A Novel Mathematical Homogenisation Technique to Link Tissue Scale Properties of the Intervertebral Disc to Whole Organ System Simulations of the Lumbar Spine

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1 Introduction

At present, there are two main numerical approaches that are frequently used to simulate the mechanical behaviour of the human spine: the finite-element method (FEM) and multi-body systems (MBS). Herein, the basic idea is to utilise MBS in simulations of the overall body and apply the FEM only to selected regions of interest. In turn, the FEM is used as homogenisation tool to deliver more accurate non-linear relationships describing the behaviour of the intervertebral disc (IVD) in the multi-body dynamics model.

The goal of this contribution is to present an approach to couple both numerical methods without using an instantaneous co-simulation. Instead of solving the respective FEM problem for a given boundary constraint, several pre-computations of the IVD are performed offline to generate for the IVD's envelope of motion an approximation of the homogenised finite-element result. In particular, the discrete degrees of freedom (DOF) of the MBS, i.e., three displacements and three rotations, are applied to the finite-element model of the IVD and the resulting homogenised forces and moments are recorded. Moreover, a polynomial function is presented with the discrete DOF of the MBS as variables and the discrete forces and moments as function values.

2 Methods

The model used for the FE simulations of the IVD is based on the Theory of Porous Media (TPM) and includes an extended biphasic approach, which is capable of capturing the porous micro structure of the IVD (Ehlers et al., 2009). The homogenisation method is the basis to link the finite-element model of the IVD with the MBS of the motion segment using response surfaces. The coupling algorithm is introduced using a simplified cylindrical IVD with homogeneous material properties. In particular, the simplified motion segment of Figure 1(a) is modelled with a homogeneous distribution of the collagen fibres in the circular annulus fibrosus (AF) using a uniform fibre angle of f = 57° with respect to the axial direction e3 in combination with constant anisotropic material parameters referring to the inner AF at a ventro-lateral position. With the exploitation of rotational symmetry and by neglecting of torsion about the axial direction e3, the complete six DOF of a rigid body in 3-d space are reduced to movements in the sagittal plane with only one rotational and two translational DOF. A sketch of the IVDs representation in the MBS is drawn in Figure 1(b). Herein, the IVD as well as the adjacent rigid vertebrae are lumped at their centres of gravity (COG) and connected to each other using so-called branch vectors. The bushing element is defined at the COG of the IVD and can be understood as a parallel assembly of a spring and a dashpot in the e_2- and e_3-direction as well as about the e_1-direction. Thus, a reaction force or moment is activated, whenever a relative displacement or orientation change is detected between the two branch vectors of the vertebrae. Assuming a relative motion of the upper vertebra with respect to the lower vertebra, the bushing element yields three DOF, i.e., the rotation f_1 and the displacements u_2 and u_3.

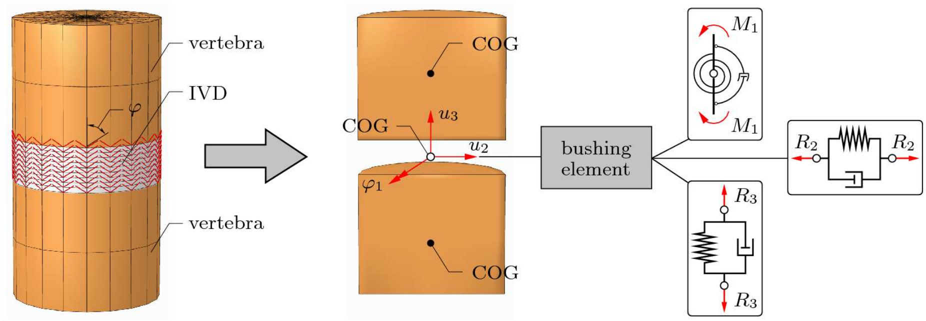

Figure 1: (a) Finite-element model of a motion segment, (b) simple 3-d bushing element which is suitable for multi-body dynamics.

3 Results and Discussion

After running 60 simulations, it turned out that the analytical representation of the homogenised response of the IVD is a full cubic polynomial fit in either degree of freedom. One first MBS simulation shows the benefits using more appropriate IVD models even for multi-body systems.

References

Ehlers, W., Karajan, N., and Markert, B., 2009. An extended biphasic model for charged hydrated tissues with application to the intervertebral disc. Biomechanics and Modeling in Mechanobiology 8(3), 233–251.