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Modeling of Normal and Atherosclerotic Blood Vessels using Finite Element Methods and Artificial Neural Networks

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***Abstract*—**Analysis of blood vessel mechanics in normal and diseased conditions is essential for disease research, medical device design and treatment planning. In this work, 3D finite element models of normal vessel and atherosclerotic vessel with 50% plaque deposition were developed. The developed models were meshed using finite number of tetrahedral elements. The developed models were simulated using actual blood pressure signals. Based on the transient analysis performed on the developed models, the parameters such as total displacement, strain energy density and entropy per unit volume were obtained. Further, the obtained parameters were used to develop artificial neural network models for analyzing normal and atherosclerotic blood vessels. In this paper, the objectives of the study, methodology and significant observations are presented.

***Keywords*—**Blood vessel, atherosclerosis, finite element model, artificial neural networks

I. Introduction

THE Blood vessels either delivering oxygenated blood - arteries, arterioles, capillaries or returning with carbon dioxide – veins and venules, display highly nonlinear elastic and anisotropic mechanical behavior and exhibit complex material properties [1,2]. The blood vessel mechanics change from vessel to vessel, change with ageing and pathologies [3].

Atherosclerotic vascular disease is the most common cause of morbidity and mortality in developed countries, and the world-wide importance of acute vascular syndromes is increasing. As people age, they tend to develop fatty plaques within the walls of their blood vessels [4]. Acute events are usually triggered by the development of plaque disruption and subsequent thrombus formation [5].

The objective of blood vessel modeling is to analyze the function of the vessel from its geometry, material properties and boundary conditions [6]. Various constitutive models were proposed to describe the tissue mechanical behavior [7], such as elastic, pseudoelastic, randomly elastic, hyperelastic, linear viscoelastic model, or more complex models [8].

Even though the simplified models cannot completely explain the actual behavior, when simplified assumptions are made some important information is often revealed [4]. In recent studies, averaged, idealized and patient-specific geometric models have been used as a basis for numerical simulations [9].The finite element method is a powerful technique for finding approximate solution of a partial differential equation where the domain boundaries of a given problem are so complex that other approaches have difficulties or fail [10]. In the finite element method, a complex domain is discretized into a number of elements, such as that a set of basis functions can be defined on the elements to approximate the solution [4].

The capability of the feed forward back propagation neural network, with as little as one hidden layer, to approximate an arbitrary function has been theoretically proven by several authors. A multilayer neural network is capable of arbitrarily accurate approximation to an unknown mapping and its derivatives, to as many orders as desired [11].

The objective of this work is to develop suitable models for analysis of normal and atherosclerotic blood vessels using finite element methods and artificial neural networks.

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II. Methodology

A. Generation of 3D finite element models of blood vessels

The 3D model of a section of the thoracic aorta was developed using Comsol 3.5a. FEM models were developed for normal vessel and vessel with 50% plaque deposition and are shown in Fig. 1(a) and (b) respectively.

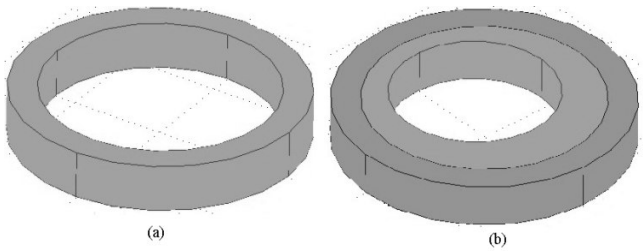

Fig. 1(a) normal blood vessel geometry, (b) atherosclerotic blood vessel with 50% plaque deposition

The geometry and mechanical properties of the vessel were adopted from literature [12]. The stiffness of the plaque component was taken to be 0.5 times that of the vessel stiffness. Further, the boundary conditions were applied to the developed models and the developed volumes were meshed using tetrahedral elements. The mesh quality was improved by fine tuning the mesh.

B. Basis Function

The stress–strain relationship is developed for a general strain energy function based on strain invariants. The first and second strain invariants $\overline{I_1}, \overline{I_2}$ and volume ratio J are chosen as the variables in the strain energy function [Shen et al (2005)]. They are defined as:

$$\overline{I_1} = \overline{\lambda_1}^2 + \overline{\lambda_2}^2 + \overline{\lambda_3}^2 \tag{1}$$

$$\overline{I_1} = \overline{\lambda_1}^2\overline{\lambda_2}^2 + \overline{\lambda_2}^2\overline{\lambda_3}^2 + \overline{\lambda_1}^2\overline{\lambda_3}^2 \tag{2}$$

$$\overline{\lambda_k} = J^{-\frac{1}{3}}\lambda_k, \quad k=1,2,3 \tag{3}$$

where, λ_k (k=1,2,3) are the principal stretch ratios and J is the total volume ratio. The strain energy function can be expressed in terms of $\overline{I_1}, \overline{I_2}$ and J ,

$$U = u(\overline{I_1}, \overline{I_2}, J) \tag{4}$$

Further, the stress-strain behavior is defined using the following equations. Writing the current position of a material point as x and the reference position of the same point as X, the deformation gradient is then defined as

$$F = \frac{\partial x}{\partial X} = \frac{\partial x_i}{\partial X_j} \quad (i,j=1,2,3) \tag{5}$$

Then J , the total volume change at the point, is

$$J = \det(F) \tag{6}$$

For simplicity, the deformation gradient with the volume change eliminated is defined as

$$\overline{F} = J^{-\frac{1}{3}}F \tag{7}$$

Then, the deviatoric stretch matrix is introduced as

$$\overline{B} = \overline{F}.\overline{F}^T \tag{8}$$

So that the first strain invariant is given by

$$\overline{I_1} = trace\overline{B} = \overline{B}_{ii} \quad (i=1,2,3) \tag{9}$$

and the second strain invariant is given by

$$\overline{I_2} = \frac{1}{2}\left\{(trace(\overline{B}))^2 - trace(\overline{B}.\overline{B})\right\} \tag{10}$$

Then the stresses associated with the strain energy function are given by

$$\sigma = \frac{2}{J}dev\{(\frac{\partial U}{\partial \overline{I_1}} + \overline{I_1}\frac{\partial U}{\partial \overline{I_2}})\overline{B} - \frac{\partial U}{\partial \overline{I_2}}\overline{B}.\overline{B}\} + \frac{\partial U}{\partial J}I \tag{11}$$

where, dev means deviatoric and is calculated as dev(A) = A – 1/3 trace(A) for matrix A. I is the Identity matrix. For incompressible material, J = 1, u is a function of I_1 and I_2 only [Shen et al (2005)]. The potential function of the arterial material is as follows:

$$\overline{U} = \frac{\mu_1}{2}(\overline{I_1} - 3) + \frac{K_1}{2}(J-1)^2 \tag{12}$$

The material constants are the shear modulus, μ_1 and the bulk modulus, K_1.

C. Forcing function

The actual blood pressure signals were obtained from the MIT database of clinical signals (www.physiobank.net). The BP signal was modelled as a function of time using the sum of sinusoids model of the following form:

$$y(t)=a_1\sin(b_1t+c_1)+a_2\sin(b_2t+c_2)+..... + a_n\sin(b_nt+c_n) \tag{13}$$

where a_1, a_2, ... a_n, b_1, b_2, ..., b_n, c_1, c_2, ... c_n are parameters of the model, 't' is the time and, 'y' refers to the amplitude of the BP signal.

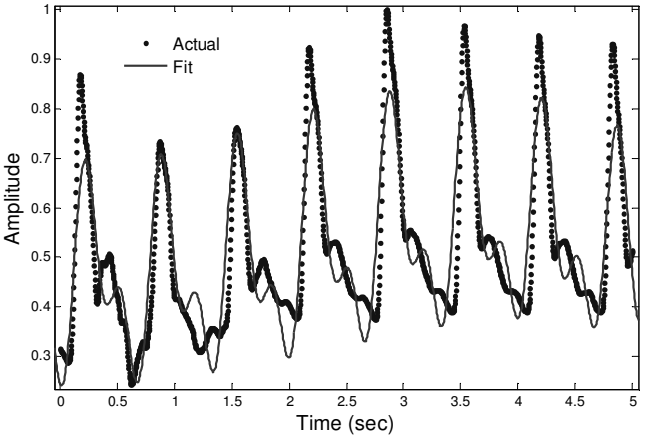

Fig. 2 The actual BP signal and the computed fit

Several models were developed by increasing the number of model terms. A model with the five sine terms was found to have the least error. The actual BP signal and the fitting function is shown in Fig 2. The obtained function was used as the forcing function for simulating the developed FEM models of normal and abnormal blood vessels. Based on the simulations performed, the parameters such as total displacement, strain energy density and entropy per unit volume were obtained.

D. Modelling using artificial neural networks

Artificial Neural Networks (ANN) are able to learn key information patterns with multi-information domain. The advantage of the neural networks is that they can be used to model normal and abnormal signals in medical diagnostics through a flexible network of weights, transfer functions and input features.

In this work, a feed forward neural network with the architecture having one hidden layer, and operating on tan sigmoid transfer function, was employed for modelling the normal and atherosclerotic blood vessels. Training of the network was performed under back propagation of the error using conjugate gradient algorithm. The blood pressure signal was taken as the input to the network and the output of the network consists of total displacement, strain energy density and entropy per unit volume. The networks with varied number of hidden layer neurons were synthesized and the training was performed using Matlab 7.1. The performance of the network and modelling accuracy was assessed using performance indices such as Integral Square Error (ISE).

III. Results and Discussion

The variation of ISE is shown as a function of the number of hidden layer neurons for normal blood vessel, in Fig. 3. It is seen that the ISE varies nonlinearly with increase in the number of hidden neurons of the ANN. In modelling the normal vessel, the error in estimation of the total displacement, strain energy density and entropy per unit volume was found to be minimum for a network with thirty hidden layer neurons. The ISE was found to increase with increase in the number of hidden neurons.

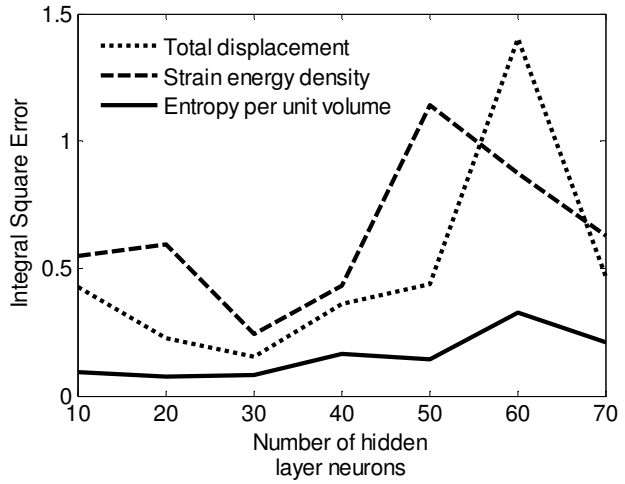

Fig. 3 The variation of integral square error shown as a function of the number of hidden neurons for normal blood vessel

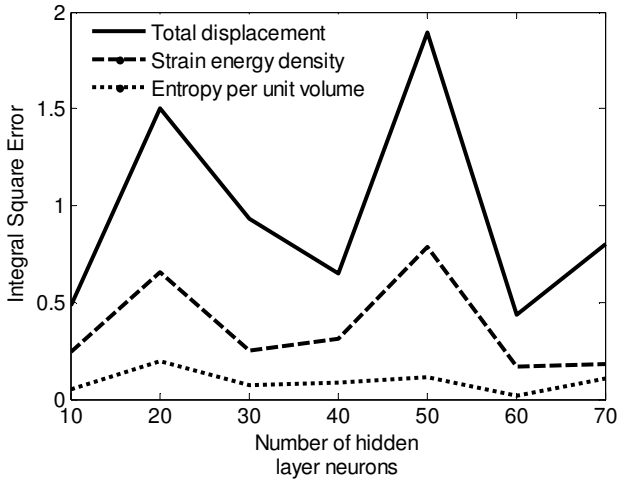

Fig. 4 The variation of integral square error shown as a function of the number of hidden neurons for blood vessel with 50% plaque formation

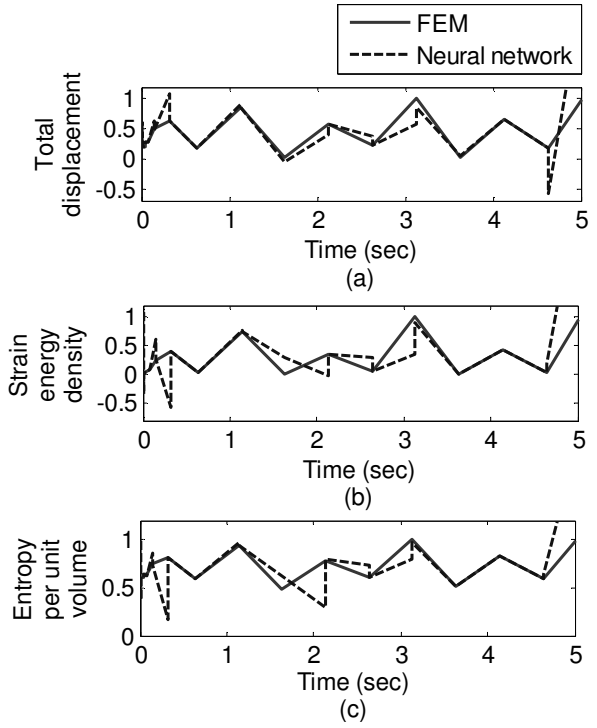

Fig. 5 The variation of normal vessel response such as (a) total displacement, (b) strain energy density and (c) entropy per unit volume shown as a function of time for FEM and ANN model

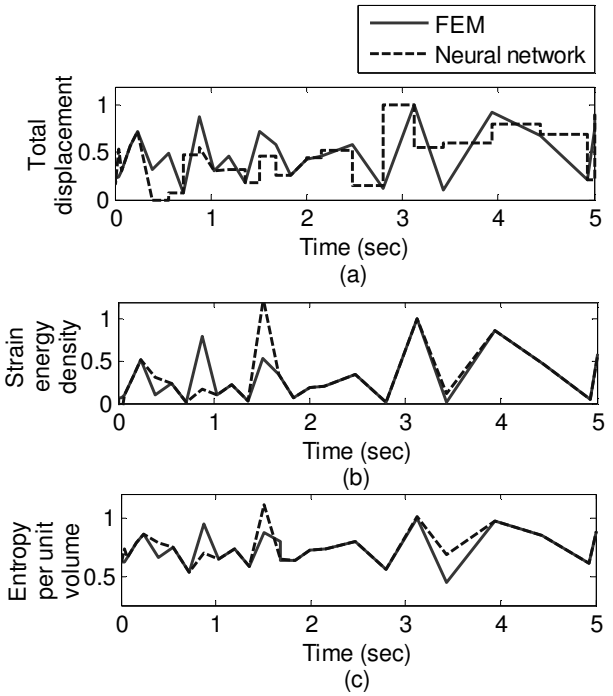

Fig. 6 The variation of (a) total displacement, (b) strain energy density and (c) entropy per unit volume for the vessel with 50% plaque deposition shown as a function of time for FEM and ANN model

Similarly, the variation of ISE is shown as a function of the number of hidden layer neurons for blood vessel with 50% plaque formation, in Fig. 4. A periodic variation was observed in the ISE with increase in the number of hidden neurons. Further, it was found that the error in estimation of the output parameters was found to be minimum for a network with fifty hidden layer neurons.

The outputs of the FEM model and ANN model of normal vessel and vessel with 50% plaque deposition are compared in Fig. 5 and 6. Fig. 5(a), (b) and (c) show the variation of normal vessel response such as total displacement, strain energy density and entropy per unit volume respectively, as a function of time. It appears that the response of the FEM model and ANN model with optimal number of hidden neurons are similar.

The variation of the considered parameters for the vessel with 50% plaque deposition is shown as a function of time, in Fig. 6(a), (b) and (c). Also, it is seen that the response of both the FEM and ANN models are comparable for abnormal conditions.

IV. Conclusion

In order to prevent, diagnose and treat vascular disease, detailed knowledge of blood vessel mechanics is essential. For examining the relationship between vascular disease and hemodynamic conditions, detailed quantitative data on vascular mechanics in the arteries is required. However, experimental studies have several limitations including the time and expense of conducting these experiments, the difficulty in replicating in vivo conditions, and the limited quantitative data which can be extracted. In recent years, computational techniques such as finite element methods have been used increasingly by researchers seeking to understand vascular dynamics. These methods can augment the data provided by in vitro and in vivo methods by enabling a complete characterization of vessel mechanics under precisely controlled conditions.

In this work, 3D finite element models of normal vessel and atherosclerotic vessels with 50% plaque deposition were developed using Comsol 3.5a. Boundary conditions were applied to the developed models and a distributed load was applied on the inner wall of the vessel. The developed vessels were subjected to a transient analysis and the parameters such as total displacement, strain energy density and entropy per unit volume were obtained for normal and atherosclerotic vessels. Further, the obtained results were utilized to develop artificial neural network models of normal and atherosclerotic vessels. The accuracy of the developed models was analyzed using performance estimates such as integral square error.

This work seems to be clinically important since the modelling of blood vessels in normal and diseased states is essential for designing stents, surgery planning, treatment and diagnosis of vascular diseases.

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