

Comparative Evaluation of Force- and Displacement-Controlled Loading Approaches in Finite Element Modeling of Progressive Lumbar Disc Degeneration: Biomechanical Implications and Methodological Considerations

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Abstract

Finite element (FE) modeling has become a widely used tool for investigating the biomechanical consequences of lumbar intervertebral disc degeneration. However, the methodological choice of loading control—specifically force-controlled versus displacement-controlled approaches—remains insufficiently discussed, despite its substantial influence on model response, interpretation of results, and physiological relevance. This study presents a comparative evaluation of force- and displacement-controlled loading strategies in FE simulations of progressive lumbar disc degeneration, with a focus on their biomechanical implications and methodological suitability for different research objectives. Force-controlled loading is generally considered closer to physiological conditions, as external loads acting on the spine in vivo are primarily determined by body weight, muscle forces, and externally applied forces rather than prescribed displacements. In the present work, force-controlled simulations demonstrated an ability to naturally capture degeneration-induced alterations in global spinal stiffness, load sharing between disc components, and changes in segmental mobility. As degeneration progressed, increased

displacements, altered stress distributions, and redistribution of internal forces emerged as direct consequences of reduced disc material integrity, reflecting a realistic mechanical response to constant external loading. In contrast, displacement-controlled loading imposes predefined kinematic conditions, effectively constraining global motion while allowing internal stresses and reaction forces to evolve. Although this approach is less representative of physiological loading scenarios, it can be advantageous for isolating specific degeneration-related trends. In the current analysis, displacement-controlled simulations enabled clearer identification of changes in stress concentration, strain localization, and internal load transfer mechanisms within the annulus fibrosus and nucleus pulposus across degeneration stages. By eliminating variability in global motion, displacement control facilitated direct comparison of internal mechanical states under identical kinematic conditions. The results indicate that the choice of loading strategy significantly affects not only the magnitude of predicted stresses and strains but also the appropriate criteria for evaluating the mechanical state of the model. Under force-controlled loading, displacement-based metrics such as segmental range of motion, compliance, and overall deformation emerge as primary indicators of degeneration severity. Conversely, displacement-controlled loading emphasizes force-based or stress-based measures, including reaction forces, intradiscal stresses, and strain energy density, as key outcome parameters. Consequently, direct comparison of results obtained using different loading controls without considering these methodological differences may lead to misleading interpretations. This study highlights the advantages and limitations of both loading approaches and discusses key factors governing their selection, including study objectives, target biomechanical quantities, degeneration modeling strategy, and intended clinical or methodological relevance. Rather than advocating a universally superior approach, the findings emphasize that the choice between force- and displacement-controlled loading should be task-dependent. Force-controlled simulations are more suitable for studies aiming to reproduce physiological behavior and global functional changes, whereas displacement-controlled simulations can be preferable for mechanistic investigations of internal tissue responses and degeneration-induced trends under standardized motion conditions. The presented comparative framework provides methodological guidance for selecting appropriate loading strategies in FE studies of lumbar disc degeneration and contributes to improved consistency and interpretability of computational biomechanics research.

Keywords:

annulus fibrosus degenerative spinal diseases displacement control finite element method force control intervertebral discs nucleus pulposus numerical modeling spinal biomechanics

