Coupled Finite Element Model-artificial Neural Networks Can Predict Mechanical Properties Of Articular Cartilage

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Introduction: Characterization of mechanical properties of articular cartilage over time potentially enables diagnosis of OA especially at early stages [1-6]. Applying stress-relaxation on the articular cartilage through indentation tests helps determine the mechanical and physical properties of cartilage such as Elastic modulus (E) and permeability (k). Using indentation test as a non-destructive method, one can obtain cartilage’s mechanical properties by fitting biphasic model to the experimental data [7-9]. Previous studies could interpret the indentation data based on available analytical formula that hold the assumption of cartilage as an elastic or viscoelastic material [10, 11]. Limitation of analytical expression of poroelastic/biphasic materials motivated us to develop a combined finite element modeling/artificial neural networks (ANNs) approach to estimate the mechanical properties of cartilage. Finally we compared the results of our proposed approach with those derived from viscoelastic based analytical relationships.

Methods: We used a finite element model program (ABAQUS) to simulate the behavior of cartilage in indentation test as a poroelastic material. The assumptions of this work as well as the mechanical properties have been extracted from the work of Spilker et al. and Warner and Pawaskar [12-14]. The specimen used in the simulations had a thickness of 3 mm. We used a spherical indenter with 5 mm radius in our simulations. Based on the mesh sensitivity analyses we applied 2160 four-node bilinear displacement and pore pressure elements. We created an ABAQUS subroutine to implement the fluid flow boundary condition at the interface of indenter and the cartilage. We simulated 121 force-data for a wide variety of mechanical properties using FEM and applied these data to train the artificial neural network.

Results: Assessment of ANN for noise-free force-displacement curve Pearson correlation coefficient equal to one for training, validation and tests of 10,000 samples (training 90%, validation 5% and test 5% of samples) and 30 hidden neurons proves the proper functionality of the trained network (Fig.1). Furthermore, we observed that the performance improvement after training the network is quite similar for training, validation and tests.

Assessment of ANN for noisy force-displacement curve After decreasing the sensitivity of ANN to noise by training ANN with different signal to noise ratios we plotted the regression diagrams. The regression diagrams resulting from validation, training and tests for 10 % noise are depicted in Fig 2. Table 1 shows that after introducing the noise (5% noise) the absolute identification error divided by the size of the intervals for each magnitude of the mechanical properties was negligible.

Discussion: In this research we could apply the artificial neural networks effectively to predict mechanical properties of articular cartilage. In case where the indentation curve was noise free, the
ANN approach provided robust results. Pearson correlation coefficient equal to one for training, validation and test under poroelastic condition explicitly demonstrated its efficacy. Moreover, we can conclude that 30 hidden neurons were sufficient to provide expected robustness. However, trained ANN failed to give correct mechanical properties of cartilage in the presence of noise in force-time curves. After training the ANN with different values of signal to noise ratio this problem have been overcome. The Pearson correlation coefficient stayed above 0.99 for training, validation and test even with large noise i.e. 10%, indicating that training with noisy data could tremendously improve the ability of the ANN to predict mechanical properties of the cartilage.

**Significance:** In conclusion using the trained artificial neural networks, one can obtain cartilage’s mechanical properties conveniently and without any need of computational modeling expertise.

<table>
<thead>
<tr>
<th></th>
<th>( \bar{\mu}_{\text{err}} )</th>
<th>( \sigma_{\text{err}} )</th>
<th>( \frac{\bar{\mu}_{\text{err}}}{(\text{Max} - \text{Min}) \times 100} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>-6.9e-4</td>
<td>1.8e-2</td>
<td>1.3%</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>1.7e-3</td>
<td>3.9e-2</td>
<td>1.5%</td>
</tr>
<tr>
<td>Permeability</td>
<td>1.5e-4</td>
<td>1.6e-3</td>
<td>1.3%</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>-1.8e-4</td>
<td>1.5e-2</td>
<td>2.7%</td>
</tr>
</tbody>
</table>

Table symbols: \( \bar{\mu}_{\text{err}} \): mean identification error, \( \sigma_{\text{err}} \): standard deviation of identification error, \( \frac{\bar{\mu}_{\text{err}}}{(\text{Max} - \text{Min}) \times 100} \): mean absolute identification error divided by the size of the identification interval.

**Figure 1.** Regression diagrams for the training (a), validation (b), and test (c) datasets of the ANN trained without the presence of inaccuracies (noise) in its training and test data.

**Figure 2.** Regression diagrams for training (a), validation (b) and test (c) datasets when neural networks were trained with noisy datasets.

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