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Faculty of Mechanical Engineering

Master Thesis

Nonlinear Material Parameter Identification of Soft Materials based on an Inverse Finite Element Method Approach

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Declaration of Authorship

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Aachen, 1^{st} of January 3000

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1 Introduction

Precise knowledge about the biomechanical characterization of soft tissues has gained attention in medical research, e.g. medical image analysis and visualization. For many years, the obtained medical diagnosis have come from assumptions of experts or accumulated experience. This information, although proven to be useful, has its limitations when computed-assisted systems like, medical diagnosis, therapy ,and training, rely on more quantificable data[1]. To gather this data, it is important to gain access to the tissues and perform in-vivo testing experiments, where in cases of organs it is nearly impossible to achieve, due to the involvement of an invasive procedure, and the lack of constant and reproducible external and internal factors.

One of the proposed techniques to execute the gathering of data is, the extraction of the solicited organ and perform some experiments in a limited amount of time. With the extracted data a approximated model is simulated, and inserted in the computed-assisted systems. One of the complications in case of extracting the organ is, some of the properties for biomaterials may change despite examining the same organ. Their biomechanical properties depends from other variables e.g., changes in blood presure, time-dependant material properties, symptoms from diseases, etc. Furthermore, another encountered issue is the lack of replication, due to the use of different individuals organs, which includes more externals factor to add to the equation. Additionally, given a tissue sample, does not mean that the obtained material properties can characterize the organ properly, as a consequence of the anisotropy propertie of soft tissues. This will cause a change a in the material properties and analogically, an inaccurate result.

In the situation where the soft material's data can be gather in a constant, fast and reliable process, the data enables the system to predict the behavior of soft tissues and give pre-operative calculations. This shows that material models represent a vital part for medical research, specially for the use of computational models, as their help to increase the accuracy of the simulation and its applications in other systems.

In soft materials analyses, a nonlinear situation is mostly encountered, for which a finite element method becomes a common approach. The application of the finite element method facilitates the analysis of complex structures with complex material behavior, and aids in solving of continuum mechanical problems. Nevertheless, in order to simulate a material with this complexity also requires complex algorithms with high computational costs.

One of the goals of this study to identify the key parameters of the soft materials, and their influence in the construction of a material model. These key parameters the attempt to approximate such a complex material will be done, and this simplified material model will be validated for its future applications in medical research.

With the application of the experiment testing ,and the finite element method is possible to identify some key parameters through an inverse finite element method approach. With this method a framework can be established and the results of computational model can be matched to the experimental data, and be validated with other experiments.

1.1 State of the art

1.1.1 Experimental techniques for soft materials

Uniaxial testing

This method allows the validation of several computational models as it provides with searched parameters done with other experimental procedure

Aspiration experiment

Tissue aspiration experiments introduces an aspiration tube which is put against the soft tissue, generating a vacuum. With the help of a mirror placed next to aspiration hole, the reflection of the side-view of the tissue can be captured with a video camera. This camera captures the images of the iluminated surface of the material and the aspiration pressure is captured through a sensor. Through this process the captured profile of the tissue is obtained and this can be used to characterize the deformation and analyze the viscoelastic properties of the soft tissue. (kauer 2002)

Indentation

Indentation have being gaining popularity in the last decades and it is now one of the most spread experiments for material parameter identification.

As some materials do not allow the use of uniaxial or biaxial tensile testing, the use of identation testing is essential for this case.

-identation in materials - Identation in soft materials (organs) - Why is identation relevant in organs -what advantages and disadvantges does identation provides - why is relevant for this project

1.1.2 Material Modeling of Soft Tissues

1.1.3 Inverse Finite Element Method for Parameter Identification

An inverse finite element (FE) approach requires usually a certain experimental model, which generates certain information e. g. load-displacement curve, and through a verified computational model match the given data curve to obtain further information of the material's behavior e. g., stress-strain curve.

Specially for nonlinear cases (husain2004), where the complexity of the problems increases, and the interest is focused to generate an action which results in a certain output response, is where an inverse finite element approach can be helpful to discover a certain variable going from an ouput data. Through an iterative process it is possible to describe the material's behavior and validate the output data it through other established testing e. g., uniaxial testing.

Though this approach does not always give a hundred percent match in all obtain points or zones, it allows the researcher to understand the influences of certain parameters for the materials. This is specially useful for complex materials as biomaterials.

Biomaterials, as mentioned previously, depends on multiple external factors, e.g., blood pressure, affected diseases and the their material properties is constantly changing. This issue does not allow the researcher to develop a proper material model which is usable for multiple use-cases.

Therefore, the importance of the inverse element method as relevant key for estimating constantly changing parameters in soft materials.

For biomechanical models, where the models require knowledge from local properties (chai 2013), as the biomaterial is not isotropic; it is possible to identify a parameter e.g. Young's Modulus from a 3D model. The model can be matched to multiple experiments and multiple samples in different areas, which allows a better representation of the material for further analysis.

The inverse FE approach can used by optimizing the searched parameter by matching the simulated data to a section of a experimental curve and extending this process through some iterations. Nevertheless, it is important to clarify that this method also requires making assumptions to some values. Furthermore, it is relevant to document these assumptions for the further analysis. With the combination of assumptions, experimental data, and a optimized and matched simulation curve, it is possible to solve the complexity of biomechanical models.

In next sections some of the experimental models and the material models for bio and soft materials are going to be explained to get a further understanding in how is possible to get a realiable computational model for further reasearch

Synthetic soft materials

Synthetics materials are commonly used to validate an inverse parameter identification process. Usually these synthetic, soft materials provide similar mechanical behavior to it's biomaterials counterparts. This characterization allows to validate a proposed inverse finite element approach process before its applicatoin with a biomaterial, where the measurements to gather the experimental data are some in-vivo, and more challenging to recreate.

For example, Silgel, a very soft gel-like material (M. Kauer, 2002) was used for the experimental validation of the inverse method proposed, to characterized the tissue of a human uteri. In this work, the tensile behavior of the material was predicted through the parameters obtained in the aspiration method.

Biomaterials

1.1.4 Standard Verification and Validation for computational solid mechanics (ASME)

VV40

2 Inverse Finite Element Method for Material Parameter Identification

2.1 Experimental model

The chosen experimental technique was indentation. In Fig.. the ellipsoidal specimen with the a first radius r_1 of 30 mm and a second radius r_2 of 60 mm is positioned in a rest status(?) on a fixed platform that suits the ellipsoidal geometry of the specimen. A metal pin with a rounded head with a radius r_3 3 mm is attached by the holding grips followed by a force load cell. The measured force data showed a very small number, so the first 50 N load cell displayed a lot of noise in the measured data. Therefore, the load cell was change to 10N to reduce this interference. The 10 N load cell displayed the initial contact between the indenter and the specimen in a finer way. In order to get the measurement of the load and unloading process of the indentation a displacement sensor was attached to the tensile machine

2.2 Material model framework assumptions

2.3 Computational model

The quasi static nature of the indentation experiment allows the use of a static structural analysis.

Their a two main factors which increases the complexity of the validation of the simulation and those are, the contact nonlinearity, and the element distortion due to indentation experiment. These issues make the computational time expensive, as it requires to manual solutions for the meshing in the area of importance, and small time steps.

A force-displacement curve, shown in Fig... is generated from the first assumption, for this case

For both cases

2.4 Material model

In an ideal and first scenario, this material can be assumed as linear, isotropic, elastic and nearly imcompressible. For this case, there are two main variables, the Young's Modulus E, and the Poisson's ratio ν.

A Frequently Asked Questions

A.1 How do I change the colors of links?

The color of links can be changed to your liking using:
`\hypersetup{urlcolor=red}`, or
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`\hypersetup{allcolors=.}`, or even better:
`\hypersetup{hidelinks}`.
If you want to have obvious links in the PDF but not the printed text, use:
`\hypersetup{colorlinks=false}`.

Bibliography

[1] M Kauer et al. *Inverse finite element characterization of soft tissues*. ¡b¿Abstract¡/b¿¡br/¿¡br/¿determinatio of material model parameters for biological soft tissues ¡br/¿¡br/¿aspiration instrument in-vivo applicability requirement ¡br/¿¡br/¿validity under more general loading conditions ¡br/¿¡br/¿explicit asymmetric fe formulation of the aspiration experiment incompressible material results in very small time steps and computationally expensive simulations ¡br/¿¡br/¿viscoelasticiy is a quasilinear formulation! ¡br/¿¡br/¿mainly it is assumed for isotropic behaviour due to large increase number of unknown material parameters ¡br/¿¡br/¿influence of the friction coefficient on the parameter determination process was studied ¡br/¿¡br/¿increase the friction as much as possible to ensure sticking of the tissue to the surface¡br/¿¡br/¿¡b¿Introduction¡/b¿¡br/¿¡br/¿For example soft tissue modelling plays an important role in the development of virtual reality based simulator is for surgery training, the performance of the simulation in both application areas highly depends on the availability of appropiate methods for calculating soft tissue deformation.¡br/¿¡br/¿fe based simulation of soft tissue deformation has been applied both in surgical simulator and elastic image registration.¡br/¿A sophisticated simulation algorithm is limited without precise information about the elastic properties of a living tissue.¡br/¿¡br/¿Only limited quantitative data is available about biomechical properties of soft tissues, especially regarding human organs¡br/¿¡br/¿Difficulties of getting this information lies in the acces to the internal organs, which needs to direct. Due to being a very invasive procedure it is mostly not possible to achieve this. Additionally traditional testing methods like tensile or compression techniques canot be performed under such circumstances, without a certain intervention in the organ. ¡br/¿¡br/¿This has originated that indentation methods gets develops for in vivo experiments. This experiments have been done in skin () and on internal organs ()¡br/¿¡br/¿The deformation of the tissue is measured by imaging techniques like ultrasound ()or MR(). Additiotnally, an aspiration technique() was also developed which describes the viscoelastic properties and characterizes the deformation of the tissue. 2002, pp. 275–287. URL: `www.elsevier.com/locate/media`.