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DEVELOPMENT OF A BIOMIMETIC FINITE ELEMENT MODEL TO STUDY THE INTERVERTEBRAL DISC DISEASES AND REGENERATION

André Castro
Center for Mechanical and Materials Technologies - Dynamics of Mechanical Systems Group
Department of Mechanical Engineering
E-mail: apgcastro@dem.uminho.pt

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INTRODUCTION

The study and numerical simulation of the Intervertebral Discs (IVD) are the paramount issue of this work. Its major expected achievements are to investigate the biomechanisms of disc degeneration and to develop of a biomimetic strategy for the IVD regeneration, under the scope of a wider European project, denominated NPmimetic, “Biomimetic Nano-Fiber-Based Nucleus Pulposus Regeneration for the Treatment of Degenerative Disc Disease”. In fact, this work intends to contribute to the main achievements of NPmimetic through the development of several numerical tools, with a special emphasis on the updating of a spine-oriented Finite Element (FE) solver, in order to contribute to the investigation of new strategies for treatment and/or rehabilitation of the Degenerative Disc Disease (DDD).

DESCRIPTION OF THE PROBLEM

The human spine is composed by 24 motion segments. Each one of these load-sharing units is composed by 2 vertebral bodies (VB), connected by an IVD and 2 facet joints. The IVDs are fibro-cartilaginous cushions serving as a shock absorbing system of the spine, which protect the vertebrae, brain, and other structures, providing both flexibility and load support. They are composed by three major components: the nucleus pulposus (NP), the annulus fibrosus (AF) and the cartilaginous endplate (CEP, also known as vertebral endplate), and they are considered as chondroid tissues (Jongeneelen 2006, Raj 2008).

The degeneration of the IVDs is one of the main problems of the spine, with a particular emphasis on the low back pain. For many years, a considerable amount of studies developed significant efforts to found the causes and possible solutions for such issue, given that spine problems are a major cause of disability on western societies. In fact, DDD (also known as spondylosis) is one of the largest health problems faced worldwide when judged by lost work time and associated costs (Shankar et al. 2009).

OBJECTIVES

The development of a biomimetic FE model of the IVD and VB, in both healthy and degenerated states, is the fundamental objective of this work. Therefore, the definition of the biomechanical parameters of both states is essential. DDD is a condition expressed by degenerated IVD, and the challenge for this work eventually starts on the definition of the etiology of IVD degeneration, which is dependent on multiple factors, such as metabolic disorders, ageing or mechanical factors (Nixon 1986, Roberts et al. 1989, Urban and Roberts 2003, Virtanen et al. 2007).

Two branches of research must be highlighted: variations on material properties and variations on cellular properties. The IVD extracellular matrix is determinant for the global behavior of the IVD, and thus further studies on either material or cellular properties are mandatory. Some of the most up-to-date publications (for instance, Natarajan and co-workers in 2008, Noailly in 2009 or Shirazi-Adl and co-workers in 2010) clearly show the trend on this subject (Natarajan et al. 2008, Noailly 2009, Shirazi-Adl et al. 2010). The present work intends to follow some of the directions revealed in the abovementioned publications, especially focusing on the variations on material properties within the IVD and adjacent structures.

NUMERICAL SIMULATION

The present work is based on the development of several computational tools. The methodology that shall be followed starts with a literature review, in order to understand all the issues related with the IVD and its degeneration, as well as the state-of-the-art concerning the numerical modeling and numerical simulation of the Human spine. This first stage has already begun and will contribute for the definition of the cases to be numerically simulated and analyzed. The next step is to start the FE modeling and simulation, based on either medical imaging data or literature data, in thigh association with the guidelines of the NPmimetic project. These models shall produce valuable information for the study of IVD degeneration and regeneration. Finally, the results from the FEA will be submitted to comparison with *in vitro/in vivo* tests (carried out by other partners of the NPmimetic project), in order to validate the developed and implemented algorithms.

As mentioned above, the crucial task to be carried in this work is related with the constitutive modeling and rheological behavior of all soft tissues integrating the IVD. This assignment will be performed using the V-Biomech FE solver (a FEA home-code), which mechanical modeling comprises several relevant features of biomechanics, namely the almost incompressibility of soft-tissues, the implementation of the most general isotropic and anisotropic hyperelastic laws, a phenomenological description of the muscle activation and short and long term viscous time affects phenomena; a fully implicit time integration scheme and mixed u-P finite elements. V-Biomech must be updated concerning the implementation of new constitutive models able to describe more accurately the mechanical behavior of both IVDs tissues and other relevant soft tissues and bones. Rheological behavior is other important features of IVD for the Human comfort and mechanical functionality of the spine. Time effects, i.e., short term (like strain rate sensitivity) and long term (like hysteresis, stress relaxation and creep) time effects shall be taken into account. For the sake of simplicity, very probably a quasi-viscoelasticity formulation shall be adopted, instead of a hypervicoelasticy, given that it will allow the decoupling between the Prony series parameters (amplitude and characteristic time) and the material parameters, unlike happens in case of more general form of hyperviscoelasticity, in which the Prony series are applied directly to the material parameters. Therefore, it is expected that this key FEA numerical tool is ready to carry out the numerical simulations of the overall spine in general and the IVD in particular.

SUMMARY

Summarizing some of the presented ideas, it should be highlighted that this work will potentiate a new and very innovative research and development approach to go forward on the knowledge of the biomechanics of the Human spine, with major emphasis on the IVDs.

In order to achieve such aim, FEA is undeniably a paramount tool for the advance of biomechanics, allowing and contributing to deepen our understanding on so complex biosystems.

In what concerns the IVD FEA studies, several possibilities and parameters have been covered, from the effects of different load types to new treatment strategies. The novelty associated to this work is based on the set of mechanical specifications expected to arise from the modeling of the VB and IVD. Such data shall allow the study and development of minimal invasive treatments based on biomimetic materials, scaffolds and tissue engineering.

REFERENCES

JONGENEELEN, C. J. M.; *Biomechanics in the Intervertebral Disc*; MSc Thesis, Department of Biomedical Engineering, Eindhoven University of Technology, The Netherlands, 2006.

NATARAJAN, R. N., WILLIAMS, J. R., LAVENDER, S. A., AN, H. S. and ANDERSSON, G. B.; *Relationship Between Disc Injury and Manual Lifting: A Poroelastic Finite Element Model Study*, Journal Engineering in Medicine, 222, 2008.

NIXON, J.; *Intervertebral Disc Mechanics: A Review*, Journal of the Royal Society of Medicine, 79, pp. 100-104, 1986.

NOAILLY, J.; *Model Developments for in Silico Studies of the Lumbar Spine Biomechanics*, PhD Thesis, Universitat Politècnica de Catalunya, Spain, 2009.

RAJ, P. P.; *Intervertebral Disc: Anatomy-Physiology-Pathophysiology-Treatment,* Pain Practice, 8, 1, pp. 18-44, 2008.

ROBERTS, S., MENAGE, J. and URBAN, J.; *Biochemical and Structural Properties of the Cartilage End-Plate and its Relation to the Intervertebral Disc*, Spine, 14, 2, pp. 166-174, 1989.

SHANKAR, H., SCARLETT, J. A. and ABRAM, S. E.; *Anatomy and pathophysiology of intervertebral disc disease*, Techniques in Regional Anesthesia and Pain Management, 13, pp. 67-75, 2009.

SHIRAZI-ADL, A., TAHERI, M. and URBAN, J.; *Analysis of Cell Viability in Intervertebral Disc: Effect of Endplate Permeability on Cell Population*, Journal of Biomechanics, 43, pp. 1330–1336, 2010.

URBAN, J. and ROBERTS, S.; *Degeneration of the Intervertebral Disc,* Arthritis Research & Therapy, 5, 3, 2003.

VIRTANEN, I.M., KARPPINEN, J., TAIMELA, S., OTT, J., BARRAL, S., KAIKKONEN, K., HEIKKILÄ, O., MUTANEN, P., NOPONEN, N., MÄNNIKKÖ, M., TERVONEN, O., NATRI, A. and ALA-KOKKO, L.; *Occupational and Genetic Risk Factors Associated with Intervertebral Disc Disease*, Spine, 32, 10, pp. 1129-1134, 2007.

AUTHOR BIOGRAPHY

ANDRÉ CASTRO was born in Arcos de Valdevez, Portugal, in 1986. He went to Universidade do Minho, where he studied Biomedical Engineering and obtained his degree in 2009. His Master Thesis was devoted to patellofemoral arthoplasty. He is now doing his PhD in Biomedical Engineering, on Universidade do Minho.