Investigation of the State of Stress Generated by High Loads in the Ovine Lumbar Intervertebral Disc Using a New Anisotropic Hyperelastic Model

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Abstract Disc herniation is one of the main causes of low back pain, and it is the pathologic condition for which spinal surgery is most often required. Many experimental and numerical studies have been conducted to investigate the mechanical failure of the intervertebral disc (IVD); however, there is not in the literature a study that defines a mechanical criterion for the disc failure. The aim of this study was to investigate the state of stress generated by the application of high loads and to define which state of stress was the most responsible for herniation. A finite element model of the ovine lumbar IVD was developed. The loading scenarios applied in an experimental study taken from the literature were applied, and the results compared to define the failure conditions. Then the effect of combined and simple rotations was investigated as well. It was found that an axial stress higher than 10 MPa in the posterior region of the annulus has a high probability of damaging the disc, and that flexion had a main role in damaging annulus tissue.

Introduction

Disc herniation is one of the main causes of low back pain, and it is the pathologic condition for which spinal surgery is most often required (Boos and Aebi 2008). In the past years, many experimental and numerical studies have been conducted to investigate the mechanical failure of the intervertebral disc (IVD) (Hansson et al. 1987; Dolan et al. 2013; Schmidt et al. 2007), but to the authors' knowledge, there is not in the literature a study that defines a mechanical criterion for the disc failure. The experimental studies used different animal species and loading conditions (Callaghan and McGill 2001; Fazzalari et al. 2001; Wade et al. 2014); at the same

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time, the most of the numerical models represented the human disc and have many aspects of complexity due to the composite nature of the annulus fibrosus (AF) (Eberlein et al. 2001; Galbusera et al. 2011; Long et al. 2016). We believe that an anisotropic hyperelastic material is a good alternative for the representation of both the fibers and the ground substance to simplify the disc modeling.

The aim of this study was to investigate the state of stress generated by the application of high loads and to define which mechanical loads and state of stress were the most responsible for disc damaging. A finite element model of the ovine lumbar disc was generated and anisotropic hyperelastic properties were assigned to the AF (Casaroli et al. 2016). Then the model was used to investigate the effect of the application of high loads conditions (Casaroli et al. 2017). Finally, the results were combined with the outcomes of a parallel in vitro study (Berger-Roscher et al. 2016) to define a mechanical criterion for the annulus failure.

Materials and Methods

A finite element model of the ovine lumbar IVD was developed. The geometry of the disc was generated by the reconstruction of the caudal and cranial vertebral bodies of a L3-4 segment (Avizo 8.0) using a specific Python script. The AF was described as an anisotropic hyperelastic material, whereas the mechanical properties of the nucleus pulposus (NP) and of the cartilagineous and bony endplates (CEP and BEP, respectively) were taken from the literature (Table 1). The anisotropic behavior was described by the Holzapfel–Gasser–Ogden formulation and implemented in Abaqus 6.14-5, and the parameters were defined using a full factorial optimization method. C_{10} and D described the ground substance and were defined combining in vitro uniaxial compressive tests (Little et al. 2010) with numerical

Table 1 Material properties assigned to the disc structures

Structure	Material behavior	C_{10} (MPa), D (MPa^{-1})	K_1 (MPa), K_2 (MPa), κ	References
Anterior AF	Anisotropic hyperelastic	0.0605, 0.311	24, 1700, 0.01	Casaroli et al. (2016)
Lateral AF	Anisotropic hyperelastic	0.0327, 0.615	5, 940, 0.01	Casaroli et al. (2016)
Posterior AF	Anisotropic hyperelastic	0.0772, 0.261	1, 50, 0.01	Casaroli et al. (2016)
NP	Neo-Hookean	0.1678, 0.120	–	Ayturk et al. (2012)
		E (MPa), υ		
CEP	Linear elastic	24, 0.4	–	Ayturk et al. (2012)
BEP	Linear elastic	1000, 0.3	–	Ayturk et al. (2012)

simulations. K_1, K_2 and k described the influence of the collagen fibers and were established based on tensile tests on annulus specimens and numerical simulations. For the sake of validation, the flexibility of the model was measured in flexion-extension (FL-EX), lateral bending (LB), and axial rotation (AR), and the range of motion compared with the literature (Reitmaier et al. 2014).

The model was then constrained at the caudal bony endplate in all degrees of freedom, and five different complex loading conditions were investigated. In the worst case an axial compression (AC) of 800 N was applied together with 4° of AR, 10° of LB and 13° of flexion FL. In the other four cases only three of these conditions were applied. The applied rotations were double of the physiological ones described by Reitmaier et al. (2014). The simulations were performed in Abaqus explicit. It was assessed that the energy balance was respected. Three sections in the posterolateral regions where failures experimentally occurred were defined, and the averaged principal stresses and strains in the circumferential, radial and axial direction were measured. A multiple linear regression analysis based on the combination of the experimental and numerical outcomes was performed to investigate which stresses were predictive for the disc failure. Thresholds defining a high and a low risk of failure were defined.

Then, the effect of each pair of rotations and of the combination of a single rotation with axial compression was investigated. The stresses were analyzed and compared to the defined thresholds. Finally, the effect of the single rotation and axial compression were analyzed as well.

Results

The values of the parameters that described the anisotropic hyperelastic behavior of the AF (Table 1) showed a good fit between the numerical and the experimental results. The flexibility of the disc was in the range defined by the literature (Reitmaier et al. 2014). The numerical simulations showed that when AC and all the rotations were applied the stress was the highest. In the circumferential direction, the stress state was highest in the anterior region of the AF, whereas in the axial and in the radial direction it was highest in the posterocontrolateral region (Fig. 1). Stress distribution was not uniform from the caudal to the cranial and from the inner to the outer part of the annulus. In the posterolateral region, the stress was highest close to the endplates in the circumferential and in the radial direction, and in the inner region of the annulus in the axial direction (Fig. 2). When FL and LB were applied, the state of stress was the highest in the axial and in the circumferential directions, whereas AC did not increase the state of stress in the tissue. The statistical analysis revealed that the axial and circumferential stress located in the caudal and in the middle part of the annulus was predictive of disc failure. When AC and all rotations were applied, the axial and the circumferential stress was up to 12 and 10 MPa respectively, whereas when FL was not applied the stress was lower than 4 and 6 MPa. Axial stress thresholds defining a high and a low risk

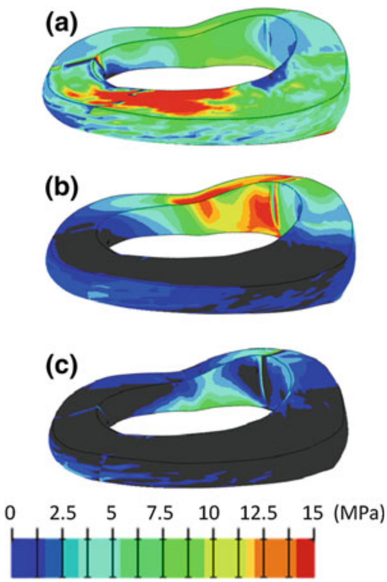

Fig. 1 Stress distribution in the AF when AC and all rotation were applied in the circumferential (**a**), axial (**b**) and radial (**c**) direction. The *gray* regions represent the parts in which the stress was negative

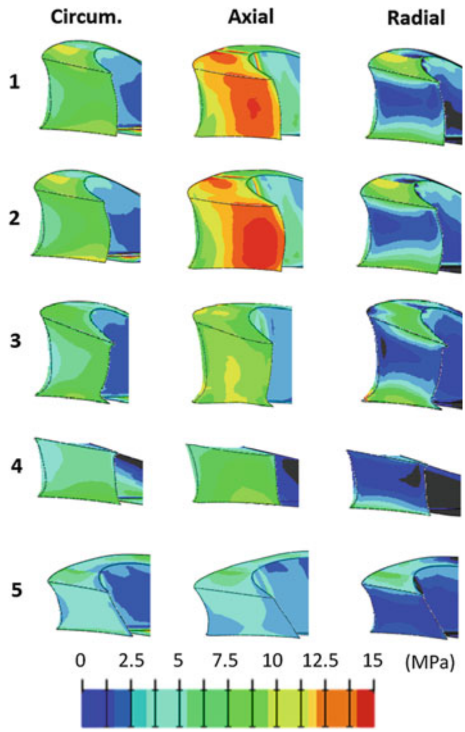

Fig. 2 Stress state distribution within the posterolateral section of the AF in the circumferential (circum.), axial and radial direction in the studied loading scenarios (1–5). The *gray regions* represent the part in which the stress was negative

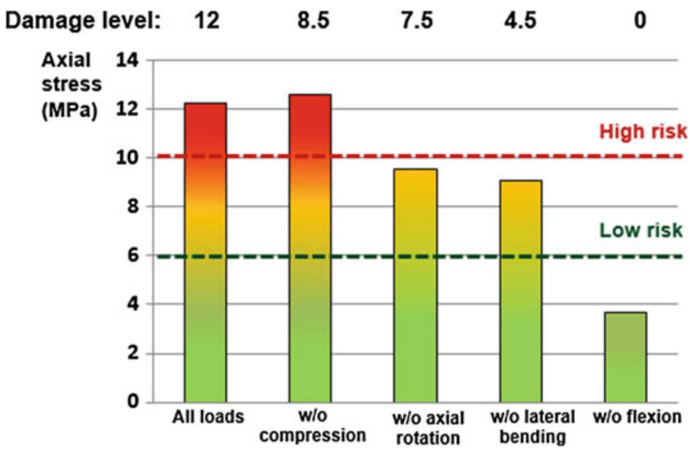

Fig. 3 Axial stress generated in the PL-1 section in the caudal region in the five loading conditions. In the *upper part* the recurring of AFF is indicated, whereas in the *lower part* the risk failure of the group is written

of failure were defined and fixed to 10 and to 6 MPa, respectively (Fig. 3). In the circumferential direction they were fixed to 9 and 6 MPa.

The application of pair of loads, showed that when FL was combined with another rotation the state of stress was the highest in all the directions, and a high risk of failure was generated only by the application of FL and AR. Finally, when single rotation was applied, only FL generated a moderate risk of failure (7 MPa).

Discussion

In this study, a finite element model of the ovine lumbar IVD with anisotropic hyperelastic material has been generated. The use of an anisotropic formulation had two advantages: it allowed simulating the presence of the collagen fibers without modeling them, keeping the mesh refinement easy, and it was based on only five parameters that were experimentally definable. Different material properties were assigned to the different regions of the AF. The flexibility of the model was in the range described in the literature, although it overestimated the average values. A possible explanation of this effect could be the geometrical dimensions.

Then, the model was used to investigate the mechanical tests conducted in a parallel in vitro study and a predictor of the risk of failure of the IVD has been proposed. The numerical results were in agreement with the experimental ones, demonstrating that complex loading conditions are responsible for disc failure. When FL was not applied the stress in posterior region of the annulus was lower than in the other cases, as well as the in vitro study has shown. The analysis of the stress state generated by less complex scenarios showed that the combinations in which flexion was included generated a high risk of failure. Moreover, the analysis of the application of single rotations supported the conclusion that flexion had a main role in damaging annulus tissue. Indeed, according to the defined limits for the disc damage, FL alone can cause disc damage, whereas the other rotations keep the annulus in a safe condition.

The highest state of stress was generated in the axial and in the circumferential directions, which defined the plane of the collagen fibers. In the circumferential direction the stress was concentrated in the anterior AF, but it was supposed to not be responsible for disc failure because it was caused by the compression of the elements: in fact, the related axial stress was negative, reducing the real stress supported by the collagen fibers. On contrast, in the posterolateral region the axial stress was high in both the circumferential and in the axial direction, ensuring the tensile state of the collagen fibers.

In conclusion, this study presents a model and its application that allows investigating the effect of any loading conditions on the disc and estimating the risk of generating failures.

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