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A CLINICALLY APPLICABLE STRATEGY FOR ESTIMATION OF IN VIVO VENTRICULAR WALL ELASTICITY

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SUMMARY

A clinically applicable approach to estimate the *in vivo* elastic material properties of the heart wall is presented. This strategy utilizes a patient-specific bi-ventricle mechanical model within an optimization-type inverse problem solution procedure that accounts for the rigid body motion of the heart to estimate elastic properties from untagged cardiac images and corresponding hemodynamic measurements. An example is examined of applying this inverse solution procedure to actual clinical patient data, including standard clinical imaging and interventricular pressure measurement. The results show that the inverse solution procedure can obtain a consistent estimate for the elastic properties of the heart wall.

Key words: *inverse material characterization, clinical, heart wall*

1 INTRODUCTION

Measures of myocardial stiffness have been identified as important features of a variety of cardiovascular diseases, such as myocardial infarction and diastolic heart failure [1]. One specific example is pulmonary hypertension (PH), which is a deadly cardio-pulmonary illness that is clinically characterized by a hemodynamic state of elevated mean pulmonary arterial pressure [2]. A particular observation relating to the effects of PH on the human heart is that PH substantially changes the mechanical properties of the heart, especially the right ventricle (RV). Although this link between mechanics and PH is clear, more detailed quantitative studies are necessary before specific features of mechanical property changes can be available for improved diagnosis and prognosis. Moreover, to study the *in vivo* mechanical property changes of the RV, a reliable method is necessary to quantify these mechanical properties from standard clinically available patient data. Towards addressing this challenge, an inverse problem solution technique is being developed, and will be presented herein, to estimate the mechanical material properties of the heart wall from clinically attainable cardiac medical images (e.g., CMRI) and measurable hemodynamics. This approach includes a bi-ventricle (i.e., left and right ventricle combined geometries only) computational representation of the passive mechanics of the heart combined with a shape-matching optimization-based inverse solution estimation procedure that includes a registration strategy to account for any rigid rotation and translation of the heart during passive function. The following details the inverse solution estimation procedure, which is followed by application of the estimation procedure to a clinical example to evaluate the solution capabilities.

2 METHODOLOGY

The overall inverse solution procedure utilized herein is based upon ongoing work of the authors to develop a shape-based strategy to inversely estimate mechanical properties of biological structures,

particularly focused on the human heart [3]. The solution procedure follows the standard pattern of a PDE-constrained optimization method for estimation of inverse problem solutions [4]. In particular, in this work a bi-ventricle representation of the heart is generated from the patient imaging data. Then, finite element analysis is used to estimate the passive diastolic process by applying the patient-specific pressure change between beginning and end diastole to the interventricular walls for a given estimate of the ventricular wall material parameters. Lastly, the shape of the ventricle(s) estimated by the finite element analysis is compared to the shape of the ventricle(s) extracted from the patient imaging data. If the comparison of the shape is sufficient, then the estimated properties are accepted as the estimate of the actual *in vivo* mechanical properties. Alternatively, if the shape comparison is not yet sufficient, the estimated parameters are updated (corresponding to a standard optimization procedure), and the process is repeated from the point of simulating diastole with the bi-ventricle model.

For the present study, the standard transversely isotropic Fung-type model for myocardium was used as the constitutive model in the bi-ventricle finite element analysis. In this representation, there are two key material parameters to determine (which were the unknowns in the inverse problem): (1) the stiffness parameter, C_0, and (2) the nonlinearity parameter, B_0. A standard gradient-based interior point optimization method was used to minimize the objective function to estimate the material parameters. Of particular importance to the present development is the strategy used to compare the estimated ventricular shape and the target shape at end diastole extracted from the patient's imaging data (i.e., the optimization objective function).

2.1 Objective Function

In order to have an approach to utilize standard clinical imaging data (e.g., without tagging) most directly, the strategy proposed is to compare shape, rather than displacement or strain, which would require additional pre-processing to obtain. For the study herein, the standard Hausdorff distance was applied for this shape comparison. Moreover, since the focus of the application of interest (PH) is on the RV, only the RV shape, specifically the RV endocardial surface (RVES), was used as the target shape extracted from the medical images. However, prior to calculating the Hausdorff distance, it is necessary to account for the potential of organ-level rotation and translation, so that only the deformation of the ventricle is compared, not its rigid motion. Therefore, the process to evaluate the objective function includes an iterative closest point rigid registration step to remove this rotation and translation. Fig. 1 shows a flowchart for this approach that was used to compare the RV shape estimated by the bi-ventricle finite element analysis to the target RV shape.

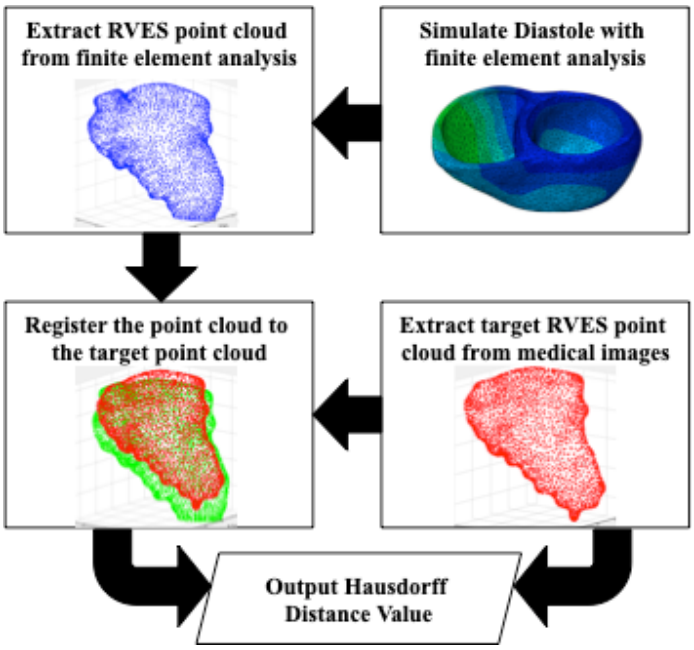

Fig.1 Flow chart for the method to quantitatively compare the estimated and target RVES shapes.

3 RESULTS AND CONCLUSIONS

3.1 Clinical Data Acquisition

Cardiovascular magnetic resonance (CMR) images from a randomly chosen patient who underwent both CMR and right heart catheterization within a 2-day period were utilized in this study. Images were acquired using a 1.5-Tesla Siemens Magnetom Espree (Siemens Medical Solutions, Erlangen, Germany) equipped with a 32-channel cardiac coil. Standard breath-held cine imaging was acquired with steady-state free precession in the short axis orientation spanning the base to apex (6 mm slice thickness, 4 mm skip). Typical imaging parameters included 30 phases per R-R interval, matrix 256 by ~144, flip angle 51 deg, TE 1.11 ms, acceleration factor 3.

4.1 Inverse Estimation of Passive Elastic Properties

The inverse solution procedure defined was applied five separate times, with a different randomly generated starting estimate of the two material parameters each time to evaluate the consistency of the result. The results were found to be highly consistent for this example patient, with each inverse estimation providing nearly identical material parameter estimates. The average estimate of the two material parameters were: C_0 = 1.15 kPa and B_0 = 9.6. These parameters are well within the normal range of stiffness and nonlinearity terms reported in the literature. More importantly, Fig. 2 shows the final RVES shape predicted by the finite element analysis with the estimated material parameters in comparison to the target RVES shape from the medical images by overlapping the corresponding point cloud representations.

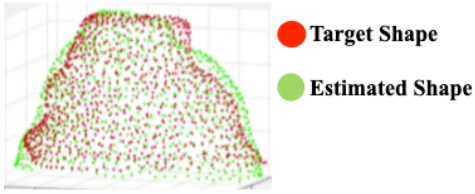

Fig.2 Comparison of the point cloud representations of the RVES shape from the inversely estimated material parameters and the RVES shape extracted from the clinical imaging data.

The material properties estimated by the inverse solution procedure clearly produce an RVES shape at the end of the simulated diastolic process that qualitatively matches well with the RVES shape extracted from the clinical imaging data at end diastole.

To further examine the behavior of the inverse problem, each of the two material parameters were varied in a feasible range, and the optimization objective function (i.e., the Hausdorff distance) was calculated for each combination of material parameters. Fig. 3 shows a plot of this Hausdorff distance for each combination of the stiffness and nonlinearity material parameters.

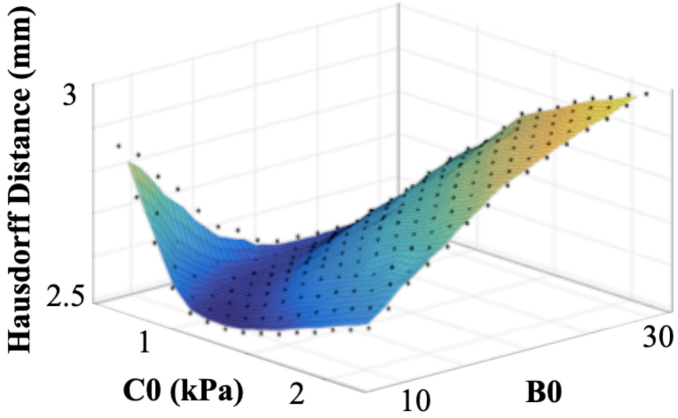

Fig.3 Hausdorff distance between the target RVES shape and the simulated RVES shape with various combinations of the stiffness and nonlinearity parameters.

What is particularly significant is that the objective function surface is smooth and convex. Therefore, it is not surprising that the inverse solution estimation procedure consistently estimated nearly the same parameters each time. However, there is a "trough" in the objective function surface where a relatively large range of parameter combinations provided a similarly low error estimation. Although this was not an issue for the current test, there could be some concern that if a similar trough exists for other cases, that there may be situations where a unique (or nearly unique) solution cannot be obtained from the inverse estimation process.

The results indicate that potential exists to use the proposed method for inversely estimating the *in vivo* elastic material properties of the heart wall with standard clinical cardiac imaging and hemodynamic data. Yet, work still remains to further evaluate and develop the proposed approach. In addition to examining more test cases, a particularly important future development is to incorporate more realistic material propeties and boundary conditions.

REFERENCES

[1] Hadjicharalambous M, Asner L, Chabiniok R, et al. Non-invasive Model-Based Assessment of Passive Left-Ventricular Myocardial Stiffness in Healthy Subjects and in Patients with Non-ischemic Dilated Cardiomyopathy. Annals of Biomedical Engineering, 2017, 45(3): 605-618.

[2] Wu J, Wang Y, Simon M A, et al. A new approach to kinematic feature extraction from the human right ventricle for classification of hypertension: a feasibility study. Physics in medicine and biology, 2012, 57(23): 7905.

[3] Xu J, Simon M A, Wong T C, et al. A Shape Analysis Based Strategy for Estimation of *in vivo* Ventricular Wall Elasticity. 5th International Conference on Computational and Mathematical Biomedical Engineering, April 2017.

[4] Aguilo M A, Aquino W, Brigham J C, et al. An inverse problem approach for elasticity imaging through vibroacoustics. IEEE transactions on medical imaging, 2010, 29(4): 1012-1021.