ANALYSIS OF CRYSTALLIZATION DEGREE DURING CRYOPRESERVATION APPLYING INTERVAL ARITHMETIC

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In the paper, we present numerical computations of heat transfer and changes in biological tissue caused by the crystallization phenomenon during cryopreservation. The homogeneous sample in cylindrical coordinate system is examined.

The purpose of cryopreservation is to store cells or tissues at low temperatures. There are several basic methods to perform them. One of the most popular approaches is cryopreservation by slow freezing. In slow freezing, the cooling rate and cryoprotectant (CPA) concentration are low. The disadvantage of this method is the formation of ice crystals, which can cause cell damage.

Heat transfer is modeled by the Pennes equation, which is based on the Fourier equation complemented by two variables called the perfusion heat source and the metabolic heat source. The model is supplemented by initial conditions and boundary conditions of the second or third type, which simulate the cryopreservation method. The mathematical description also includes the phenomenon of phase changes using the method named the 'one domain method' or the 'fixed domain method'. Furthermore, the non-isothermal kinetic equation is applied to predict the non-equilibrium crystallizing process.

Tissues and other biological structures are not inherently characterized by strictly defined properties. During experimental studies, the element of randomness is present. Despite this, scientists often take averages of the values of measured quantities and examine the deterministic model. The second modelling approach is to use stochastic models, for which a lot of computational time is usually spent. In our study, we decided to use the so-called golden mean. The numerical analysis is performed using the finite difference method (FDM) with the application of interval arithmetic. Thermophysical parameters such as the thermal conductivity and the volumetric specific heat are introduced as interval numbers. In effect, the results of the simulation are ranges of values determined.

The final version contains details of the numerical algorithm and discussion of the temperature distribution, and the degree of crystallization received from the calculation.

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THE IMPACT OF TRANSVERSE CONNECTOR IN SPINAL FIXATION: THE NUMERICAL AND EXPERIMENTAL ANALYSIS

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Current clinical practice focuses on minimally invasive surgery. This technique saves functional spinal units and thus significantly shortens the procedure. Therefore the question arises, whether it is beneficial to use transverse connectors in the construction of fixation system, in the case of a compression vertebral fracture, in order to improve the stability of the damaged spine column [1-2]. The use of two connectors is a classic stabilization technique, thanks to which the frame system is obtained. However, such systems are increasingly being replaced by a single connector. At the same time, discussions are ongoing on the desirability of using transverse connectors in the fixation system.

The main aim of study was the analysis of the impact of using transverse connector of pedicle screw fixation on mechanical parameters of the thoracolumbar spine (Th7-L5) under conditions of its instability. The assumed aim of the study was carried out through experimental research (on an animal model of the spine) and numerical simulations using the finite element method.

In both studies, five configurations of the model were considered: physiological, with compression fracture of the Th12 vertebra, with long segment stabilization, with long segment stabilization and one connector, with long segment stabilization and two connectors. In each of the cases considered, a pure bending moment in flexion (equal to 7 Nm) was applied to the superior endplate of the upper vertebral body (Th7). All configurations of the model were fixed by deducting all degrees of freedom on the inferior endplate of the lower vertebral body (L3).

Experimental and numerical studies allowed analysis of stiffness and dissipation energy, as well as evaluation of the range of mobility and intradiscal pressure in individual intervertebral discs during the use of various configurations of the fixation system.

On the basis of the analysis of the impact of transverse connector on the obtained results, it was shown that their use in the constructs of stabilization causes a slight increase in stiffness and limitation of mobility, in relation to the stabilization without connectors. However, in both cases of a configuration with a single connector or two connectors, the increase in the average value is in the range of 2-4 Nm/rad. It should be noted that the elimination of transverse connectors can contribute to shortening the time of the surgical treatment, additionally avoiding damage to the spinous process and interspinous ligaments.

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MODELING OF THE PROCESS OF FUNCTIONAL ADAPTATION OF THE BONE TISSUE AROUND THE IMPLANT

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Bone is mineralized tissue with a complex hierarchical structure, whose microscopic and macroscopic arrangement gives it specific biological and mechanical properties. It undergoes continuous remodeling processes which change the bone tissue structure quantitatively and qualitatively, and this process is influenced by a number of mechanical, biological and chemical factors. This study undertook a biomechanical analysis of the implant-bone interaction and the determination of its effect on bone tissue remodeling.

Several types of bone tissue adaptation models can be found in the literature [2][3], but the authors focused on a bone tissue adaptation model which was based on the assumptions of the Beaupré and Carter model [1]. The developed model of iterative simulation of the process of functional adaptation of bone tissue allowed to evaluate the influence of mechanical stimuli and biological factors on the process of tissue remodeling around the implant. The influence of selected biological factors such as age and disease of a patient was analyzed.

A case of a canine long bone fracture stabilized with an intramedullary nail was analyzed. The geometrical model of the bone was created based on medical imaging data, and the material parameters implemented in the model were taken from literature results and our own research. The iterative adaptive procedure model allowed authors to compare bone tissue behavior during fracture healing using intramedullary nails locked with bicortical bolts, which are embedded in both sides of the femur cortex, and monocortical bolts, embedded only on one side of the femur cortex.

Analysis of results of the simulations, which took into account biological factors, showed that the factors have real influence on the intensity of changes in the remodeling process. The results showed differences in the process and final state of remodeling depending on mechanical stimulation and biological factors.

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BIOMECHANICAL ANALYSIS OF THE CHORDAE TENDINEAE STRUCTURE OF THE DOGS ATRIOVENTRICULAR APPARATUS

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The mitral atrioventricular apparatus is composed from the mitral ring, valve leaflets, papillary muscles, and chordae tendineae (CT). CT are responsible for the mechanical functions of the valve [1]. The chordae tendineae are deciding of the leaflet suspension system of valve tension at end of systole and are built from inelastic cords of fibrous connective tissue that connect the papillary muscles to the tricuspid valve and the mitral valve in the heart. Myxomatous mitral valve disease (MMVD) is the most common acquired cardiovascular disease in dogs and accounts for approximately 75% of chronic heart failure disease. The etiology of the myxomatous process is still unknown [2]. Myxomatous mitral valve disease is characterized by disorganization of the structural elements of the leaflets and weakening of the chordae tendineae. These changes cause a significant loss of mechanical properties of the valve and often lead to valve prolapse and/or mitral regurgitation. Accumulation of collagen and glycosaminoglycans is observed in the mucinous mitral leaflets. This degenerative process also affects CT [3].
This study investigated the mechanical properties of chordae tendineae for physiological and dysfunctional cases and the effects ofthese changes were analysed in the biomechanics point of view of the atrioventricular apparatus in dogs.
A mechanical characterization was performed for the chordae tendineae using a static tensile test. Histological studies were performed to verify the structural CT.
The material for investigation was taken post mortem from the hearts of 40 dogs. 5-7 CT were preparand from one dog. Two chordae tendineae from each animal were examined histopathologically, and the rest were examined biomechanically. The study provided data for the development of a numerical model of the atrioventricular apparatus in dogs, taking into account the structures of the chordae tendineae.
The results were analyzed to explain whether changes in the mechanical strength of the chordae tendineae are linked to changes in their structure. The work provides insight into the process of chordae tendineae fracture that occurs during degenerative mitral valve disease in dogs.

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DESIGN AND EXPERIMENTAL VERIFICATION OF THE STENTS FOR THE TREATMENT OF URETHRAL STENOSIS

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Urethral stenosis is a disease affecting mainly men. Treatment is based on restoring patency of the lower urinary tract [1]. Current treatment relies on the use of metal stents. This approach involves reoperation to remove the sent, which additionally causes discomfort and trauma. These problems prompt the require of material with specific mechanical, chemical, and biological properties characterized by auto-degradation. This process should a care out within the time frame necessary for the tissue remodelling of urethra. As a result, there has been a suggestion for treatment using hybrid stents with a rigid core and a surface layer based on sodium alginate. This seems natural because of the biological properties of alginate, i.e., biocompatibility, biodegradability, and tissue-forming ability, as well as because of the benefits of not needing to remove the stent from the tubular canal after treatment [2].
The purpose of this study was to analyse the effect of using a hybrid stent with a rigid core and hydrogel layer in removal of obstruction of the urethral canal in the treatment of urethral stricture.
The experimental studies and numerical modelling were used during the analysis. In the first stage, numerical studies were performed to reproduce the conditions in the urethra with the inserted stent during urine flow. The results of this part provided information on the different variants of the designed stents. The study allowed identification of the most optimal stent. The in-vivo experiments on New Zealand White Rabbits were used for definition of boundary condition for numerical models.
This study examined the possibility of developing stent designs in the restoration of urethral canal patency during the treatment of urethral stenosis.

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CERVICAL SPINE INJURIES DURING CAR COLLISIONS WITH ROAD SAFETY BARRIERS - FINITE ELEMENT STUDY

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Every year number of people die on roads and are injured. Often, outcomes of accidents involve spine injuries, including its cervical section. One of the measures of injury risk is the Neck Injury Criterion, which was described in FMVSS208. It indicates the probability of cervical spine injury based on internal forces analysis. In practice, these forces are determined from crash test dummies, however, they can be also acquired from numerical simulations. This research focused on conducting numerical simulations of vehicle collisions against three types of road safety barriers (RSBs). The aim was to compare the specific safety characteristics between the analyzed RSBs.

The FEM environment - LS-DYNA was used to carry out simulations. The models used for the simulations were first validated with experimental results, as in NHTSA DOT-HS-812-545 report. For validations of RSBs, the PDCEN/TR16303 report was used, along with statistical techniques suggested in report of NCHRP project 22-24. After the models were validated, the normative TB32 test was simulated with three types of RSBs: the L1W4A cable barrier, the H1W4A w-beam barrier and the H2W5B concrete barrier. For all tests, the impact severity indices were determined, according to EN1317. Additionally, Neck Injury Criterion (NIC) and Head Injury Criterion (HIC) were calculated according to FMVSS 208.

The simulation results showed that all of the analyzed barriers acquired impact severity classes consistent with those presented in the European certificate. The concrete barrier was classified as severity class B, while the cable and w-beam barrier were classified as class A. HIC metrics for all considered collisions were below the safety limits, indicating a low risk of skull fracture during these accidents. NIC values indicated that the cases of cable and w-beam barriers had a low risk of neck injury, where the maximum NIC was for tension-flexion mechanism and equaled 0.96 and 0.84, respectively. For the concrete barrier that was not the case, where maximum NIC equaled 1.30 under coupled compression-extension, which indicated a high risk of injury in the cervical spine.

The analysis showed that for the TB32 crash test against the H2W5B concrete RSB there is a risk of cervical spine injury. This risk was estimated on the basis of the NIC index, which is described in the US Standard. Basing on this index, it was also observed the possible injury mechanisms differ between the analyzed barrier types. For the concrete barrier, the maximum NIC indicated the injury in compression-extension. On the other hand, the other types of barriers had the maximum NIC in the tension-flexion of the cervical spine.

THE INFLUENCE OF TEST CONDITIONS ON IDENTIFIED PARAMETERS OF THE CONSTITUTIVE MODEL OF THE KNITTED ABDOMINAL PROSTHESIS

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Abdominal prostheses are used to cure ventral or groin hernia. To develop medical procedures mechanical calculations are made in which behaviour of different materials under physiological load is simulated. The prostheses are usually knitted or woven structures with anisotropic properties. Constitutive modeling of such structures demand preferably biaxial tests. Two different ways to provide such tests are presented in the literature. They are force-driven [1] or displacement-driven [2] tests. The authors in [3] point that in the force-driven biaxial tests case alone different parameters of constitutive model are obtained when applying different parameters of the control. The authors of the preset paper show a major difference in the parameters of Gasser-Ogden-Holzapfel (GOH) model of a selected abdominal prosthesis when identified based on force- or displacement-driven biaxial tests with various ratios in two directions of control [4]. To select a test providing the proper parameters to be used in simulations of the implant behaviour under intraabdominal pressure, results of different numerical set-ups were compared to outcome of ex-vivo experimental observation of the prosthesis under pressure. In this model the implant was fixed to a portion of porcine abdominal wall by surgical staples and such system was loaded by dynamic pressure, simulating cough. Position of a damaged fixation point pointed at position of extremal reaction force. Taking this position as a tip, numerical models with different sets of constitutive parameters were investigated to find the set leading to similar position of extremal reaction force as obtained experimentally. The approach allowed to recommend equibiaxial force-driven test to determine parameters of GOH law to model behaviour of the prosthesis under pressure load.

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FINITE ELEMENT- AND META-MODELLING OF ABDOMINAL WALL WITH AN IMPLANTED HERNIA MESH

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Although the procedure for treating an abdominal hernia is quite common, it requires further development due to the number of relapses and other postoperative issues, like pain or discomfort. A solution may come from in silico testing, where computational models can be employed to predict the behavior of a complex system consisting of an abdominal wall and a surgical mesh. To use the model in the optimization of hernia repair parameters, the uncertainty quantification (UQ) and the sensitivity analysis (SA) should be performed as steps of model credibility assessment.

The presented work concerns the modeling of the abdominal wall with an implant using the finite element method. The abdominal wall with a hernia orifice covered by an intraperitoneal onlay mesh subjected to intraabdominal pressure is modelled by shell finite elements. The material parameters of hyperelastic Gasser-Ogden-Holzapfel [1] model used for abdominal wall and its fibers direction are assumed to be uncertain and treated as random variables. What is more, orthotropic implant orientation is also a random variable. Regression-based polynomial chaos expansion is used as meta-modelling method to perform uncertainty propagation and global SA with low computational cost [2]. The choice of sampling points is based on previous study on UQ in case of local models of surgical mesh [3]. Performed analyses is focused on the quantities important for further optimization [4]. First quantity of interest (QoI) is the maximum force in the connection of the implant and the abdominal wall as hernia recurrences are usually caused by failure of the connection. Second QoI is the displacement of the implant related to the issue of too extensive bulging of the surgical mesh. Sobol indices are computed as a measure of global SA.

The influence of each variable uncertainty on the variance of outputs for cases of various commercial surgical meshes is reported. The research is a step towards a credible model of abdominal wall-implant system and its further optimization.

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