Analysis of properties used to simulate healthy and degenerated intervertebral discs

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Abstract. In the world, one of the main causes of hospitalizations and disabilities is a herniated disc. Therefore, understanding the mechanisms that lead to the development of this pathology is of great medical interest. To this end, articles on 3D models of a lumbar section with a herniated disc will be analyzed using tools such as the Finite Element Method (FEM). The 3D model was generated from real imaging exams, such as computed tomography and magnetic resonance imaging. Subsequently, with the aim of analyzing the mechanical properties (elasticity modulus E and Poisson's ratio, or hyperelastic model) of the structures of interest (annulus fibrosus, nucleus pulposus), another point of interest is the geometry of the elements used in FEM analysis. The main objective of this project is to understand which combinations of loads and movements lead to structural damage, primarily affecting the annulus fibrosus, resulting in the decompression of the nucleus pulposus. After analyzing the healthy models, the representation of the failure mechanisms of the structure was examined, verifying the variations in mechanical and physical properties due to different degrees of pathology (protrusion, prolapse, extrusion, and sequestration). This stage will contribute to a better understanding of the interaction between the components of the intervertebral disc, monitoring the development of the pathology and the constraints imposed by its progression.

Keywords: Finite element model, Lumbar Spine, Degenerative Disc Disease, Disc herniation, 3D model.

1 Introduction

3D element modeling is widely used, applied in various fields since 1963. It can be used for animations, films, games, and also for modeling in engineering applications, allowing the analysis of construction methods, failure prediction, and simulations of reactions to dynamic loads. Following these application lines, the use of 3D models allows for the visualization of complex structures and the prediction of their reactions and displacements.

In the literature, it is possible to find combinations of both fields, medicine and engineering, where engineering tools are used to model complex systems of the human body (Friedel [1]; Ramírez [2]). By using nonlinear analyses, these complex tissues can be well represented, allowing a better reproduction of the movements and pathologies that can affect these tissues. This is due to the relative ease of combining 2D images from exams such as CT and MRI to form 3D models.

The intervertebral disc (IVD) in the lumbar region has the greatest thickness, measuring 9 mm. This occurs because it is primarily responsible for dissipating mechanical energy through the deformation it undergoes (Linhares [3]). This deformation is possible due to the combination of constituent elements, which are the nucleus pulposus (NP) and the annulus fibrosus (AF), forming a set with elastic properties (Moore [4]).

According to Kapandji [5], the AF has little resistance to compression, being responsible for resisting only 25% of the axial load that reaches the IVD. However, its function is to resist the horizontal loads produced by the NP when compressed during flexion. The oblique arrangement of the fibers promotes greater resistance to rotational loads due to their perpendicular arrangement (Moore [4]).

However, this good interaction occurs only when both are healthy. With the degeneration of the NP, it allows for greater infiltration of fluid into the cartilaginous layer, leading to a reduction in the thickness of the IVD (Tortora [6]). This results in a disc with reduced pre-tension. The same occurs in cases of rupture of some layers of the AF, causing a reduction in the nucleus' encapsulation capacity (Kapandji [5]). This failure increases the vertical load that the AF resists, increasing the damage to the annulus fibrosus layers, which can protrude (herniate) the NP material (Appel [7]).

According to Alves Filho [8], disc herniation consists of the rupture of the AF of the IVD, which can be caused by high energy (impacts and falls) or low energy (movement with loads, poor posture, or rotations). This pathology in the disc can press on the nerve roots, causing pain and limiting the mobility of the affected limb. It can be classified into four levels: disc protrusion, disc prolapse, disc extrusion, and disc sequestration (Vialle [9]).

2 Objective

This article aims to analyze the studies from the last 10 years that involve the 3D modeling of lumbar spines with herniated discs. It seeks to compare the properties adopted for the nucleus pulposus (NP) and the annulus fibrosus (AF), the mesh geometry, and finally, to analyze how disc degeneration is treated through variations in mechanical and physical properties.

2.1 Methodology

For the purposes of this article, the PubMed database was searched using the keywords “finite element model, lumbar spine, Degenerative Disc,” with a 10-year filter. Eighty-seven articles dated between 2014 and 2024 were found, the articles were selected through reading their abstracts and methodologies, excluding articles that did not present the relevant data or had a different purpose than desired. Among these, nine articles were selected, which deal with simulations of lumbar segments with herniated discs. After pre-selection, the articles were analyzed to understand how progressive disc degeneration was portrayed. The data were then transferred to tables 1 and 2, and the results were discussed. These models were compared with in vitro models, allowing for the validation of the obtained results.

Table 1. Healthy DIV Properties and Elements

Author/Year	Healthy Nucleus Pulposus	Healthy Annulus Fibrosus	Element Type
Qasim et al., (2014) [10]	E = 1 MPa v = 0,40	E = 4,2 MPa v = 0,10	Hexahedron
Von Forvel et al., (2015) [11]	Bulk Modulus = 1720	Anisotropic E = 20.9, 0.42, 0.29 v = 2.27 ,0.79, 0.61	Hexahedron
Natarajan et al., (2016) [12]	E = 2,4 Mpa	Mooney–Rivlin com C1 e C2 constant 0,6 Mpa	-
Li et al., (2017) [13]	E = 1 MPa v = 0,49	Mooney–Rivlin C1 = 0.2, C2 = 0.05 E= 385 - 550 MPa	Hexahedron
Bashkuev et al., (2020) [14]	E = 0,1 MPa v = 0,499992	E = 1,5 MPa v = 0,2 Fibers hyperelastic Marlow model e=0,0001 between 30 e 45 degrees	Hexahedron

Du et al., (2021) [15]	Mooney–Rivlin C1 = 0.12, C2 = 0.03	Mooney–Rivlin, C1 = 0.18, C2 = 0.045	Hexahedron
Ding et al., (2021) [16]	E = 1 MPa v = 0,499	E = 92 MPa v = 0,45 Fibers E = 4,2 MPa v = 0,45	Hexahedron
Lu et al., (2022) [17]	E = 0,1 MPa v = 0,49	E = 4,2 MPa v = 0,49	Hexahedron
Ardatov et al., (2024) [18]	Mooney–Rivlin C1 = 0.12, C2 = 0.03 v = 0,4995	E = 2 Mpa v = 0,45	Tetrahedron

2.2 Discussion

To depict disc degeneration, changes were made to the physical properties, such as the reduction in IVD height: 15-20% for mild degeneration, 30-40% for moderate degeneration, and 50-60% for severe degeneration, as well as a reduction in the area of the NP.

As for the changes in the mechanical properties in linear analyses, they were represented by a progressive increase in stiffness according to the degree of degeneration (Young's Modulus (E)) and a reduction in the Poisson's Ratio of the NP and AF. In hyperelastic analysis, there was an increase in the C1 and C2 values of the Mooney-Rivlin model.

Among the analyzed articles, 5 defined the NP (nucleus pulposus) with linear elastic properties (E and ν) [10, 13, 14, 16, and 17], 2 portrayed it with hyperelastic material using the Mooney-Rivlin formulation [14, 18], 1 represented it linearly elastic using the Young's modulus and material permeability [12], and 1 portrayed it using the bulk modulus [11].

Regarding the AF (annulus fibrosus), it was represented using hyperelastic analysis by 4 authors [12, 13, 14, 15]. One author defined the AF with anisotropic properties [11], and 4 with linear elastic properties [10, 16, 17, 18].

As can be observed in table 2. Qasim [10] represented IDD degeneration by increasing the E of NP and AF, reducing the water volume in IDD, and its permeability.

Von Farrel [11] reduced the bulk modulus value of NP to 70, and altered the values of E and ν of AF to (E = 22.9, 0.32, 0.35 ν = 1.88, 0.46, 0.61) and reduced the IDD height by 16.5%.

Nataranjan [12] increased the E of NP to 2.8 MPa while reducing its permeability. For AF, the E value was reduced to 0.3 MPa.

Li [13] increased the E of NP to 1.6 MPa and reduced ν to 0.4. In the hyperelastic analysis of AF, the values of C1 and C2 were increased to 0.9 and 0.23 respectively. The height of IDD was also reduced, and the NP area was replaced by AF material.

Bashkuev [14] kept the E value of NP fixed but slightly reduced ν to 0.4975. The E value of AF was increased to 10 MPa, and the analysis of hyperelastic fibers was kept fixed.

Du [15] represented IDD damage progression by increasing the values of C1 and C2 for NP and AF to C1 = 0.19, C2 = 0.045 and C1 = 0.9, C2 = 0.23 respectively. The disc height and NP area were also reduced.

Ding [16] and Lu [17] treated IDD degeneration solely through the reduction of disc height and NP area.

Ardatov [18] represented it by increasing the Young's modulus of AF to 8 MPa.As can be observed, the methods of simulating disc degeneration are diverse, yet all have shown good results when compared to the literature and in vitro models. This is due to the high complexity of the simulated human tissue, which increases further when considering tissue degeneration.

Table 2. Properties of the Degraded DIV

Author/Year	Degraded Nucleus Pulposus	Degraded Annulus Fibrosus	Volume and Area variation
Qasim et al., (2014) [10]	E = 1,2 MPa v = 0,40	E = 5 MPa v = 0,10	Yes
Von Forvel et al., (2015) [11]	Bulk Modulus = 70	Anisotropic E = 22.9,0.32,0.35 v = 1.88,0.46,0.61	Yes
Natarajan et al., (2016) [12]	E = 2,8 Mpa	Mooney–Rivlin com C1 e C2 constant 0,3 Mpa	No
Li et al., (2017) [13]	E = 1,6 MPa v = 0,4	Mooney–Rivlin C1 = 0.9, C2 = 0.23 E = 385 - 550 MPa	Yes
Bashkuev et al., (2020) [14]	E = 0,1 MPa v = 0,4975	E = 10 MPa v = 0,2 Fibers hyperelastic Marlow model e=0,0001 between 30 e 45 degrees	No
Du et al., (2021) [15]	Mooney–Rivlin C1 = 0.19, C2 = 0.045	Mooney–Rivlin, C1 = 0.9, C2 = 0.23	Yes
Ding et al., (2021) [16]	E = 1 MPa v = 0,499	E = 92 MPa v = 0,45 Fibers E = 4,2 MPa v = 0,45	Yes
Lu et al., (2022) [17]	E = 0,1 MPa v = 0,49	E = 4,2 MPa v = 0,49	Yes
Ardatov et al., (2024) [18]	Mooney–Rivlin C1 = 0.12, C2 = 0.03 v = 0,4995	E = 8 Mpa v = 0,45	No

3 Conclusions

The changes made to simulate intervertebral disc degeneration are aligned with the literature, where the nucleus pulposus loses volume as degeneration progresses and the annulus fibrosus becomes more rigid and less deformable due to dehydration. This reduces the existing elastic properties due to the combination of the two elements, which allow for the support and dissipation of loads from the upper part of the human body.

The predominance of the geometry adopted in these articles indicates that the intervertebral disc is appropriately represented by hexahedrons due to the simple geometry of the disc. This also facilitates the representation of the annulus fibrosus fibers, allowing for a lower use of elements while maintaining the quality of the model, which is extremely important when it comes to the finite element method.

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