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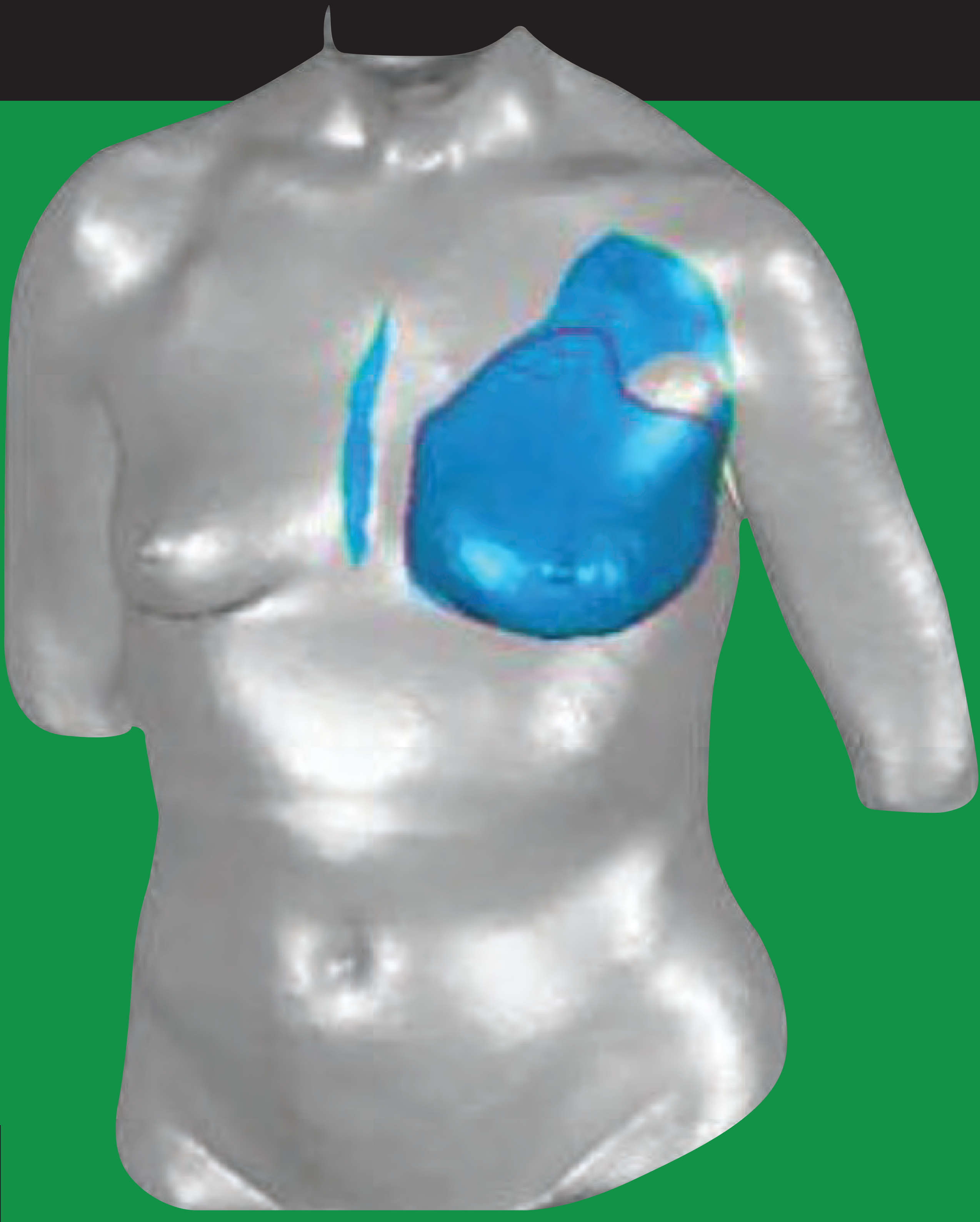

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Since time immemorial, artists and sculptors have attempted to capture that most elusive and imperfect form – the human body.

From The Bird Girl to Venus de Milo, the female form has been sculpted, painted and modelled by the great and the good, for the purposes of art and beauty. In the 21st century however, modelling of the human body takes on a new meaning. Computer Aided Plastic Surgery is an emerging area of CAE, and more and more is using FEA and related technologies to create accurate models of the human form which will behave in the same way as the real thing, to advance medical procedures and allow accurate planning of surgery in a non-invasive and precise manner. This article, which won the Best Paper award for Most Innovative Use of Simulation Technology at the recent NAFEMS World Congress, discusses parameter identification for the hyper-elastic material modelling of constitutive behaviour of the female breast's soft-tissues, based on MRI data, 3D surface scanning, and FEA.

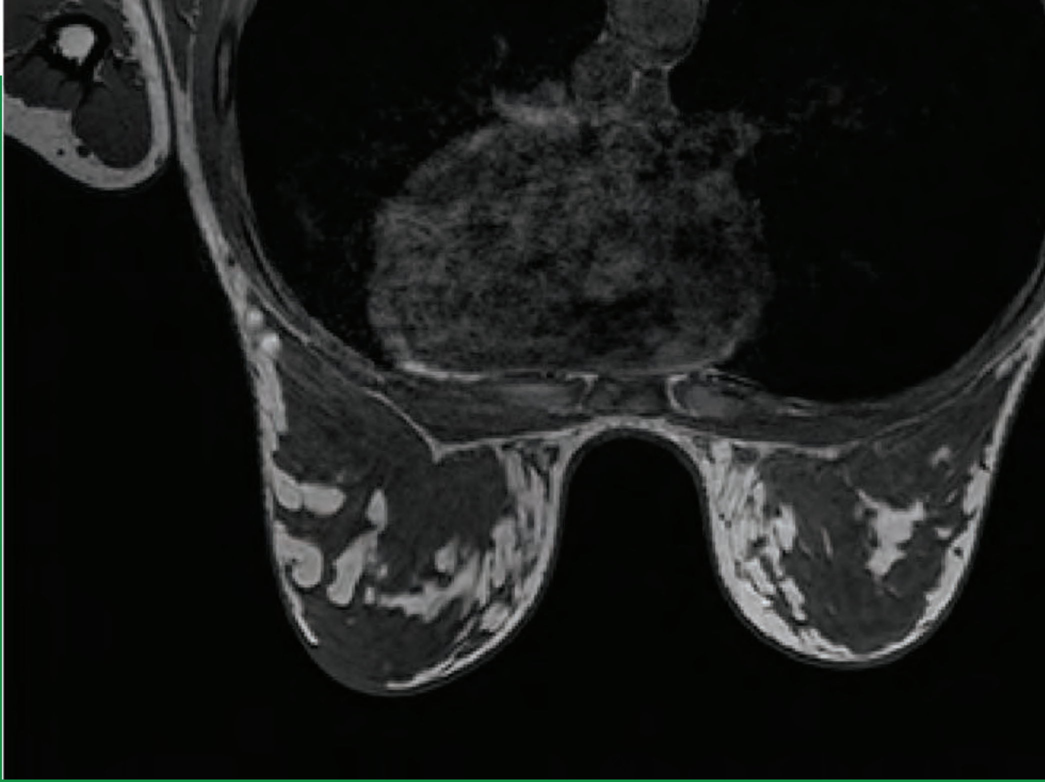

Figure 1:
MRI Images of the breast in prone position. Different anatomical compartments, such as adipose and glandular tissues of the breast can be captured due to differences in gray-values.

Surgical interventions due to breast cancer are a very common surgical procedure in women with 140,337 cases in Germany alone in 2010 [1]. After breast removal, it is often chosen to reconstruct the amputated breast in order to regain symmetry and to improve the life quality of the patients. These reconstructive surgeries are especially difficult due to the large soft tissue flaps that are necessary to reconstruct the missing breast with accurate volume and in the desired shape. Today, these operations are planned by drawing reference lines manually on the breast and the donor site. The success of the reconstruction thus mainly depends on the surgeon's skills and experience. For the improvement of breast surgeries in this scope, there is a desire to have access to planning tools that take advantage of modern measurement tools such as 3-D surface scanning and up to date simulation techniques such as FEA. For these simulations, the mechanical properties of the human soft tissues are highly relevant. It is only possible to reliably plan breast surgery operations if the physical behaviour of these structures can be modelled accurately.

Biomechanical studies of the mechanical deformations in the human body often use numerical simulations, such as the FEA. Shape changes in the female breast under varying load conditions, such as plain gravity or compression in mammography plates [2], are a current area of interest, both in the computational engineering science and in the medical sector. During radiological diagnostics, the breast is exposed to different mechanical loading conditions than at the stage of the operation planning and in the operation room. For better operation planning, a prediction of these mechanical deformations with modern imaging and simulation techniques on the computer is desirable. However, to generate realistic results that consider the physics of biological materials, it is essential to have a sufficient understanding of the theoretical constitutive models and the material parameters that describe the soft tissue of the breast. Although numerous studies have been performed to acquire material parameters, as yet, no consensus of reliable parameter sets can be generated. We think that three-dimensional body scanning can have a decisive role for the determination of soft

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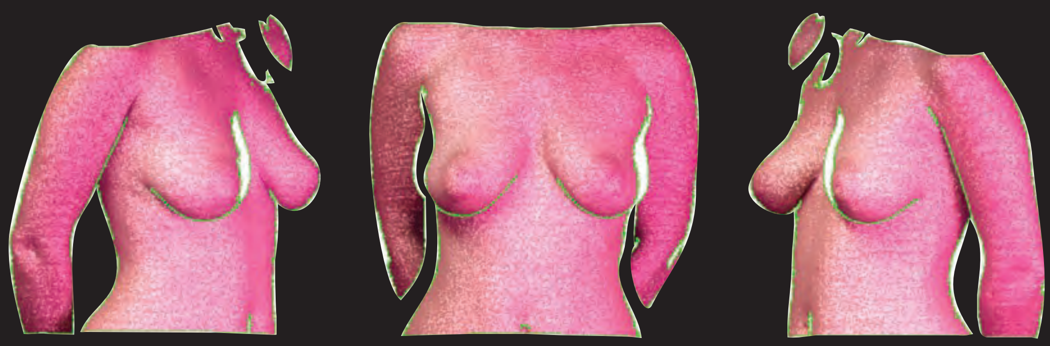

Figure 2:
Three surface scans acquired with the Konica Minolta Vivid device. The upright positions have been varied in 30 degrees to both sides in order to get the test person's side viewed surface information as well. These single shots have to be merged in a manual procedure to yield one surface representation.

tissue parameters of the breast: In the study presented here, 3-D surface scanning is used in combination with volumetric Magnetic Resonance Imaging (MRI) to capture the breast shape in different positions. Simulations with the geometrical volume models from MRI are performed and the simulation results can be validated by using a comparison to 3-D surface scans. With this workflow, it is possible to evaluate whether a certain material formulation is suitable for the simulation of the breast tissue.

Material and Methods

In the presented study, we use MRI data taken from six healthy test persons in prone position and derive volumetric finite element models out of this data. All volunteers gave their written informed consent to take part in the study and the Declaration of Helsinki protocols were strictly followed. Volunteers with a known history or hereditary risk of breast cancer, acute breast infections, known autoimmune or infectious diseases, severe breast malformations and thoracic deformations or fibrocystic mastopathy and previous breast surgeries were excluded from the study. No indications of existing breast asymmetries were observed and none of the volunteers had previously undergone any surgical interventions in the breast area, nor did they plan to do so in the future.

With the aid of FEA a force free reference state is calculated, using an iterative heuristic approach to overcome the deformations caused by unavoidable gravity loading. Starting from the obtained gravity free model, the shape of the breast in the upright position is calculated. This result is then compared to the real volunteers' breast surfaces, acquired with a 3-D surface scanner, in order to evaluate the applicability of the simulation procedure.

Volumetric Image Acquisition

Volumetric Magnetic Resonance Imaging (MRI) data of the six volunteer was captured with the aid of a Philips Achieva 1.5 Tesla MRI scanner (Philips Medical Systems DMC GmbH, Hamburg, Germany) using a T1-weitghted imaging sequence with a 512 x 512 x 179 voxel resolution and a spacing of 0.994 mm x 0.994 mm x 2 mm (imaging parameter: 4.6 ms ecco time and 9.2 ms repetition time). No intravenous contrast agent was applied. The thoracic images were obtained with the participants lying in prone position. The breasts did not touch the MRI bench. This was achieved with pillow supports located above the clavicle and in the shoulder region as well as caudal down to the lower belly area and the pelvic crest region, see Figure 1. With this support structure, all compressions of the breast due to contact with the bench could be omitted. However the breast's soft tissue is not stress free because gravity forces still act. Thus the shape of the free hanging breast can be made available for further processing and segmentation in suitable imaging software packages. The resultant models can finally be used for finite element simulations. But we have to keep in mind that these simulations do not start right away from an unloaded state, due to the gravitational forces acting on them.

3-D Surface Scanning

The post-operative outcome of breast surgery with respect to symmetry is typically evaluated in standing position. However, it is not yet common practice in clinical routine to use upright MRI systems due to their cost and the difficulties in the stable positioning of the patients when standing without further support. Usually in hospitals, there are only horizontal tube MRI devices available that permit the image acquisition for patients solely in lying position. Thus, the data for the internal anatomical structure is available either in prone or in supine positions. Three-dimensional surface scanning systems in contrast allow a variety of different positions of the patient including standing upright. Thus these techniques permit an indispensable advantage for the presented study. Due to their relatively low cost, they bear additional advantages for plastic surgeons that work as resident doctors and have no direct access to clinical MRI devices.

The imaging in upright position was performed using a surface scanner working with laser triangulation (Konica Minolta Co., Ltd., Osaka, Japan). This system has largely shown its applicability to breast shape measurements in preliminary studies [3-

7]. The 3-D surface scans of the participants were performed in standing position on predefined markers on the ground under standardized lighting conditions (light intensity 350 400 lux) with a 10 degree upward angle of the scanner facing the participants +30, 0 and -30 degrees relative to the lens in standing position [7]. During acquisition, the test persons were asked to hold their breath, while the arms had to be put down the side at the height of the pelvis and the back was supported by a wall to guarantee reproducible data by minimizing potential artefacts due to breathing and movement due to unstable standing.

These single shots from different angles (see Figure 2) of each volunteer were converted into virtual 3-D models using the appropriate software tool (Geomagic Studio 12®, Raindrop Geomagic, Inc., NC, USA) that has already proven its applicability and reliability [3-7]. All potential problems for later work with the data such as holes due to insufficiently clear scanning data or intersections between different acquisitions were fixed. For all models, the three single images (frontal, right 30° and left 30°) could be merged into one representation of the full frontal part of the breast region. No holes or overlapping surface parts are present in the prepared models. In Figure 3 an exemplary overview of different surface models derived from 3-D laser scanning is given. The obvious variance of the test persons overall build and especially the variations in breast size and shape make it a particularly difficult task from an engineer's perspective to derive comparable models out of this data. In traditional engineering, when working with technical parts, sizes and shapes are less variable and thus the geometric modelling is a less complex step.

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Finite Element Modelling and Simulation

For the generation of individual specific volumetric simulation models, the underlying data for each FE model is reconstructed from the MRI scans of the six participants. The images were saved in DICOM format and loaded into the software Mimics® 14.0 (Materialise Inc., Leuven, Belgium), where the different anatomical regions of interest could be

Figure 3: Surface scans of the breasts of eight exemplary test persons that participated in the study. The anatomical variance in breast size and shape and the overall built is obvious and leads to an especially challenging task for the engineer.

Figure 4: 3-D segmentations of the test person data coming from MRI scans taken in prone position; left: whole body of the chest region of the test person. Breathing artefacts do not disturb the accuracy of the skin segmentations. Right: inner anatomy of the test person. It is possible to segment all relevant compartments of the breast, consisting of glandular tissue, main pectoral muscles and the bony parts consisting of the clavicles and the thoracic wall.

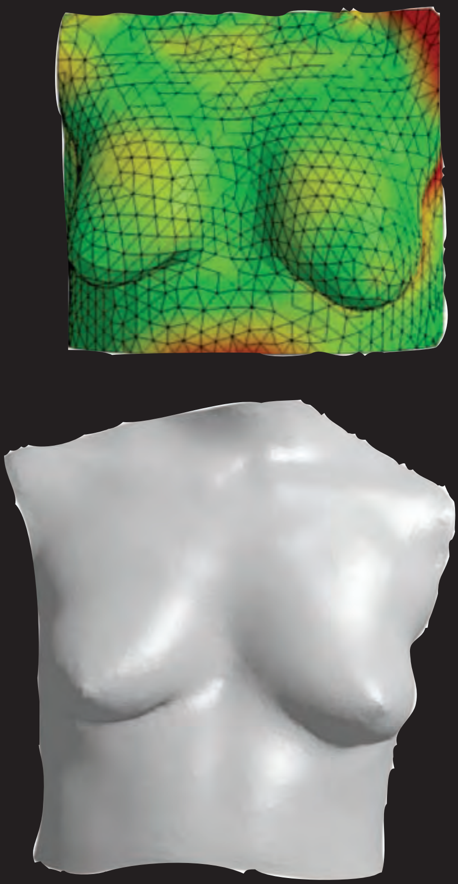

Figure 5: 3-D surface scan (right) and comparison between FEM simulation result and scan (left) visualized as coloured deviations on the deformed finite element mesh.

automatically segmented and triangulated in different parts. Since the scope of benchmark magazine is mainly on finite element modelling and simulation, the study presented here focusses on these parts more than on the detailed anatomical modelling. The anatomical regions that are considered to be relevant for the simulation in the study are limited to a simplistic modelling of only one compartment that describes the whole soft tissue of the breast. Hence this compartment is a representation of a smeared material behaviour that summarises all tissues of that breast area, i.e. adipose and glandular tissues as well as the pectoral muscles (see also Figure 4). The skin is not considered as a separate part in this modelling. However, its effect is to a certain extent included in the identified parameter sets since the simulation results are compared to the overall mechanical behaviour of the in vivo breast that contains all anatomical parts. In consequence, the parameter configurations that are found to be optimal for the description of the constitutive behaviour of the breast are meant to represent the whole soft tissues. Comparable studies of Rajagopal et al. (2008) and Lapuebla-Ferri et al. (2010) also considered the breast tissue as homogenous material for finite element simulation, meaning that glandular and fat tissues are summarized in these works as well. Samani et al. (2007) found the mechanical properties of the two tissues to be of comparable magnitude (3.24 kPa for elasticity modulus of fat versus 3.25 kPa for glandular tissue), hence these simplifications seem appropriate.

The thoracic wall was modelled as a continuous surface, thus the intercostal muscles were considered to be one part, together with the ribs and the breast bone (see also Figure 4). The anterior part of the thoracic wall is used as a posterior demarcation of the deformable model since its deformability is considered to be negligible in comparison to the movement that the soft tissue undergoes. The other bony parts, the clavicles, were modelled in this study as well as the non-deformable, rigid bodies that are directly connected to the thoracic wall. Hence all movements of the shoulder region are locked and we have to make the assumption that shoulder positions in prone positions are comparable to the standing upright positions.

The segmented surfaces were prepared in an adequate 3-D surface processing software (Geomagic Studio 12®, Raindrop Geomagic, Inc., NC, USA and Blender®, Blender Foundation, Amsterdam, Netherlands) to improve the surface quality and reduce segmentation artefacts that

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could disturb subsequent mesh generation. The triangulated surfaces treated in this manner can be utilized for the division of the complex anatomical shapes into volumetric tetrahedron meshes. For the generation of the FE model the meshing software ICEM® (Ansys Inc. Canonsburg, PA, USA) has been applied. Three surfaces containing the thoracic wall, the clavicles and the soft tissue as an entire component consisting of skin, fat, muscle and gland were imported to ICEM® in triangulated STL format. In order to eliminate the irrelevant parts of the breast model for the FE simulation, a box was defined to demarcate the model on different sides. The definition of these system boundary conditions is essential for the demand of standardizing the model generation procedure in order to maintain an inter-test-person comparability. This is the most crucial step in modelling the geometric anatomy, since the system boundary locations have a major effect on the overall performance of the FEA models. For the simulation, tetrahedron solid elements were used with u-p mixed formulation. This theoretical element formulation is suitable for general material formulations including incompressible materials, due to a hydrostatic pressure calculation. The programming language APDL (Ansys Parametric Design Language) was used for implementation and automation of the whole process.

Boundary Conditions

As boundary conditions the system boundaries as described above applied by the demarcation box have to be clearly defined in a standardized way to permit reproducibility. The system boundaries on the upper and lower boundaries, as well as at the lateral delimitations have been considered as fixed boundaries, i.e. all finite element nodes at these locations are kept initially fixed. In preliminary studies, a different variation with symmetry boundary conditions has been investigated as well, but this did not yield any significant difference in the simulations outcome. This finding stands in good accordance to literature (Tanner et al. [2]), where the influence of the boundary conditions is found to of minor importance. For the dorsal boundary conditions we considered the backward delimitation of the model to be the thoracic wall. The bony structure of the thorax can be considered as being very stiff in comparison to the soft tissues constitutive behaviour. Furthermore the clavicles are fixed and do not permit any movement. External force boundary conditions are not applied: gravity is the only loading that is put on the models.

Iterative Algorithm

Due to the soft constitution of the tissue, the breast is highly deformed even if no other forces are acting besides gravity. Therefore, in all possible spatial positions, the geometry of the breast is deformed at least due to gravity. But for mechanical simulations, an unloaded state of the geometries has to be known as the starting point of 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 hyper-elastic material behaviour, a simple recalculation with inverse gravity is not satisfactorily accurate. Previous studies did not consider these effects and used a single step method instead [23]. But recently, more advanced investigations on this subject have been conducted taking these influences into account [18,19]. Rajagopal et al. presented an inverse algorithm for breast soft tissue simulation to address this topic. The study presented here uses a similar method for the iterative calculation of the unloaded reference state.

In this heuristic approach, a first approximation of the non-deformed configuration is made by a one-step backward calculation (inverse gravity). The result is then taken as the starting point to perform a forward calculation, while it is again considered to be initially stress free. It is now possible to check the error of the first inverse calculation by comparing the new result with the initial geometry that is deformed by gravity (derived from the MRI data). Since the meshing of the model does not change, the positions of all finite element nodes can be compared directly. The differences of these two models are used to make a better estimation of the unloaded configurations by adding these nodal deviations to the node positions of the first approximation of the unloaded configuration. Thereby, a better estimate may be achieved, which can be used again as an unloaded configuration for a new forward calculation. The newly calculated deformed position can again be compared to the segmented positions from MRI data and subsequently the comparison result can be used to further increase the estimate of the unloaded configuration. This procedure is performed iteratively and can be conducted in a loop where the estimate of the unknown reference state can be improved in each step. Here, a maximum repetition of 5 iterations was chosen.

Applied Material Model and Parameter Identification

Different material models are applied for the simulation of the female breast tissue by other

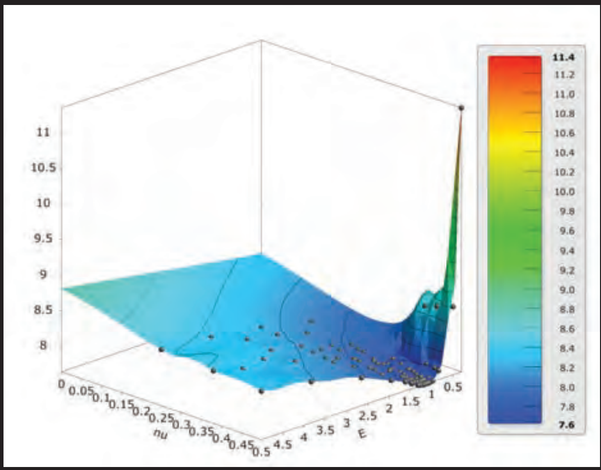


Figure 7: Typical response surface of an optimization. Young's modulus (E, factors to 0.13 kPa, as proposed in [12]) and Poisson's ratio (PR) are plotted. Mean deviation between 3-D surface scan in standing position and FEA result in mm is shown as the height of the response surface as it is objective value that is to be minimized.

research groups: Starting from linear elastic to piecewise-linear elastic, exponential elastic and hyper-elastic constitutive models that have been proposed by several authors. Different methods of deriving the relevant parameters that describe the stiffness of the materials have been used: Krouskop et al. [8], Wellman et al. [9] and Samani et al. [10] obtained the necessary material parameters based on ex vivo indentation tests. Tanner et al. [2] used different material models in one publication including linear elastic, Neo-Hookean and Mooney-Rivlin hyper-elastic models according to different earlier publications [8], [10] and [11].

Linear elastic material models, as used by Tanner et al. in [12] do not permit enough deformation to describe the movement of the breast tissue due to gravity, thus these constitutive models have not been used in this study. Even if only gravity loading is applied, the strains exceed the Hookean domain of linear stress–strain relationship. Thus, it is inevitable to use hyper-elastic material formulations to describe the deformations of the breast with finite element simulations. In the scope of the presented work, for the soft tissue modelling, hyper-elastic material behaviour was assumed and the Neo Hookean model was used as the theoretical model. This model bears the advantage of having only two input parameters (initial shear modulus and initial bulk modulus that can be transferred into Young's modulus and Poisson's ratio as commonly used in linear material modelling). Hence the material formulation is well suited for parameter identifications and optimizations, as the number of design variables can be limited to only two and thus even full samplings of the parameter spaces can be performed within reasonable calculation times. For the automatic variation of material properties as well as the results visualization, the software package optiSlang® was used (Dynardo, Weimar, Germany). Within the work presented here, full design space sampling was performed (Young's modulus ranging from 0.065 kPa to 0.195 kPa and Poisson's ratio ranging from 0.3 to 0.5, divided into eleven and three steps, respectively).

Comparison of Simulations and 3-D Surface Scans

The finite element simulation provides the breast geometry in upright position. To determine the usability of a certain material parameter set for this type of calculation, a comparison with the real world has to be made for the purpose of validation. Thus, the result surface of the calculation as it is meshed in the finite element model is exported as a triangulated surface. This result can be compared to the 3-D laser scans of the breast shape. For accurate positioning of both models, bony landmarks close to the shoulders, the clavicles and the sternum have been used.

For the 3-D comparisons, a specially developed algorithm has been used that calculates the node to node root mean square integration of the 3-D distance between the two models (in mm), according to the method described in [14]. Figure 5 shows a coloured visualization of a comparison between finite element result and 3-D surface scan. The whole workflow is automated and can be run in batch mode to allow fast processing of data with minimal efforts.

Results

The applicability of the presented workflow for the simulation of the breast was demonstrated. The whole process is automated and thus permits an easy to use interface for the comparison of different material parameters.

> "Due to the softness of the breast tissue, it undergoes high deformations even at moderate loading conditions. Even gravity load alone is enough to exceed the linear Hookean domain."

Due to the softness of the breast tissue, it undergoes high deformations even at moderate loading conditions. Even gravity load alone is enough to exceed the linear Hookean domain (Figure 6). Thus, the representation of the breast's soft tissue with purely linear elastic material models is insufficient. The finite element simulations did show a numerically instable behaviour (divergence) when these material models have been applied. Thus, hyper-elastic material modelling (Neo-Hookean) was used for all presented results. Convergence cannot be guaranteed however: in 182 out of the 198 performed simulations, a converged solution could be returned (91.9 %), but convergence were solely in regions of very soft parameter sets that were far away from the corresponding optima. Hence the convergence problems do not interfere with out parameter identifications in this particular case.

In Figure 7, a typical result of the simulations is shown. It is evident 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 often used modelling of biological soft tissues as incompressible or at least nearly incompressible can be confirmed by our findings. Since this is true for all tested models, in future work it seems unnecessary to deal with compressible material models, resulting in the reduction of unknown material parameters.

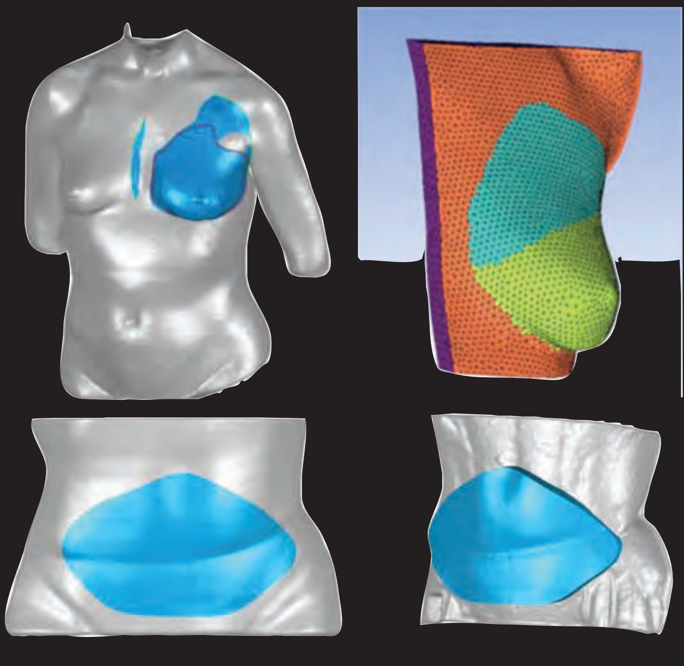
When we take a look at the material stiffness, as described by the Young's modulus, a clearly defined optimal position can be found. The model behaviour is described by a shallow slope when coming from high Young's moduli and a relatively steep increase when the material parameters become too soft. For all optimizations performed in the presented study, defined global optima could be found. The optimal Young's modulus as mean value of the six test persons was found to be 0.121 kPa with a standard deviation of 0.028 kPa.

Conclusion

The advantage of the method presented here is its 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. Since the whole workflow of simulation and data evaluation is automated, multitudes of simulations can be performed with little additional effort.

However, the models have certain limitations. Firstly, the level of detail in these models is relatively low, since we are summarizing all soft tissue compartments as one material with homogeneous mechanical properties. In future work, it is intended to augment the modelling in order to derive models that are better suited to represent the real physiology of the breast by dividing the soft tissue into different parts of adipose tissue, glandular tissue and the relevant muscles. Furthermore, consideration of the skin's impact on the simulation results should be evaluated. Here in particular, the question of how to model the skin as shells or volumetric finite elements arises. Any direction dependency of the material properties is neglected in our modelling. Anisotropy of the biological tissues could also be taken into account, however it is a challenging task to find physiological directions that can be applied to individual anatomical models.

Figure 6: Simulation results of the standing position with different material parameter sets. From stiff (left) to soft (right)



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Nevertheless, the material parameters derived with the method presented here for the breast tissue can deliver patient specific material parameter sets with the advantage of circumventing any invasive tissue damage, as would be inevitable for ex vivo mechanical testing with experimental devices. The data acquired might be helpful in oncology for tumour tracking by integrating comparison of multimodality images into the simulation model, and could improve plastic and reconstructive breast surgery planning in the future.

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