POROELASTIC PARAMETER ESTIMATION OF INTERVERTEBRAL DISC: A FINITE ELEMENT AND EVOLUTIONARY BASED ALGORITHM

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INTRODUCTION

During the last two decades, a more realistic approach to the modelling of the intervertebral disc (IVD) has been used based on the theory of consolidation and poroelasticity (Simon et al, 1985). Together with these mathematical and numerical simulations, more sophisticated experimental studies based on the rate dependent and creep behaviour of the IVD have also been introduced (Martinez et al, 1997).

Finite element analysis (FEA) as a computational tool for numerical evaluation of stress, strain, and displacement in structural systems has become well known in biomechanics. The FEA technique has been used extensively to predict time dependent behaviour of the IVD under various loading schemes, kinematic boundary conditions, and material properties.

The accuracy of the FEA results is highly dependent on the correctness of the initial input values for material properties. In recent years there has been substantial application of classical identification methods to estimate the properties of materials. The traditional technique of parameter estimation for structures is formulated in an abstract setting in Hilbert spaces, and an optimization technique, e.g. least squares and feasible directions, is then used to solve the identification problem (Katoozian, 1999). The basic ideas is to discretize the model into a FEA mesh and then use an iterative identification task to estimate parameter values that minimize the error between the simulated FEA output and the experimental data.

Earlier optimal control approaches suffered from a major weakness of being trapped in local extremum. Although some initial parametric and sensitivity analyses would enable one to make a proper initial guess for unknown parameters, convergence to the global extremum is still not guaranteed. In this study a new approach based on the application of Genetic Algorithm (GA) to the biomechanical parameter estimation has been introduced.

Evolutionary Algorithms (EA) are powerful optimization techniques taking inspiration from genetics and natural selection. Unlike classical search methods, EAs with heuristic capability can effectively explore very large solution spaces.

METHODS

The commercial FEA code ABAQUS 5.8 for nonlinear poroelastic analysis has been used. The poroelastic FEA model in ABAQUS is based on multi-phase material using effective stress to describe the behaviour of the solid phase. This code employs principles of the theory of consolidation with emphasis on Darcy’s law for low velocity fluid phase.

The genetic algorithm code, GAfortran 1.6.4 (Carol, 1997), was incorporated into the estimation process using an interface program. The GA code initializes a random sample of individuals with parameters to be optimized using evolution via ‘survival of the fittest’. The selection scheme used is tournament selection with a shuffling technique for choosing random pairs for ‘mating’. The routine includes binary coding for the individuals, jump mutation, creep mutation, and the option for single-point or uniform crossover.

Variation of nodal displacement at each load increment to be evaluated by FEA code is a function of IVD poroelastic properties (elastic modulus and permeability). In this problem, by using known values of displacement at the specific sensor sites, the error function was computed. This function (objective function to be minimized) was taken as the sum of the weighted errors at each load increment;

$$error = \sum_j \sum_i \left(w_i (u_i - u_{ei})^2 \right)_j$$

where $u_i=u_i(E_a,k_a,E_n,k_n)$ is the displacement field which is a function of poroelastic properties. E_a, k_a, E_n, k_n are elastic modulus and permeability of annulus and nucleus respectively. Index i and j refer to nodal points at the sensor site and load increment during each step of loading. w is the weighting factor

and u_{ie} is the experimental displacement data that was conducted using vertebral units obtained from tails of freshly slaughtered bovines (Race et al, 2000).
The parameter estimation process begins by incorporating some initial values for parameters using the GA technique, then performs an evolutionary search, and ends with final values of variables that minimize the error function.

RESULTS AND DISCUSSION

Figure 1 shows the axisymmetric FEA model of the IVD and Figure 2 presents the convergence history of the algorithm. The percent reduction in error estimator function during the computation was 80%. Final values of the poroelastic parameters are summarized in Table 1.

This study utilises the Evolutionary Algorithm technique to estimate the system characteristics such that the error between experimental data and model output is minimized. The numerical results indicate the effectiveness of the algorithm in estimating IVD characteristics. Following the considerable reduction in error estimator function (Figure 2) meaningful estimated poroelastic parameters were computed. In this kind of analysis there is always a compromise between the level of accuracy of estimation and the number of function calls (FEA runs), this being about 5000. This number is substantially greater than that required in classical optimisation techniques.

Further studies will be conducted using a 3-D model of the human spinal motion segment to obtain poroelastic parameter values. The effects of anisotropy and swelling should also be considered in order to determine more realistic characteristics.

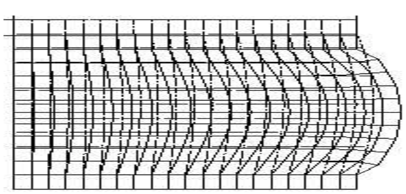

Figure 1: Deformed and Undeformed IVD mesh

Table 1: Estimation Results of Poroelastic Properties

Material	***E* (MPa)**	***k* (m/s)**
Nucleus	4.63	0.1E-10
Annulus	7.30	0.2E-11

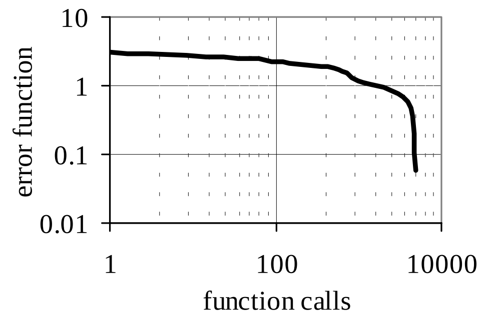

Figure 2: Convergence History

SUMMARY

An axisymmetric finite element model of the intervertebral disc of bovine tail was constructed and the load controlled experimental data of the same specimen was used. Two sets of poroelastic isotropic material properties for annulus and nucleus were determined by using the Genetic Algorithm technique to minimize the displacement error between the experimental data and the corresponding finite element results. Fairly meaningful values of elastic stiffness and permeability have been achieved after a considerable number of iterations.

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