INVESTIGATION ON THE EFFECT OF DEGENERTIVE CHANGES IN THE BIOMECHANICS OF A C5-C6 MOTION SEGMENT-A PORO ELASTIC FINITE ELEMENT MODEL STUDY

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INTRODUCTION: Disc degeneration is a complex mechanism that involves the structural and tissue-matrix compositional changes. To date, no study exists that incorporates the change in the proteoglycan concentration and strain-dependent permeability due to disc degeneration to study its effect on the biomechanics of a cervical motion segment. The aim of the present study was (1) to develop and validate a poro-elastic finite element model of a healthy C5-C6 functional cervical spine segment that includes both the effects of change in proteoglycan concentration and change in permeability due to strain (2) to modify this validated model to include various degrees of degeneration and thus understand changes in the biomechanical response due to the progressive disc degeneration.

METHODS: A three-dimensional FE model of a healthy C5-C6 functional spinal unit was developed from the computed axial tomographic (CT) scan. The model included all the required anatomic components of the cervical motion segment. The drained material properties were taken from the literature to build a non-linear elastic model of the motion segment (NE). The poroelastic tissue properties were included to build a porous-permeable (PP) model. Another model (SW) that included the effect of change in the proteoglycan concentration with in the disc was formulated by including swelling pressure into the poro-elastic disc (PP) model. The swelling pressure (p_i^{swell}) is given by (1):

$$p_i^{swell} = Pf_i \frac{f_i^2+1}{\alpha f_i^2+1}$$

where f is the proteoglycan concentration which is dependent on the fixed charged density, P=0.66 MPa, α=0.15. The effect of change in the strain-dependent permeability (ST model) was added to the porous-permeable model (PP) by including an internal pressure (p_i^{strain}) given by (2-5):

$$-p_i^{strain} = \frac{E\varepsilon_i - \frac{1}{2}H_A \dfrac{\frac{2}{M}\ln\left[\left(\frac{k_i}{k_0}\right)\left(\frac{e_0}{e_i}\right)\right]}{\left[1+\frac{2}{M}\ln\left[\left(\frac{k_i}{k_0}\right)\left(\frac{e_0}{e_i}\right)\right]\right]^{\beta+\frac{1}{2}}} \exp\left\{\beta\frac{2}{M}\ln\left[\left(\frac{k_i}{k_0}\right)\left(\frac{e_0}{e_i}\right)\right]\right\}}{1-\left[\varepsilon_i+\phi_0^f\left(1-\varepsilon_i\right)\right]}$$

where E is the elastic modulus, ε is the axial strain, H_A is the aggregate modulus, M is the strain-dependent permeability coefficient, k is the permeability, e is the void ratio, β is the nonlinear stiffening coefficient, φ^f is the porosity. Subscript 0 corresponds to initial condition; while subscript i correspond to the instantaneous condition. The effects of both swelling pressure and strain-dependent permeability were included (SWTU model) into the porous-permeable model (PP) and the resulting pressures were uniformly applied on the nodes at the superior and inferior interface of the endplates. A further refinement to the SWTU model was performed by subdividing the annulus and nucleus into four quadrants – anterior, posterior, right and left lateral - to include the regional effects (SWTWQ model). Due to the paucity of poro-elastic material data in the cervical spine, most of these were taken from the lumbar spine. This model was previously validated with the *in vivo* study under diurnal compressive load of 40 – 350 N (6).

Moment loads were created by applying appropriate equal and opposite loads on the superior surface of C5 keeping the inferior surface of C6 fixed. The flexion, extension, axial rotation and lateral bending moments of 5.0, 1.5, 2.0 and 4.0 Nm respectively were applied to the model. These values were based on the average of mean motions along the three principal directions computed from the *in vivo* studies (7,8). A compressive pre-load of 73.6 N was applied using the follower load technique.

Two degenerated disc models were developed based on the Thompson's disc grading criteria corresponding to the moderate (disc grade II & III) and severe (disc grade IV) degeneration. Structural changes due to disc degeneration were included in the development of these models (reduction in disc height, increase in disc area and reduction in nucleus area). Both the elastic and poro-elastic material properties were modified appropriately to represent the effect of disc degeneration. An initial pore pressure of 0.041 MPa, 0.037 MPa and 0.022 MPa were applied at all the nodes in the disc for the three disc grades (1). The biomechanical response was investigated with the progressive disc degeneration under flexion, extension, axial rotation and lateral bending.

RESULTS: Figure 1 shows the comparison with *in vivo* results of the rotational motions of C5 with respect to C6 in the three principal planes for all the FE models developed in this study. The porous-permeable model including the regional effects of proteoglycan concentration and strain-dependent permeability (SWTWQ) agreed best with the *in vivo* studies under moment loads. This model coincided with the *in vivo* sagittal motion prediction, while the model over-predicted the transverse plane motion by 24% and under-predicted the motion in the frontal plane motion by 38%.

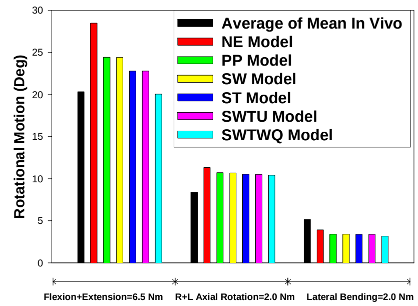

Figure1: Comparison of the rotations in the three principal planes obtained from the model study with the *in vivo* results

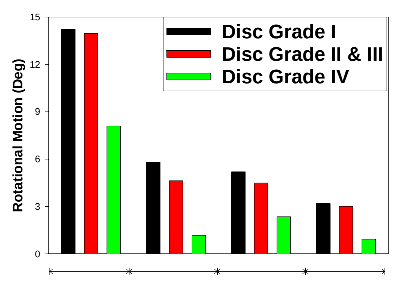

Figure 2: Comparison of the rotational motion with disc degeneration

The results from the model study showed that the stiffness of the disc increased as the degree of degeneration increased. As the disc degenerated to grades II & III, rotational stiffness increased only nominally (5% to 20%). A much higher increase in stiffness was seen in discs with grade IV degeneration (50% to 80%). This differs from the lumbar spine data in which the stiffness decreased with moderate degeneration and then increased with severely degenerated category.

DISCUSSION: The predominant motion of the cervical spine, namely motions in the sagittal plane, predicted by the poro-elastic FE model that included the regional effect of proteoglycan concentration and strain-dependent permeability in the disc agreed with the average of mean *in vivo* rotational motion. The percentage change in the biomechanical response from healthy to moderately degenerated disc was comparatively small while the corresponding changes from moderate to severely degenerated disc was large.

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