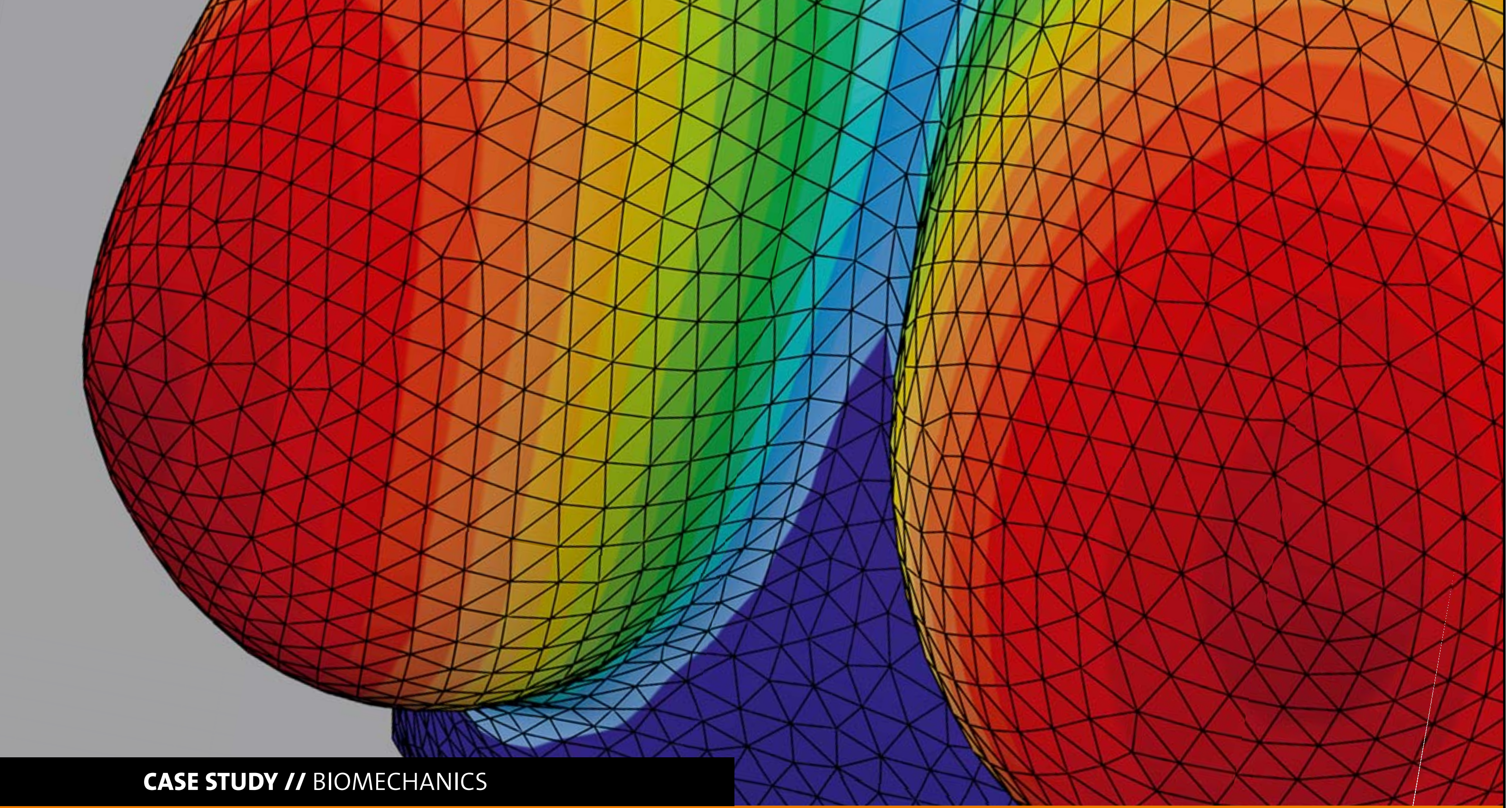

CASE STUDY // BIOMECHANICS

OPTIMIZATION IN THE PLANNING PHASE OF OPERATIONS ON THE FEMALE BREAST

For the surgical constitutive modelling of the female breast, material parameters can be optimized using finite element simulation with optiSLang and ANSYS based on MRI data and 3-D surface scanning.

Optimization task

In the planning phase of operations on the female breast, e.g. breast reduction or breast reconstruction after tumour removal, surgeons usually have to rely solely on their experience acquired in previous procedures and their individual set of skills. Today, these interventions are commonly planned by manually drawing reference lines on the breast. Modern, computer-based planning tools have not yet found their way to the operating room. The benefit of these methods has been shown in other disciplines like engineering and physics, but still there is a lack of acceptance in the medical sector, especially when it comes to surgery planning. However there is remarkable potential for these computational methods in this field of application.

For an accurate planning of breast surgeries it is fundamental, to have sufficient understanding of the behaviour of the biological soft tissue under mechanical loading. For the simulation of the resulting deformations, numerical approaches such as the finite element analysis (FEA) are commonly used in mechanical and civil engineering. Even though numerous studies have been published to acquire material parameters with various material testing devices, yet no consensus could be found nor on the theoretical models to be used to simulate the mechanical behaviour of the breast's soft tissue, nor on reliable magnitudes of parameters that describe its stiffness. Theoretical models range from simple linear elastic models over various hyper-elastic approaches, such as Neo-Hookean, Mooney-Rivlin or Ogden to visco-elastic formulations. In addition the stiffness which is described in literature for these tissues is not even always in comparable magnitudes: up to a factor of 30 lies between the softest and hardest material formulation that has been proposed, depending on the strain level. It is evident that there is further need for research on this subject.

Here, we want to introduce a method that takes advantage of the optimization algorithms provided by the software optiSlang to find the optimal set of material parameters for the mechanical modelling of the breast's soft tissue. The presented approach is applicable for different theoretical models and may deliver patient individual optimal material properties that may further be used as valuable input data for the simulation and planning of surgical interventions. For this procedure, a combination of magnetic resonance imaging (MRI) and three-dimensional body surface scanning (3-D) together with finite element simulations with the software package ANSYS is used in an automated process chain. Material properties of the investigated tissues are used as design variables for parametric optimization loops on this process chain where simulation results are compared to the acquired patient individual imaging data.

Material and Methods

In contrast to other approaches that use tensile testing devices to create stress-strain relationships for the investigated biological materials the procedure which is described in this paper does not involve any real physical test on specimens. Instead it relies on two modern non-invasive imaging methods that do not require any contrast agents to acquire the necessary patient individual data.

Firstly, MRI imaging data is used to access the inner anatomy of the chest region of the test persons. However this imaging technique has the shortcoming that conventional MRI can only be performed for the patients lying horizontally in the tube. Though, open MRIs where patients can stand upright do exist, they are more expensive and by far less common compared to the standard horizontal MRI devices that are available in most hospitals.

Hence to acquire the standing positions a different technique was used: 3-D surface scanning. This bears the advantage of being relatively economically. With scanning devices that more and more leave the niche of expert applications and enter the consumer market, they can easily be afforded even for resident physicians in private practices. But of course these devices are only suited for the acquisition of the patients skin surface geometry and deliver no information about the underlying anatomical parts. Thus, a combination of both imaging modalities is still necessary. For the presented study, 3-D data derived from a collective of eight healthy female test persons was used.

3-D Surface Scanning

The imaging in upright position was performed using a surface scanner that uses laser triangulation technique (Konica Minolta Co., Ltd., Osaka, Japan). This system has largely shown its applicability to breast shape measurements in preliminary studies of the research group Computer Aided Plastic Surgery at Klinikum rechts der Isar in Munich. The 3D surface scans of the subjects were performed in standing position on predefined markers on the ground under standardized lighting conditions with the scanner facing the participants in +30, 0 and -30 degrees relative to the lens in standing position. The volunteers were asked to inhale and hold their breath for the time of the acquisition. The so produced data was processed in appropriate software (Geomagic Studio 12®, Raindrop Geomagic, Inc., NC, USA) to create one surface representation of each volunteer's chest.

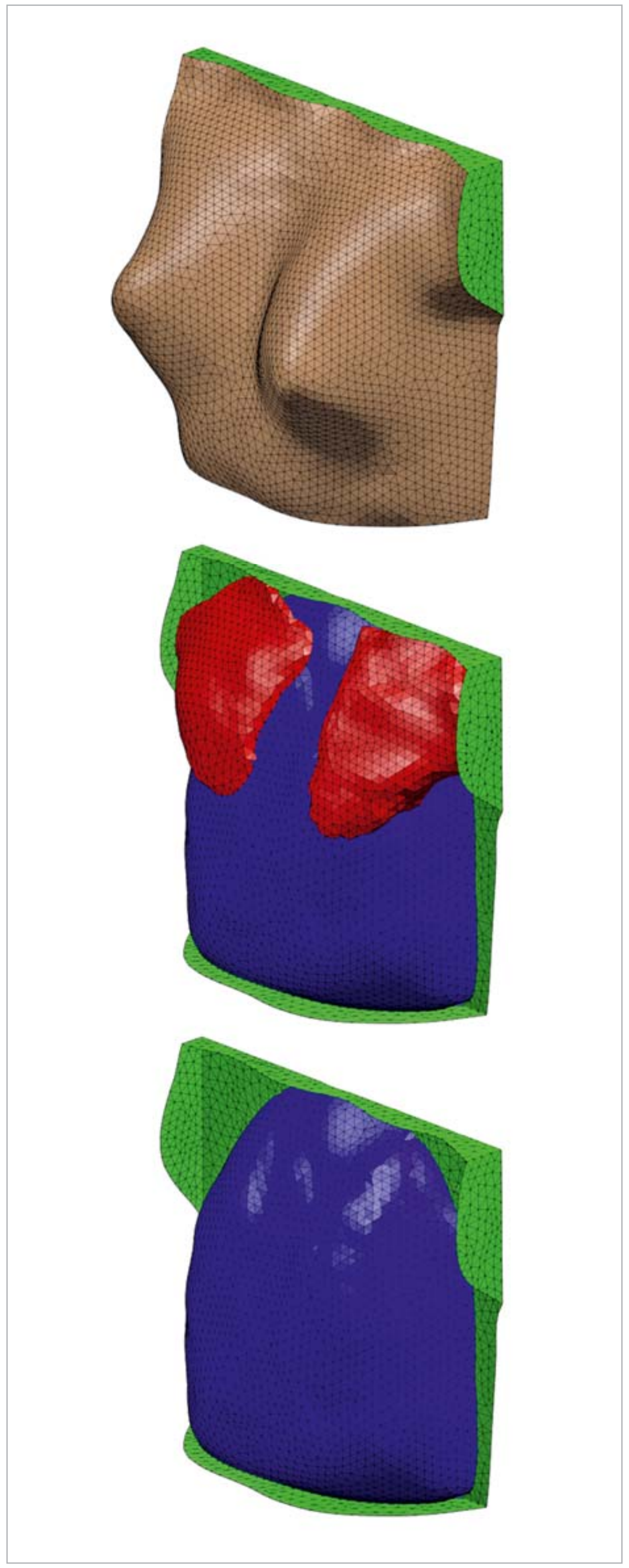

Fig. 1: Finite element models derived from segmentations of MRI data in prone position. Full body model (top), internal geometry of the pectoral muscles (middle), thoracic wall and fixed system boundaries (bottom)

Magnetic Resonance Imaging

Volumetric Magnetic Resonance Imaging (MRI) data of eight volunteers was acquired with the aid of a Philips Achieva 1.5 Tesla MRI scanner, using a spacing of 0.994 mm x 0.994 mm x 2 mm. The thoracic images were obtained

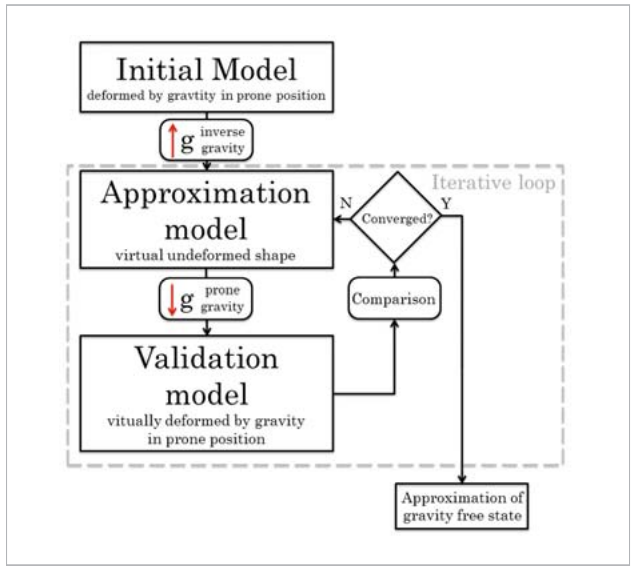

Fig. 2: Principle sketch of the iterative procedure for the approximation of the load free configuration.

with the participants lying in prone position. It was taken care that the breasts did not touch the bench, which was achieved by pillow support at the clavicle, neck and shoulder region as well as further down to the lower belly area and the pelvic crest region. However the breast soft tissue is not without deformed because gravity forces still act and cause a non-negligible deformation of the breast. Thus only the shape of the free hanging breast can be delivered for further processing in imaging software packages. The volumetric MRI data was segmented (used software: Mimics® 14.0, Materialise Inc., Leuven, Belgium) into different anatomical compartments and finite element models were derived out of this data.

Finite Element Simulations

Boundary conditions in the simulation were rigid fixation at the thoracic wall (i.e. the rib cage) and at the lateral system boundaries that have been defined by a standardized box around the region of interest of the simulation. In order to focus on the breast soft tissue behaviour solely, in the here used modelling the muscular tissue has been approximated to be rigidly fixed as well. An example for a utilized finite element mesh including the system boundaries is shown in figure 1. The theoretical material model that has been used in this particular study was the hyper-elastic Neo-Hookean formulation.

Iterative inverse calculations

As previously mentioned the starting configurations of the models that are based on MRI images taken in prone positions may not directly be used for finite element simulations because of the unknown initial deformation due to gravity. Due to the soft constitution of the tissue, the breast is highly deformed even if besides gravity no other forces are acting. But for mechanical simulations, an unloaded state of the geometries has to be known to be used as the starting geometry by the simulation. Calculating the non deformed reference state out of a known deformed configuration can be classified as an inverse problem. Due to the high deformation and the hyperelastic material behavior, a simple, one-step inverse calculation with inversed gravity loading is not satisfyingly accurate. To address this issue in this work, a heuristic approach has been used and has been implemented in ANSYS APDL. This procedure is capable of calculating a stress free representative of the model based on a geometry which has been acquired under gravitational loading. The principle workflow of the method is shown in figure 2.

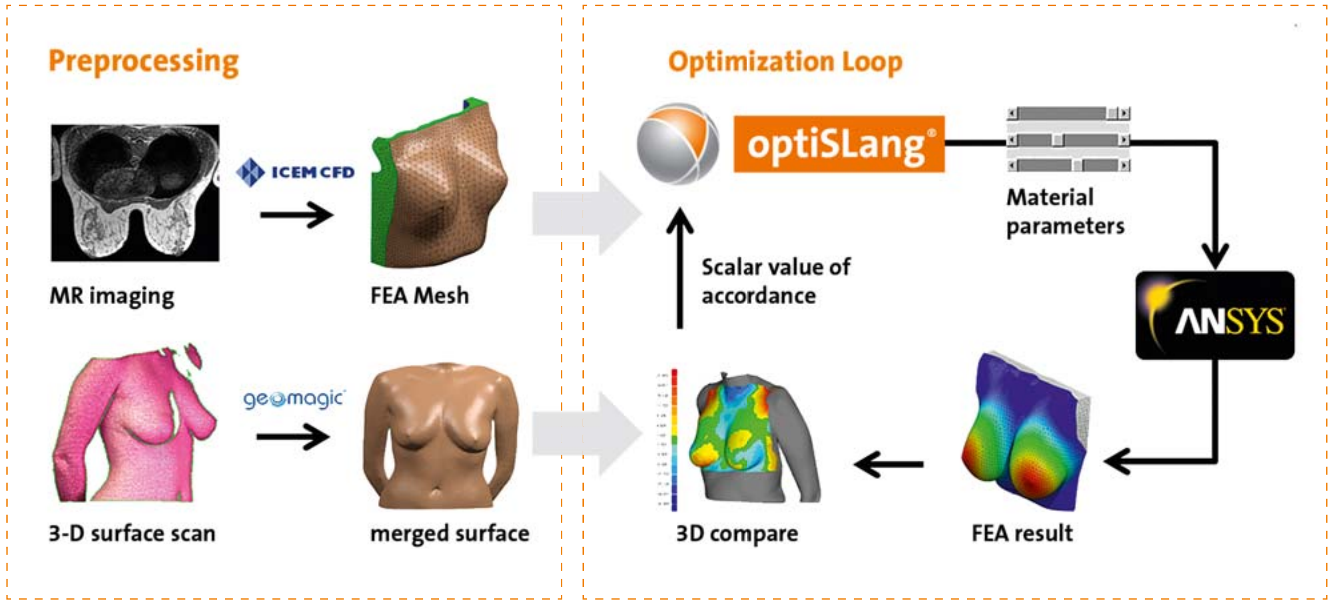

Figure 3: Principle workflow of the whole approach. The ANSYS calculation includes the iterative procedure visualized in Fig. 2.

This inverse procedure delivers an approximation of the stress free geometry of the breast. This model may be used for further simulations of different loading scenarios, while in the present workflow it is used to calculate the breast geometry in upright standing position.

Optimization loop

For the integration of the described procedure into an optimization loop, it is necessary to define an objective value. Since we need to find material parameter sets that are suitable for the utilization for accurate person individual simulation planning, a comparison between the simulation result of the standing position and the real skin surface of the volunteers taken from the 3-D scans is performed.
It is essential to bring the 3-D surface scan in best alignment with the simulation result in order to compute the 3-D displacement, formulated as the area integrated 3-D distance at each node of the FEA mesh. This leads to one single output parameter that can be interpreted as the correspondence between surface scan and FEA simulation result. Thus, it becomes possible to summarize the whole deviation into one value that needs to be minimized with the appropriate parameters for the mechanical behaviour. The whole process chain is visualized in figure 3.
As design variables that describe the mechanical behaviour of the soft tissue with Neo-Hookean material, Young's modulus and Poisson's ratio have been used that are inside the loop transformed to their hyper-elastic representations in initial shear modulus and initial bulk modulus.
For these particular optimizations the design space boundaries were set to be 0.39 - 1.17 kPa for the Young's modulus. This equals a variation of +/- 50 % in relation to a value from literature that has shown to be a fairly good first guess for the material stiffness. The second design parameter was the Poisson's ratio which has been varied in the scope of 0.3 to 0.5, meaning fully incompressible material behaviour.
Adaptive response surface method was used to optimally illuminate the design space and to draw maximal information about the overall system behavior out of the performed simulations.

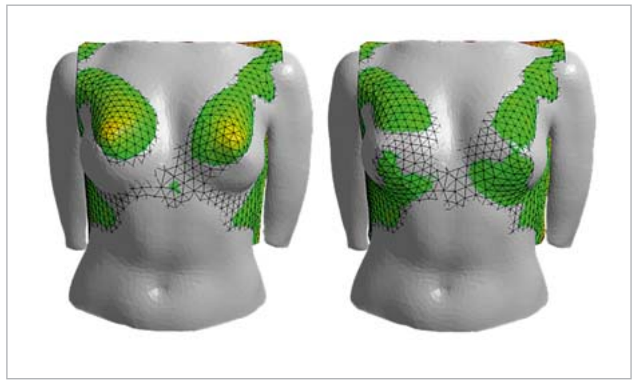

Fig. 4: Simulation results of the standing position with different material parameter sets: A much too stiff material behavior (left) and a more appropriate configuration (right). Deviations between the calculated standing position and the scanned 3-D surface visualized as color plots.

Results

The applicability of the presented workflow for the simulation of the breast could be shown. The whole process chain is automated and thus provides an easy to use interface for the validation of different material parameters. In figure 5, a typical result of an optimization run is shown. It is evi-

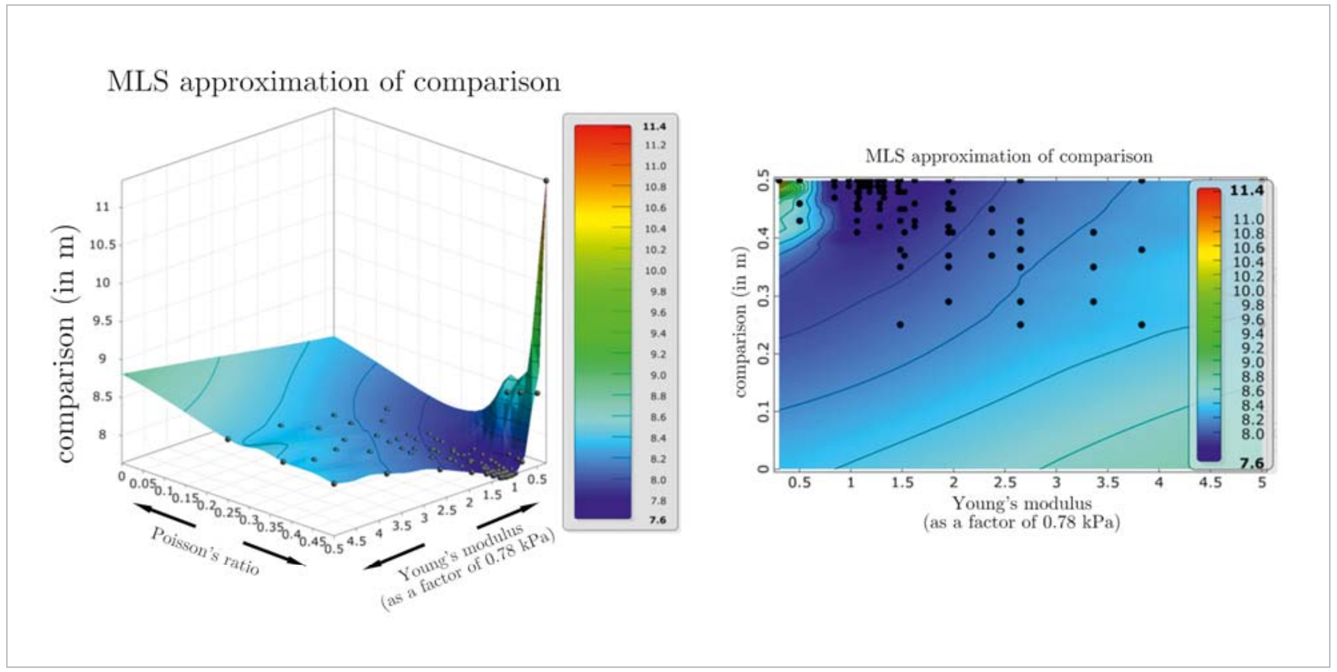

Fig. 5: Example of a response surface of an optimization with ARSM (adaptive response surface method). Young's modulus (E, factors to 0.13 kPa) and Poisson's ratio (PR) are plotted. Mean deviation between 3-D surface scan in standing position and FEA result in mm is shown as the height of the response surface as it is objective value that is to be minimized.

dent that there is a clearly defined optimum, i.e. the set of material parameters that is best suited to describe the real mechanical behaviour of the correspondent test person's breast. Looking first at the variations in Poisson's ratio, there is a decrease towards higher values, meaning less compressibility. Thus the commonly used assumption of biological soft tissues to be incompressible or at least nearly incompressible can be confirmed by these findings. Since this is true for all tested models, in future work it seems no more necessary to deal with compressible material models at all, resulting in the reduction of unknown material parameters.

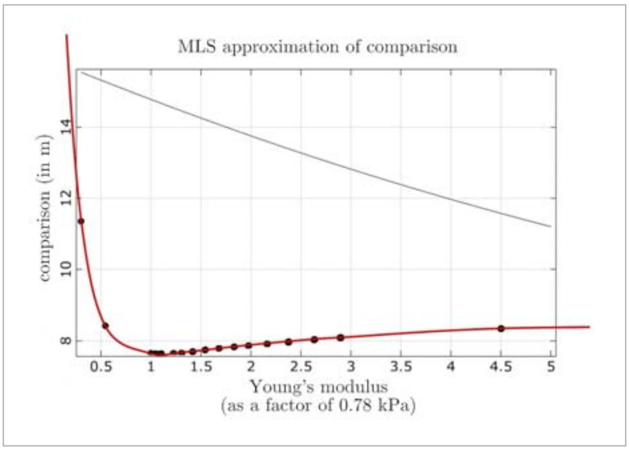

Fig.6: Reduction of the design space to have only one free design variable which is the Young's modulus. The Poisson's ratio in this variant is fixed to full incompressibility. Then, clearly defined optima can be found as see by the red approximation curve.

Taking a further look at the material stiffness (figure 6), the Young's modulus, a clearly defined optimal position can be found. The model behaviour is described by a shallow slope when coming from high Young's moduli and a relatively steep increase when the material parameters become too soft. For all optimizations performed in the present study, defined global optima could be found. The individual optima for the eight test persons were found within the range of 0.494 kPa to 0.852 kPa for the Young's modulus. Hence, between the different test persons relatively high differences in soft tissue stiffness of 72.5% could be investigated, underlining the need for patient individual simulations.

Discussion

The advantage of the whole workflow presented here is the non-invasive character as a combination of volume imaging (MRI) and 3-D surface scanning (laser triangulation) and the involvement of the computer for the actual simulation. No tissue samples of the patient's soft tissue have to be harvested what is especially a critical issue if the mechanical information derived from these specimens should be used in operation planning, because this would mean an additional intervention for the patient. Furthermore, the expensive and cumbersome experimental testing can be circumvented.

The high variation in stiffness of almost a factor of 2 between the softest and the hardest optimal material parameter set found in this study shows the distinct need for the patient individual assessment of soft tissue material parameters. Thus patient specific simulations seem inevitable. Hence, the advantages of this non-invasive and fully computerized approach become obvious.

Outlook

The workflow presented in this publication may in the future be used for the material parameter assessment of hyper-elastic parameters that are suited for patient individual modelling of the constitutive behaviour of the female breast soft tissue. These data may subsequently be utilized for numerical simulations and planning of complex surgical interventions in plastic surgery.

The presented approach is not limited to its application in plastic surgery of the female breast. Other uses of this procedure for different body parts, e.g. for abdominal surgery or the simulations of soft tissue compression caused by prostheses in orthopedic treatments, are also possible but need to be further investigated. Besides these medical utilizations, there are also applications beyond that scope in other fields of science, e.g. in the determination of material properties of polymer components.

However, more complex models as the ones that have been used in the study presented here may in future be necessary when it comes to the application in breast surgery planning. For instance, more different anatomical regions such as the muscular soft tissue as well as a distinction of soft tissue into an adipose and a glandular compartment may yield more accurate anatomical models. These models may contain more tissues with unknown material properties, thus the dimensionality of the design space increases and hence the optimization task becomes more complex. Furthermore the influence of the modeling of the skin may have a decisive role, especially when the anisotropic material properties are considered. For these models, as well as for the use of more complex theoretical models such as Mooney-Rivlin or Ogden with more parameters than just stiffness and compressibility that can be varied, the benefit of the optimization software OptiSlang becomes instantly more pronounced.

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