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Research Paper

Specimen specific parameter identification of ovine lumbar intervertebral discs: On the influence of fibre–matrix and fibre–fibre shear interactions

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ABSTRACT

Numerical models of the intervertebral disc, which address mechanical questions commonly make use of the difference in water content between annulus and nucleus, and thus fluid and solid parts are separated. Despite this simplification, models remain complex due to the anisotropy and nonlinearity of the annulus and regional variations of the collagen fibre density. Additionally, it has been shown that cross-links make a large contribution to the stiffness of the annulus. Because of this complex composite structure, it is difficult to reproduce several sets of experimental data with one single set of material parameters. This study addresses the question to which extent the ultrastructure of the intervertebral disc should be modelled so that its moment–angle behaviour can be adequately described. Therefore, a hyperelastic constitutive law, based on continuum mechanical principles was derived, which does not only consider the anisotropy from the collagen fibres, but also interactions among the fibres and between the fibres and the ground substance. Eight ovine lumbar intervertebral discs were tested on a custom made spinal loading simulator in flexion/extension, lateral bending and axial rotation. Specimen-specific geometrical models were generated using CT images and T2 maps to distinguish between annulus fibrosus and nucleus pulposus. For the identification of the material parameters the annulus fibrosus was described with two scenarios: with and without fibre–matrix and fibre–fibre interactions. Both scenarios showed a similar behaviour on a load displacement level. Comparing model predictions to the experimental data, the mean RMS of all specimens and all load cases was $0.54 \pm 0.15^{\circ}$ without the interaction and $0.54 \pm 0.19^{\circ}$ when the fibre–matrix and fibre–fibre interactions were included. However, due to the increased stiffness when cross-links effects were included, this scenario showed more physiological stress–strain relations in uniaxial and biaxial stress states. Thus, the present study suggests that fibre–matrix and fibre–fibre interactions should be considered in the constitutive law when the model addresses questions concerning the stress field of the annulus fibrosus.

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1. Introduction

The intervertebral disc is a very versatile structure, which is able to transmit compressive loads of a multiple of the body weight and, at the same time, acts as a flexible joint. This behaviour is determined by the interaction of its three main components: water, collagen fibres and proteoglycans. Because the proteoglycans contain negatively charged aminoacid chains, they tend to imbibe water, thus creating a swelling pressure which balances the external loads (Urban and McMullin, 1988). Water and proteoglycan content highly correlate with each other (Marinelli et al., 2009) and are highest in the nucleus pulposus and lowest in the annulus fibrosus. The distribution of the collagen fibres is the opposite.

The three-dimensional concentric arrangement of the lamellae with alternating fibre directions in the annulus has been shown in scanning electron microscopy by Inoue and Takeda (1975). Then, morphologic changes in radial and circumferential direction were reported. Furthermore, it was observed that lamellae on the posterior side were thinner compared to the anterior side (Inoue and Takeda, 1975; Cassidy et al., 1989). Later, Skaggs et al. (1994) investigated the tensile properties and biochemical composition of single lamellae of the human annulus fibrosus. They reported higher stiffness of the anterior part of the annulus than the posterior part. This behaviour was confirmed by experiments on both multi-lamellar (Ebara et al., 1996) and single lamellar samples (Holzapfel et al., 2005). Additionally, a varying orientation of the fibres which are aligned more vertically on the posterior side compared to the anterior side of the annulus was reported (Holzapfel et al., 2005).

Adams and Green (1993) showed that the stiffness of multi-lamellar samples cannot solely be explained by the tensile properties of the collagen fibres and deduced that fibre–matrix interactions exert a significant impact on the load bearing behaviour of the annulus. Results of Michalek et al. (2009), who measured strain fields in simple shear using confocal microscopy and Elliott and Setton (2001), who determined Young's Moduli of annular lamellae in various orientations, led to the same conclusion. Chuang et al. (2007) increased the cross-link density in bovine lumbar discs with Genipin, which resulted in increased strength and yield stress of the test specimens. Cross-links have an increasing effect on the load-bearing behaviour of the annulus as the pre-strain of the fibres and thus the stiffness increases. This was reported by Fujita et al. (2000), who investigated the shear behaviour of multi-lamellar sheet specimens taken from the annulus. When a pre-strain of 10% in the axial direction was applied, the shear stiffness in the circumferential direction increased up to 2.5 times. Guo et al. (2012) compared different biaxial stress states of annular lamellae and reported that the shear modulus was up to 10 times higher when the fibres were under tension compared to compression.

There is abundant literature on numerical models of spinal motion segments or the intervertebral disc. All state of the art models consider two families of fibres to describe the anisotropy, either as embedded truss elements or with a continuum mechanical approach. It is common practice to calibrate the properties of fibres and ground substance using moment–angle relations from the literature. However, models of which geometrical description and experimental data are not based on the same specimen frequently fail to reproduce all three load cases, i.e. flexion/extension, lateral bending and axial rotation (Weisse et al., 2012; Ezquerro et al., 2011; Ayturk et al., 2010). Schmidt et al. (2006) performed in-house tests with a L4–L5 segment and thus were able to validate their model of a denucleated disc with matching experimental data. Assuming constant properties of the fibres throughout the disc, the fitted model was not able to reproduce flexion, bending and axial rotation simultaneously. When circumferential variations of the fibre properties around the annulus were considered, each of the three load cases could be modelled with the same set of parameters. Eberlein et al. (2003) proposed a hyperelastic, anisotropic constitutive law to model the annulus fibrosus and determined material parameters based on stress–strain relations of single lamellae later published by the same group (Holzapfel et al., 2005). A homogeneous stiffness distribution of the collagen fibres was assumed throughout the annulus. Comparing the model to in-house experimental data, good agreement in extension and axial rotation could be achieved, but not in flexion and in lateral bending.

The influence of geometry on the biomechanical behaviour of motion segments was emphasized in a probabilistic finite element analysis by Niemeyer et al. (2012). Noailly et al. (2011) investigated the influence of circumferential and radial variations of fibre orientation. The fact that even complex arrangements of fibres orientations could not predict the experimental data in all motions indicates the relevance of segment morphology as well.

Constitutive laws, which include fibre–matrix and fibre–fibre interactions, include the phenomenological approach by Peng et al. (2006), which is based on the shear deformation between collagen fibres and the matrix. Caner et al. (2007) used a microplane constitutive law, which does not have two discrete fibre directions, but employs a probability density function, which also governs the shear interaction. Elliott and Setton (2000) developed a linear material law, which was able to describe the components matrix, fibres, fibre–fibre and fibre–matrix interactions separately using an appropriate set of invariants. Each of the above-mentioned three constitutive laws was tested on experimental data from isolated samples of the annulus and demonstrated the relevance of shear interaction.

Using published experimental moment–angle relations entails that the geometries of the modelled and the tested specimens do not match. However, for a realistic identification of material parameters it is essential that the geometry of the tested specimen is known, when simulations are compared to experiments. Furthermore, the effect of cross-links and fibre–matrix interactions has been intensively studied on isolated samples of the annulus, but has not been investigated on models of the entire intervertebral disc.

Thus, this study addresses the question, which structural components of the intervertebral disc a simplified, numerical model should include, so that material parameters can be identified based on moment–angle relations. Therefore, not only the anisotropy arising from the collagen fibres was modelled, but also fibre–matrix and fibre–fibre interactions.