Calibration and validation of a CT-based finite element model of the human spinal motion segment L4-L5 for functional biomechanical evaluation of new implant designs.

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Introduction

During the process of new product development, pre-clinical functional biomechanical evaluation of new implant designs through computational models offers large advantages over physical evaluation of prototypes in cadaver bones or bone substitutes. However, the inherent complexity of the spine makes model calibration and validation a challenge.

The common model building practice (from CT images segmentation to input of average biomechanical quantities collected from literature) cannot of itself be expected to lead to a validated model. Indeed, material parameters, loads and boundary conditions are in general specific to the particular motion segment (MS) used. Therefore, typical literature data should be used only as a starting reference point for a proper model calibration and validation.

This study is aimed at developing a suitably sophisticated and detailed finite element model of an L4-L5 MS, including calibrated anisotropic, non-linear material models (intervertebral disc and ligaments), in addition to optimized loading and boundary conditions (optimal follower load [1]). Model predictions were iteratively calibrated with respect to literature data for all relevant physiological motions so as to achieve model validation. To the author's knowledge, this is one of the first attempts to both calibrate material parameters and optimize loading and boundary conditions within the same study.

Materials and Methods

An L4-L5 MS was reconstructed starting from CT scans of a 61 years old female donor without any sign of relevant bony deformity. The model includes bones, endplates, intervertebral disc, all ligaments and facet joint cartilage (Figure 1L). A bone mineral density-based approach was used to assign isotropic, linear elastic material properties to each bony element. The annulus fibrosus was split in 4 regions (inner and outer rings, ventral and dorsal), each with specific material parameters, with associated a self-implemented, anisotropic, hyperelastic constitutive law [2]. The nucleus pulposus was modeled as an incompressible fluid, while cartilaginous endplates and facet joint cartilage as linear elastic solids. All ligaments were modeled by means of tension-only connector elements with non-linear elastic material properties. Frictional contact with f = 0.01 was activated at the facet joint interfaces.

Two reference points were connected to the L4 and L5 endplates: L4 was free to move and L5 was fixed. The two reference points were linked via a connector element to implement a follower load (Figure 1L). Erect standing was simulated with the application of a compressive follower load; flexion, extension, lateral bending and axial rotation were obtained applying moments to L4 (±10Nm) after the follower load.

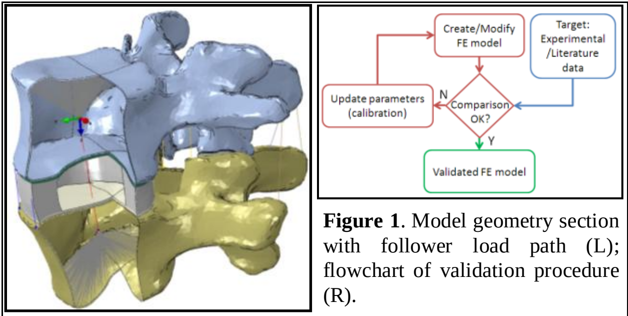

Figure 1. Model geometry section with follower load path (L); flowchart of validation procedure (R).

Initial material parameters were assigned to ligaments [3] and annulus fibrosus [4]. Their values were changed through manual iterations based on biomechanical considerations (Figure 1R), so as to reach the target behavior for the simulated MS defined by literature data. Reference point locations and follower load were adapted iteratively and simultaneously, in order to find the optimal follower load path (no intervertebral rotations in erect standing [1]) and magnitude (match of in-vivo measured average nucleus pressure [5][3]). Facet joint contact forces and coupled intervertebral motions were also compared to literature data [6] for enhancing the model output validation.

Results

In erect standing, the follower load path optimization allowed for negligible intervertebral rotations; a force of 550N matched nucleus pressure values. Quantitative comparisons of predicted range of motion, nucleus pressure and facet joint contact forces with literature data for flexion, extension, lateral bending and axial rotation resulted in successful calibration of material parameters. Notably, posterior ligaments and the dorsal portion of the intervertebral disc needed adjustments. In full flexion and extension, the follower load magnitude was increased to 1400N and 1000N, respectively, to match nucleus pressure values. An extract of model predictions for flexion extension is shown in Figure 2 and 3.

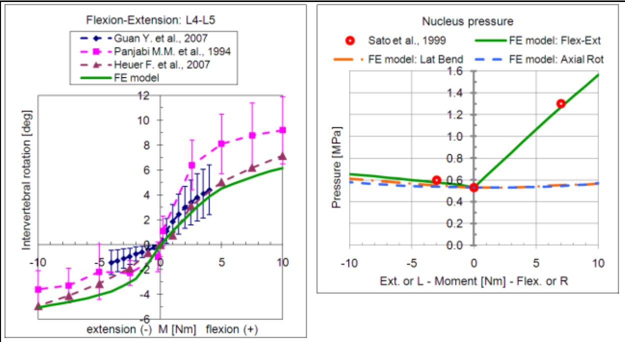

Figure 2. Validated model output vs. literature data: range of motion curve in flexion-extension (L); nucleus pressure (R).

For all relevant physiological motions, predictions of coupled intervertebral motions [6] and helical axis of motion evolution (Figure 3R) showed a satisfactory qualitative agreement with literature data, after model calibration.

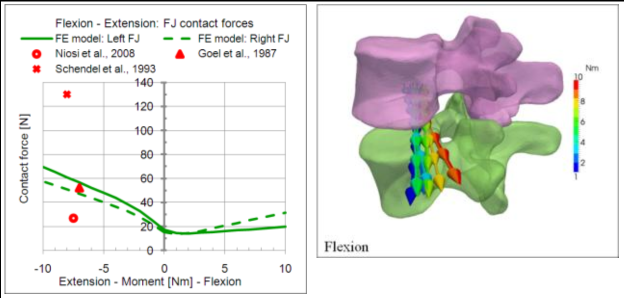

Figure 3. Validated model output vs. literature data: facet joint contact forces (L); helical axis of motion evolution for flexion (R).

Discussion and Conclusion

After calibration, the model was able to consistently predict quantities that are generally relevant to spinal biomechanics and can therefore be considered validated. Future application of the model, given its accuracy with respect to the available literature data, would allow for confidence in the evaluation of the biomechanical performance of new implant designs.

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