INTRODUCTION: It is the unique combination of poro-elastic behavior and fluid flow into and out of the cervical discs that provide the strength and flexibility necessary to bear the physiological loading of the spine. This can be accomplished in numerical modeling by including the poroelastic behavior of the disc in combination with modeling the change in proteoglycan content and permeability with deformation of the disc. The aim of the current research is to develop a finite element model of a cervical disc including the fluid flow into and out of the intervertebral disc in response to loading and unloading of the spine. This study also looks at the effect of poro-elasticity, change in osmotic pressure and change in permeability on the biomechanical characteristics of the cervical disc. One of the purposes of this study is to investigate which factor between swelling pressure vs. strain-dependent permeability is more important in predicting the biomechanical behavior of the cervical spine under external loading.

METHODS: A three-dimensional finite element model of a C5-C6 motion segment was built from a CT scan of a 38 year old woman. Permeability, porosity and drained elastic properties of various components of the motion segment were obtained from literature. The effect of change in the concentration of proteoglycans contained within the disc was modeled by incorporating a pressure, in this case referred to as the swelling pressure, which is dependent on the fixed charge density.

Knowing the water content of the disc, the swelling pressure is then calculated using an equation proposed by Broberg (1):

\[ p_{swell} = Pf_i^{f_im} + 1 \]  

(1)

where \( P = 0.66 \) MPa, \( \alpha = 0.15 \) and \( f_i \) is the fixed charge density at time \( t_i \). Similarly, the effect of the change in permeability resulting from the axial strain in the tissue was modeled by including an internal pressure acting on the disc. This pressure (\( p_{perm} \)) was calculated using the equation (2,3):

\[ E, -1/2 \frac{2}{M} ln \left( \frac{k_i}{k_f} \frac{\alpha_i}{\alpha_f} \right) \]  

\[ 1 + 2 \frac{1}{M} \ln \left( \frac{k_i}{k_f} \frac{\alpha_i}{\alpha_f} \right) \]

\[ -p_{perm} = \frac{1}{1 + \frac{1}{M} \ln \left( \frac{k_i}{k_f} \frac{\alpha_i}{\alpha_f} \right) - 1 - \left[ \epsilon + \beta \left( \frac{1}{1 - \epsilon} \right) \right]} \]  

(2)

In equation 2, \( E \) is the Young’s modulus, \( \epsilon \) is the strain in the tissue, \( H_s \) is the aggregate modulus, \( \alpha \) is the void ratio, \( k \) is the permeability, \( \phi \) is the volume fraction of fluid, \( \beta \) is the nonlinear stiffness coefficient and \( M \) is the strain dependent permeability coefficient. Regional variations in the elastic and poroelastic material properties and water content of the various disc tissues (annulus, endplate and nucleus pulposus) were also defined using values available in the literature.

Four finite element models were developed for the current study. The first model included the poro-elastic behavior of the disc alone. The second and the third models incorporated in addition to the effect of poro-elasticity, included either the effect of swelling of the proteoglycans or the effect of change in permeability due to axial strain. Fourth model included the poro-elastic behavior as well as both the effects of swelling and change in permeability due to displacement of the disc.

Circadian variation of disc height was calculated using all the four models and the results were compared with the measured cervical disc height loss (4). Height loss in a single cervical motion segment was obtained by taking 11% of the total circadian variation measured (5) and dividing it by six (number of cervical motion segments). Loads that act on the cervical spine during normal daily activity was simulated by applying a compressive load of 250 N (6) that was reduced to 40 N to represent the load during sleep.

RESULTS: Circadian variation of C5-C6 disc height obtained from all the four models included in this study were compared with the height loss measured in-vivo (4) and presented in Figure 1. The results for the disc height change obtained using the poro-elastic model that included both osmotic pressure and the effect due to strain dependent permeability compared very well with the in-vivo results during loading as well as during relaxation periods thus validating the current model. The results from the four model showed that the maximum disc height loss just before sleep was over predicted by 127% when poroelasticity alone was considered, 118% when the poro-elastic model included swelling pressure alone and 3% when the poro-elastic model included strain dependent permeability. When the pro-elastic model included both swelling pressure and the effect of strain dependent permeability, the model under predicted the maximum disc height loss by 2%.

Combined effect on the cervical disc due to both osmotic pressure and the strain dependent permeability gradually increased over the normal daily activity period and reached a maximum just before sleep. Maximum combined effect due to osmotic pressure and strain dependent permeability was seen in the nucleus (0.8 MPa) and the corresponding effect in the annulus was 0.7 MPa.

DISCUSSION: The poro-elastic finite element model that included both the effects of osmotic pressure and strain dependent permeability was developed and the model was able to predict the biomechanics of an in-vivo disc under load accurately. The effect of change in permeability due to strain was found to be predominant factor in predicting the biomechanical behavior of a cervical spine under physiological loads. Strain-dependent permeability is therefore important to incorporate into FEM of the intervertebral disc in order to be more relevant and applicable to the in vivo situation.

REFERENCES:

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