Review of PhD Thesis "The noninvasive technique of determining local stiffness of human arteries" by Mr Mateusz Mesek.

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It was with interest and pleasure that I read and assessed the PhD dissertation "The noninvasive technique of determining local stiffness of human arteries" by Mr Mateusz Mesek, submitted for evaluation to Silesian University of Technology.

1. Format and parts of the dissertation.

The dissertation contains seven chapters, an appendix, and references, 113 pages in total. In terms of length and volume of information it meets the criteria for a PhD thesis.

The first two chapters: 1. Introduction and 2. Theory contain description of the state of the art as well as objectives described within the state of the art, supported by appropriate references. Chapter 2 Theory contains necessary preliminaries, which are of high theoretical interest and difficulty as they contain aspects of non-linear solid mechanics, material modelling, inverse problem theory, filtering, and control.

2. Assessment of the appropriateness of the bibliography

The dissertation cites 97 references. These references were chosen appropriately and correctly place the candidates work within the state of the art. One aspect that could be considered when preparing publications based on this dissertation is the bibliography on modern Machine Learning – based techniques for model parameter estimation, see e.g. these papers from Ellen Kuhl's lab at Stanford.

Mark Alber, Adrian Buganza Tepole, William R. Cannon, Suvranu De, Salvador Dura-Bernal, Krishna Garikipati, George Karniadakis, William W. Lytton, Paris Perdikaris, Linda Petzold & Ellen Kuhl "Integrating machine learning and multiscale modeling—perspectives, challenges, and opportunities in the biological, biomedical, and behavioral sciences" NPJ digital medicine 2 (1), 115, 2019;

K Linka, E Kuhl "A new family of Constitutive Artificial Neural Networks towards automated model discovery" Computer Methods in Applied Mechanics and Engineering 403, 115731, 2023.

3. Assessment of PhD research objectives

The objective of the presented work is very clear and crisp: to develop a non-invasive method to estimate stiffness of Left Common Cartoid Artery (LCCA). The method is based on ultrasound measurement of displacements and pressure measurements. Nevertheless, it needs to be pointed out, that the aim stated in Introduction, page 8, point to all ultrasound accessible arteries, not only LCCA.

The objective is appropriate as a goal of PhD research.

4. Assessment of scientific methodologies utilised in the presented research.

Research tools use by the candidate are diverse and multidisciplinary. They include ultrasound-based measurement of displacements, applanation tonometry, as well as sophisticated mathematical and numerical modelling and computer simulation. These tools are appropriate for the objective of the study. Mastery of these research tools and methodologies confirm the candidate's ability to conduct sophisticated, multidisciplinary research.

5. Detailed assessment of research methods, results, discussion, and conclusions.

Experiments are described in Chapter 3, Numerical model and its validation in Chapters 4 and 5, and key results in Chapter 6.

Especially interesting is Section 6.2.2 "Medical data". Table 6.5 containing the results for stiffness estimation for 3 patients confirms that these estimates fall within the expected range reported in [91] cited in the dissertation.

Below I offer suggestions for consideration for the defence of the Theses and possible improvements in publications stemming out of this dissertation, Chapter by Chapter.

Chapter 1.

"elevated arterial wall stiffness increases the risk of aneurysm rupture" - Please be prepared to provide reference or justification. Such controversial statements cannot be left "hanging".

2nd paragraph. In publications, please add calcification as one of the main reasons for increased stiffness.

Bottom of 3rd paragraph. Please be prepared to clarify statements about work required to eject blood. It appears that the stiffer the wall, the less work is needed...

Page 8, 3rd paragraph. Please be prepared to discuss and justify your statement on the influence of changes in geometry on identified stiffness parameter. It is hardly possible that changes in geometry of the order of microns can lead to large changes to the estimated tissue stiffness.

Page 9, 2nd paragraph. Did the candidate build the testing rig or somebody else did? Please be explicit here. Also, please be prepared to discuss literature on modern methods for model discovery based on machine learning.

Section 1.2 Outline is not compatible with the Table of Contents -> can this be corrected?

Page 11, 3rd paragraph. "the total computational time for the sequential approach – for model parameter estimation ? – is of the same order as forward simulation" – I think this cannot possibly be true. Please check carefully what you want to say here and be ready to explain during the defence.

Chapter 2. Theory

Page 20, eq. 2.4 -> Please be prepared to distinguish tensor notation from index notation.

Page 22, 1st paragraph. The assumption of the existence of unloaded configuration, for which strain energy is zero. This needs to be very carefully considered. Strict application of this requirement to mechanics of leaving tissues and organs would prohibit the use of hyperelastic theory because we do not know unloaded configurations of leaving tissues, and they are never "unloaded" in reality – we only observe leaving organs in different loaded states, e.g. an artery loaded by different pressures but not zero pressure.

Page 23, bottom. The text about using confined compression creep and unconfined compression stress relaxation needs careful consideration, as these tests are for the identification of hyperviscoelastic materials (or biphasic/multiphasic models) and not hyperelastic materials.

Chapter 3. Experiments

Please clarify who built the rig.

Is your phantom of anatomical shape or straight? (if straight, please be ready to explain why it can be used for your purpose).

Chapter 4.

Please be ready to explain why you chose FEMBio and not one of the standard commercial codes such as e.g. ABAQUS.

Please be ready to provide detailed information about element types used as well as the selected solution procedure for both static and dynamic scenarios.

Please be ready to explain why you chose RMSE and not its normalised version NRMSE – the standard way of confirming mesh convergence.

Please be ready to explain how you obtained reliable displacements from linear elastic model which assumes infinitesimal deformations (and therefore is predominantly used for stress recovery, not displacements).

Table 4.5. Please be ready to explain large differences in Poisson's ratio. Such differences in Poisson's ratio would lead to very different apparent stiffness in volumetric deformation.

Page 54. Please be ready to explain why the Poisson's ratio of the phantom was very different to that assumed for the real artery.

Chapter 6.

p. 71. Please be ready to explain where equation 6.1 is coming from.

Please be ready to explain why FEMbio was used, exactly what element formulations you chose and exactly what solution procedures you used.

Chapter 7.

Please be ready to explain why and how average thickness was measured by X-ray and not simply thickness at a given point.

p. 82. Please be ready to explain why you are suggesting a reduced order model when the full FEM model is very simple and very fast in the first place.

6. Information regarding practical application of PhD research results.

Practical applications of developed techniques are not discussed in detail in the thesis, but undoubtedly the ability to non-invasively measure stiffness of arteries would be extremely beneficial for diagnosis, prognosis, and treatment planning of vascular diseases.

7. Information about errors in the dissertation.

The presented work is technically sound and as far as I can say, does not contain errors. In Point 5 above I indicated a few aspects that perhaps would require further consideration before submitting this work for publication and discussion during the defence.

In my opinion this dissertation presents and original solution to a scientific problem and meets the criteria for a PhD thesis. As demonstrated in Chapters 1 and 2, placing this work within the state of the art as well as the choice and correct application of multidisciplinary methodology, this dissertation confirms the candidate's ability to conduct independent scientific research.

Winthrop Professor Karol Miller

Pilsen, 15 January 2025