L4/L5 Lumbar Motion Segment Finite Element Model Details

The geometry of the lumbar motion segment was generated from a serial computed axial tomographic scan (CT) of an L4/L5 disc body unit. Using this CT scan a 3-dimensional finite element model was generated for the motion segment consisting of vertebra-disc-vertebra unit. The cortical bone, cancellous bone, posterior elements, endplates, facet cartilage, and nucleus pulposus were modeled as 8-node, 3-dimensional elements. The left and right superior and inferior articulating surfaces of the facet cartilage were approximated by flat trapezoidal moving frictionless contact surfaces. In the intervertebral disc, the annulus matrix was assumed as a composite material consisting of fibers embedded in a homogenous matrix material. The annulus ground matrix was discretized by 8-node, 3-dimensional solid elements. The annular fibers were assembled in a criss-cross fashion at an angle approximately 30° to the transverse plane. Annular fibers were modeled as the truss elements connected to the 3-dimensional solid elements of the annulus ground substance using rebar option. Nodes were generated at the intersections of the rebar lines representing the annular fibers and the faces of the 3-dimensional solid elements of the annulus ground substance. Constraint equations between the generated nodes and the three corner nodes of the 3-dimensional element faces ensured that annular fibers deform with the annulus ground substance. The nucleus pulposus was represented by 3-dimensional fluid elements. The seven major ligaments were modeled by 2-node nonlinear cable elements and their attachment points were taken from the literature.

The effect of change in the concentration of proteoglycans contained within the disc was modeled by incorporating a pressure, referred to as the swelling pressure (p_{swell}), which was dependent on the fixed charge density. The swelling pressure was calculated using an equation proposed by Broberg (Natarajan et al., 2006; Williams et al., 2007):

$$p_{swell\,i} = P f_i \frac{f_i^2 + 1}{\alpha f_i^2 + 1}$$

Where f_i is the fixed charge density at time t_i and P and α are constants.

$$f_i = \frac{\mathrm{m}}{\mathrm{WC} * \mathrm{V}_i}$$

Where m is reference volume, WC is water content of the disc and V_i is the volume of the disc.

The effect of change in permeability resulting from the strain in the tissue was modeled by including internal pressure acting on the disc. This pressure (Pstrain) was calculated using the equation (Natarajan et al., 2006; Williams et al., 2007):

$$p_{strain_i} = \frac{(Ee_i) - \left(\frac{1}{2} H_A \frac{(e_i+1)^2 - 1}{(e_i+1)^{2\beta+1}} \exp\left[\beta\left((e_i+1)^2 - 1\right)\right]\right)}{-\phi_i}$$

Where E is the Young's modulus, H_A is the aggregate modulus, e is the axial strain in the disc tissue, ϕ is the porosity at any time t and β is the nonlinear stiffness coefficient.

Convergence Study

A convergence study was carried out to determine the appropriate mesh density for the FE model. Three mesh resolutions for the annulus, the nucleus and the endplates were used. The coarse mesh was refined to intermediate mesh by dividing each element into four new elements. The elements in the intermediate mesh were further divided into four new elements to achieve a fine mesh. The diurnal changes in the total stature for the three mesh densities were compared with the in vivo results. Intermediate mesh density was found to be suitable for the subsequent analyses (Williams et al, 2007; Tyrrell et al, 1985).

Model Validation

The FE model was validated by calculating the diurnal changes in the total stature and comparing the results with the in vivo measurements on eight young adults (Williams et al,

2007). The results predicted by the FE model were similar to those observed in vivo (Tyrrell et al, 1985). Loss in the total stature predicted by the FE model under short term creep loading and short term cyclic loading were also similar to the reported in vivo results (Williams et al, 2007; Tyrrell et al, 1985)