Graduate School of Creative Science and Engineering
Waseda University

博士論文概要
Doctoral Thesis Synopsis

論文題目
Thesis Theme

Medical-Image-Based Aorta Modeling with Zero-Stress-State Estimation Correlated with Anatomical Observation

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Arterial wall and blood flow are mutually dependent. That is a fluid–structure interaction (FSI) problem. It has been studied that there is a strong correlation with arterial endothelial disease and the wall shear stress (WSS) due to the blood flow. Either measuring or calculation can obtain such values from a computed result. The accuracy has been improving in both fields. However, the damage itself is a property of the arterial wall itself. It is more natural to see the structural properties, such as strain and stress from a computed result. Hence, we focus on the structural mechanics part of computational modeling. In the modeling, a challenge associated with a patient-specific analysis exists. The set of images does not come from the zero-stress state (ZSS) of the artery. It means the geometry is already loaded with blood pressure and hence it is prestressed. Thence of prestress is measured, and some researches described the importance of the prestress for structural and FSI computations.

Many researchers have been proposing methods to estimate the prestress or ZSS. The approaches can be classified into four categories: The first approach is the estimated zero-pressure (EZP) method, which compresses the artery to obtain a geometry with zero blood pressure. The second one is the modeled-prestress method, which finds prestress tensors when the deformed shape is matched to the target geometry. This assumes all of the regions has the uniform stress conditions and different elastic moduli. The third one uses a modeled-ZSS, which can be based on anatomical observation or some other consideration. This approach does not guarantee the deformed shape to be the target shape, which is from the medical images. The last one is based on inverse design analysis. This guarantees the deformed shape to be the target shape. However, anatomical ZSS is not considered. Our research team has been introducing a method combining the second and the last approaches. It is called the element-based ZSS (EBZSS) with finite element discretization. At first, we split the artery into the tube segments and map into a straight tube. Then estimate ZSS based on an anatomical observation. Using that ZSS as an initial guess, an iterative method is performed such that the loaded shape becomes the target shape. However, there are two challenges here: convergence incompleteness according to the geometry complexity, and the converged ZSS without anatomical observation. The first challenge appears from the medical-image-based geometry involves convex-concave and branched regions. The second challenge is caused by the gap between the initial guess and the converged result. It means the anatomical design might not be kept to the converged ZSS.

The objective of this thesis is to introduce the medical-image-based aorta modeling with ZSS estimation with anatomical observation. For the objective, the following three approaches are set to solve the challenges above: apply higher-order shape functions to EBZSS, impose integration-point-based strain, and design a ZSS initial guess with analytical solutions of the force equilibrium.

In Chapter 2, the formulations and boundary conditions for structural mechanics are described, it is based on total Lagrangian. The element-based total Lagrangian (EBTL) method is also described. The EBTL is a version where the ZSS is split into elements on arbitrary orientation. A hyperelastic Fung’s model is also given. In this thesis, the arterial wall is assumed as a single layer and an isotropic material. Here, the extension to multiple layers with anisotropic materials is straightforward.

In Chapter 3, the shape functions for discretization are given. They are for B-splines, non-uniform rational B-splines (NURBS), and T-splines. A finite element (FE) analysis based on these functions is called isogeometric analysis (IGA). We call this representation as isogeometric discretization. All the core functions can be represented by Bernstein polynomial functions with linear transformation matrices. Those matrices are constant within an element, and they are called Bezier extraction operators. This representation generalizes the discretization, and that makes it easier to understand the shape of an element, and it simplifies the implementing algorithms.

In Chapter 4, the objective is to apply higher-order shape functions to the EBZSS estimation method as the abovementioned. By using the isogeometric discretization, the process in the previous EBZSS method that is mapping between the artery and straight-tube segments is not needed. The higher-order shape functions give a direct calculation of curvatures and represent a convex-concave shape within an element. In this extension, the shape representation and the iterative method are modified. 2D test computations with straight-tube configurations are presented to show how the new EBZSS method works. The computations also aim to decide enough resolutions in the circumferential direction and the circumferential residual stretch as the ZSS design parameter. A 3D computation with matches the deformed shape to the medical-image-based geometry with the resolutions and the design parameters obtained in the 2D computations are also presented and represents how the method can be used.

From the above results, the following challenges remained. The first challenge is the ZSS initial guess was far from the converged ZSS. It means the anatomical ZSS design was not applied well on the converged ZSS. The second challenge is that the EBZSS iterative method depends on the control mesh structure. The method imposes displacements, calculated from the stretch on the surface, on element-based control points. T-spline is a useful representation for more complex geometry, but the control mesh could be unstructured connections. Since that connections could set the point far from the physical surface, T-spline representation with the EBZSS has convergence difficulty.

In Chapter 5, with the results obtained in Chapter 4, the EBZSS process imposes modifications on element-based control points, and it was succeeded with geometries without branches. For more complex geometries, the EBZSS with control mesh complexity has convergence difficulty. The objective of this chapter is to impose integration-point-based strain using the components of its metric tensor. The method which is introduced in this chapter tries to directly impose the residual strain at each integration point, which is on the physical position on the geometry, instead of element-based control points. This is the reason why the new ZSS is called IPBZSS. Metric tensors with the natural coordinate system, which are introduced in Chapter 2, are effective ways to describe geometrical information without its control mesh. In particular to the ZSS initial guess, the ZSS is based on an inner-surface geometry and its design parameters. Therefore, how to extend the information to the radial direction is needed. With the method, conversion between T-spline and Bezier representations is not needed. To show how the new method for estimating the ZSS performs, a 3D test computation with a Y-shaped tube is first presented. Then, the 3D computation where the target geometry is coming from medical images of a human aorta, which includes branches is presented. Two challenges remained. First, unphysical stretch values are observed at branched points of the patient-specific aorta geometry. Second, the ZSS initial guess was far from the converged ZSS: it means the anatomical ZSS design was not applied well on the converged ZSS. Given that these problems might have related each other, more anatomical ZSS initial guess modeling could estimate more reasonable results.

In Chapter 6, the objective is to design ZSS initial guess with analytical solutions of the force equilibrium. The force equilibrium in the normal direction is based on Kirchhoff–Love shell theory and the plane-stress condition, which gives proper constraints of the ZSS design parameters. Calculating the ZSS initial guess based on the analysis solution could improve estimation accuracy, and that makes converged ZSS reaching the ZSS target design quite well. In addition, given that a convergence difficulty is observed at the branched point which described in Chapter 5, an update of the wall coordinate system, is required. To show how the new ZSS initial guess techniques perform, 3D test computations with straight-tube configurations are first presented. The computations also aim to observe the effects of the modified wall coordinate system. A Y-shaped tube computation is presented to observe the perform at the branched points. Then, a 3D computation where the target geometry is coming from medical images of a human aorta is also presented. After how the method works were shown, the results are compared to the last results in Chapters 5.

In conclusion, the objective of this thesis was to introduce medical-image-based aorta modeling with ZSS estimation with anatomical observation. For the objective, the following challenges obtained from the existing researches were focused: Convergence incompleteness according to the geometry complexity, and the converged ZSS without anatomical observation. The following three approaches were set for the challenges: apply higher-order shape functions to the EBZSS, impose integration-point-based strain, design a ZSS initial guess with analytical solutions of the force equilibrium In Chapters 4 and 5, the ZSS estimation was successfully adapted to the geometries which have convex-concave and branched regions. In particular, the IPBZSS estimation method described in Chapter 5 was successfully applied to patient-specific aorta geometries which have branches with well-converged results. In Chapter 6, the ZSS initial guess was improved with analytical solutions of the force equilibrium based on the Kirchhoff– Love shell theory and the plane-stress condition. Given that the converged result was very similar to the initial guess, we could conclude that the converged ZSS was successfully based on the anatomical observation. From the results in Chapters 4–6, both Challenge 1: convergence incompleteness according to the geometry complexity and Challenge 2: the converged ZSS without anatomical observation, were solved. Thus, the ZSS modeling with anatomical observation was successfully introduced, finally.

早稲田大学　博士（工学）　学位申請　研究業績書

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種 類 別 (By Type)	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む） (theme, journal name, date & year of publication, name of authors inc. yourself)
Journal Articles (Peer-Reviewed)	○ 1. **T. Sasaki**, K. Takizawa, and T.E. Tezduyar, "Aorta zero-stress state modeling with T-spline discretization", *Computational Mechanics*, (**published online**). ○ 2. **T. Sasaki,** K. Takizawa, and T.E. Tezduyar, "Medical-Image-Based Aorta Modeling with Zero-Stress-State Estimation", *Computational Mechanics*, (**in printing**). 3. K. Takizawa, T.E. Tezduyar, and **T. Sasaki**, "Isogeometric hyperelastic shell analysis with out-of-plane deformation mapping", *Computational Mechanics*, (**published online**). 4. K. Takizawa, T.E. Tezduyar, H. Uchikawa, T. Terahara, **T. Sasaki**, and A. Yoshida, "Mesh refinement influence and cardiac-cycle flow periodicity in aorta flow analysis with isogeometric discretization", *Computers & Fluids*, (**published online**). 5. K. Takizawa, T.E. Tezduyar, T. Terahara, and **T. Sasaki**, "Heart valve flow computation with the integrated Space–Time VMS, Slip Interface, Topology Change and Isogeometric Discretization methods", *Computers & Fluids*, **158** (2017) 176–188. 6. K. Takizawa, T.E. Tezduyar, and **T. Sasaki**, "Aorta modeling with the element-based zero-stress state and isogeometric discretization", *Computational Mechanics*, **59** (2017) 265–280.
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	6. **T. Sasaki**, K. Takizawa, T.E. Tezduyar, H. Uchikawa, and K. Itatani, “Zero-stress state estimation in structural mechanics modeling of a human aorta with NURBS representation”, in *Proceedings of KSME–JSME Joint Symposium on Computational Mechanics & CAE 2015*, Tokyo, Japan, 2015. 7. **T. Sasaki**, K. Takizawa, T.E. Tezduyar, H. Uchikawa, and K. Itatani, “Zero-stress state estimation in structural mechanics modeling of a human aorta with NURBS representation”, in *Extended Abstracts of JST CREST–PRESTO Symposium 2015 — Mathematics for the 22nd Century*, Tokyo, Japan, 2015. 8. **T. Sasaki**, H. Uchikawa, K. Takizawa, T.E. Tezduyar, K. Itatani, S. Miyazaki, and K. Miyaji, “Arterial wall modeling with time-dependent medical images”, in *Extended Abstracts of the 13th US National Congress on Computational Mechanics*, California, USA, 2015. 9. **T. Sasaki**, K. Takizawa, T.E. Tezduyar, H. Takagi, K. Itatani, S. Miyazaki, and K. Miyaji, “Arterial dynamics computation with surface-extraction medical-image-based time-dependent anatomical models and element-based zero-stress estimates”, in *Extended Abstracts of the 18th International Conference on Finite Elements in Flow Problems*, Taipei, Taiwan, 2015.
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	13. T. Terahara, K. Shiozaki, **T. Sasaki**, K. Takizawa, and T.E. Tezduyar, “Heart valve flow analysis with isogeometric discretization and resolved jet flow near leaflet surfaces”, in *Extended Abstracts of Mechanical Engineering Congress 2017*, Saitama, Japan, 2017. 14. A. Yoshida, **T. Sasaki**, T. Terahara, K. Takizawa, and T.E. Tezduyar, “Estimation of zero-stress state in patient-specific aorta models with branches”, in *Proceedings of the 22nd Japan Society for Computational Engineering and Science Conference*, Saitama, Japan, 15. K. Shiozaki, T. Terahara, **T. Sasaki**, K. Takizawa, and T.E. Tezduyar, “Space–time isogeometric analysis of aortic-valve fluid mechanics and flow validation near the leaflet surfaces”, in *Proceedings of the 22nd Japan Society for Computational Engineering and Science Conference*, Saitama, Japan, 2017. 16. H. Uchikawa, T. Terahara, **T. Sasaki**, K. Takizawa, and T.E. Tezduyar, “Fluid and structure analysis of the human aorta — fluid mechanics analysis with space–time isogeometric discretization —”, in *Proceedings of the 22nd Japan Society for Computational Engineering and Science Conference*, Saitama, Japan, 2017. 17. A. Yoshida, **T. Sasaki**, T. Terahara, K. Takizawa, and T.E. Tezduyar, “Estimation of zero-stress state in patient-specific aorta models with branches”, in *Proceedings of JSME 29th Bioengineering Conference*, Aichi, Japan, 2017. 18. K. Shiozaki, T. Terahara, **T. Sasaki**, K. Takizawa, and T.E. Tezduyar, “Computational analysis and experimental validation of aortic valve fluid mechanics with experiment-based anatomical models”, in *Proceedings of JSME 29th Bioengineering Conference*, Aichi, Japan, 2017. 19. K. Shiozaki, T. Terahara, **T. Sasaki**, K. Takizawa, and T.E. Tezduyar, “Computational analysis of aortic-valve fluid mechanics and experimental validation”, in *Proceedings of the 30th Symposium on Computational Fluid Dynamics*, Tokyo, Japan, 2016. 20. H. Uchikawa, T. Terahara, **T. Sasaki**, K. Takizawa, and T.E. Tezduyar, “Vortex structure and periodicity studies on aorta and aortic valve flow analysis”, in *Proceedings of JSME 94th Fluids Engineering Conference*, Yamaguchi, Japan, 2016. 21. **T. Sasaki**, K. Takizawa, T.E. Tezduyar, and K. Itatani, “Aortic zero-stress state estimation with isogeometric discretization”, in *Proceedings of JSME 29th Computational Mechanics Division Conference*, Aichi, Japan, 2016. 22. **T. Sasaki**, K. Takizawa, T.E. Tezduyar, and K. Itatani, “Aorta modeling with zero-stress estimation, material-point tracking, and isogeometric discretization”, in *Proceedings of the 21st Japan Society for Computational Engineering and Science Conference*, Niigata, Japan, 2016. 23. **T. Sasaki**, K. Takizawa, H. Uchikawa, T.E. Tezduyar, and K. Itatani, “Zero-stress state estimation of aortic wall with NURBS representation”, in *Proceedings of JSME 28th Bioengineering Conference*, Tokyo, Japan, 2016. 24. **T. Sasaki**, H. Uchikawa, K. Takizawa, T.E. Tezduyar, K. Itatani, S. Miyazaki, and K. Miyaji, “Arterial wall modeling with time-dependent medical images”, in *Extended Abstracts of Mechanical Engineering Congress 2015*, Hokkaido, Japan, 2015. 25. **T. Sasaki**, H. Uchikawa, K. Takizawa, T.E. Tezduyar, K. Itatani, S. Miyazaki, and K. Miyaji, “Physically based mapping and arterial wall modeling”, in *Proceedings of the 20th Japan Society for Computational Engineering and Science Conference*, Ibaraki, Japan, 2015. 26. **T. Sasaki**, K. Takizawa, K. Itatani, H. Takagi, T.E. Tezduyar, S. Miyazaki, and K. Miyaji, “Arterial wall modeling and medical image mapping based on element-based zero-stress state estimation method”, in *Proceedings of JSME 27th Bioengineering Conference*, Niigata, Japan, 2015. 27. **T. Sasaki**, K. Takizawa, K. Itatani, H. Takagi, T.E. Tezduyar, S. Miyazaki, and K. Miyaji, “An aorta dynamics computation with the element-based zero-stress state estimation method”, in *Proceedings of JSME 25th Conference on Frontiers in Bioengineering*, Tottori, Japan, 2014. 6 others.