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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

Presented by:	Nadia Pinedo Oruna, B.Sc.
Study programme:	General Mechanical Engineering M.Sc.
Matriculation number:	397 011
Reviewer:	Univ.-Prof. Dr.-Ing. Mikhail Itskov
Supervisor:	Rasul Abdulsalamov, M.Sc.
External supervisor:	Prof. Kazumi Matsui

Declaration of Authorship

I declare that this work has been composed by myself, and describes my own work, unless otherwise acknowledged in the text.

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This work has not been and will not be submitted for any other degree or the obtaining of ECTS points at the RWTH Aachen University or any other institution of higher education.

Aachen, 1st of January 3000

Nadia Pinedo Oruna, B.Sc.

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1 Introduction

Precise knowledge about the biomechanical characterization of soft tissues has received 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 quantifiable data[1]. To gather this data, it is important to gain access to the tissues and perform in-vivo testing experiments. For organs, this procedure 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 complications associated with the extraction of the organ is that some material properties may change despite examination of the same organ. Their biomechanical properties depend on other factors, such as changes in blood pressure, changes in material properties over time, symptoms from diseases, etc. Furthermore, another encountered issue is the lack of replication, due to the use of different individuals organs, which includes more external factors to add to the equation. Moreover, given a tissue sample, it is difficult to characterize the organ's material properly due to its anisotropy property. The material properties change, resulting in 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 it is possible to identify some key material 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 afterwards 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. An advantageous feature of this experiment is that it can be perfomed in-vivo and ex-vivo. 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[1].

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 [1] was used for the experimental validation of the inverse finite element 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. The matching procedure is optimize through an objective function, which consists of the squared differences between the simulation and exprimental data. With an optimization algorithm an optimal set of the following parameters was found: the material parameters μ_i [N/m^2] and the bulk Modulus κ [N/m^2]. This method showed good prediction quality of the mentioned material parameters.

Biomaterials

Biomaterials as mentioned before, represent a challenge due its difficult access and lesser replicability. Therefore these materials are usually used for the experimetnal validation of a methd applied previously in synthetic materials. Following the first example of the Silgel in the previous section, the inverse finite element parameter estimation is applied now on human uteri [1] through in vivo and ex vivo measurements of the human tissue of different patients. It was mentioned, that in comparison from the silgel the uterus possesses a complex multi layered structure with strongly anistropic and viscoelastic properties. Nevertheless, five material parameters were determined, based on the strain energy function to model a human uterus (Yamada 1970). Through the same inverse method applied with the synthetic material, the obtained parameters facilitated the prediction of stress-elongation curves for tensile experiments. The resulting curves showed the difference of stiffness for in vivo and ex vivo measurements and the material singurality for each uterus.

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

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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
`\hypersetup{citecolor=green}`, or
`\hypersetup{allcolor=blue}`.
If you want to completely hide the links, you can use:
`\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”. In: *Medical Image Analysis* 6 (2002), pp. 275–287. URL: `www.elsevier.com/locate/media`.