A First Step Towards Numerical Simulation of Intervertebral Disc Herniation Using a Phase-Field Modelling Approach

Yousef Heider, Marzieh Azarnoosh, Agnes Beckmann and Bernd Markert

Institute of General Mechanics (IAM)
RWTH Aachen University
Templergraben 64, 52062 Aachen, Germany
e-mail: heider@iam.rwth-aachen.de, web page: www.iam.rwth-aachen.de/

ABSTRACT

From a mechanical perspective, the intervertebral disc (IVD) is considered as a flexible damping element, which connects two vertebrae and comprises the annulus fibrosus (AF) and the nucleus pulposus (NP). The NP includes proteoglycan proteins, which bind water due to electronegative branches, and is surrounded by the collagen-fibre-reinforced AF. Under compressive stresses, interstitial fluid pressure and deformations develop inside the NP leading to a lateral bulging, which is, in nonpathological cases, resisted by the AF through its collagen fibres under tension, see, e.g. [1]. IVD herniation belongs to the most prevalent indications of spinal surgery. Due to disc degeneration, the AF becomes thinner and less resistant. Therefore, the pressurised NP may lead to unphysiological bulging or even fracturing of the AF, which could affect the spinal nerves and cause lower back pain.

The IVD belongs to the class of charged, hydrated, porous soft biological tissues. The modelling and simulation of such cartilaginous materials can be carried out using continuum porous media theories, see e.g. [2]. In general, relevant effects such as the interstitial fluid flow, the deformation-dependent permeability, the anisotropy of the viscoelastic solid matrix as well as electro-chemical properties can be considered in the macroscopic model. This treatment leads to a strongly coupled system of differential algebraic equations (DAE), which demands special numerical schemes for a stable solution within a finite element framework, see [3] for an overview and references.

Phase-field modelling (PFM) is a powerful technique for simulation of microstructural evolution such as crack propagation on a macroscopic scale, see e.g. [4]. In the present work, the tension-driven degradation or fracturing in the solid matrix of the AF is modelled using a diffusive interface approach, which augments the aforementioned porous media model. This way of fracture modelling results in an additional partial differential equation to the coupled DAE system governing the phase-field evolution and further challenging the numerical solution procedure. To reveal the ability of the proposed modelling strategy in capturing realistic features of IVD herniation, numerical examples using the finite element method (FEM) will be presented (Fig. 1).

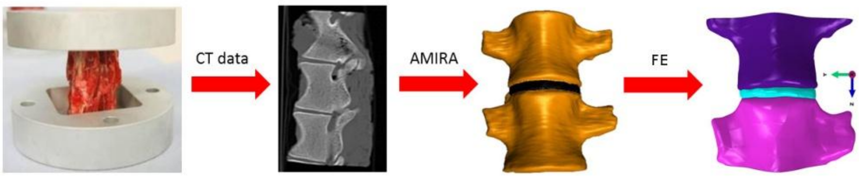

Fig. 1: Experimental and numerical modelling of IVD.

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