Significance of the collagen criss-cross angle distributions in lumbar annuli fibrosi as revealed by finite element simulations

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1. ABSTRACT

In the human lumbar spine, annulus fibrosus (AF) fibres largely contribute to intervertebral disc (IVD) stability, and detailed annulus models are required to obtain reliable predictions of lumbar spine biomechanics by finite element (FE) modelling. However, different definitions of collagen orientation coexist in the literature for healthy human lumbar AFs and are indiscriminately used in modelling. Therefore, four AF fibre-induced anisotropy models were built from reported anatomical descriptions and inserted in a L3-L5 lumbar bi-segment FE model. AF models were respectively characterized by radial, tangential, radial and tangential, and no fibre orientation gradients. IVD local biomechanics was studied under axial rotation and axial compression. A new parameter, i.e. the Fibre Contribution Quality parameter, was computed in the anterior, lateral, postero-lateral and posterior AFs of each model, in function of fibre stresses, load distributions, and matrix shear strains. Locally, each AF model behaved differently, affecting the IVD biomechanics. The Fibre Contribution Quality (FCQ) parameter established a direct link between local AF fibre organization and loading, while other biomechanical data did not. It was concluded that local AF fibre orientations should be modelled in relation to other segment characteristics. The proposed FCQ parameter could be used to examine such relations, being, therefore particularly relevant to patient-specific models or artificial disc designs.

2. INTRODUCTION

In lumbar spine IVDs, the AF is an organised network of collagen bundles embedded into a ground substance (GS) matrix. Within each AF region, collagen bundles are distributed into concentric layers characterized by preferential fibre orientations[1]. Typically collagen fibres have no compressive stiffness but provide most of the AF mechanical strength, as they can locally reorient and stretch[2] to resist tissue tractions and/or bulging. AF collagen bundles can also stretch as a response of IVD shear deformations, playing, therefore, a key role under any kind of loadings.

Since before stretching, AF fibres align with the local loads felt by the annulus, IVD reinforcement should depend on the undeformed fibre orientations. Two levels of orientation-related collagen organisation can be identified in human lumbar AFs. The first level is the layer-to-layer fibre criss-cross pattern through the AF thickness. The second organisation level corresponds to the radial and tangential variations of the absolute angle between the criss-crossed bundles and the concentric layer axes. There, various descriptions co-exist for healthy IVDs. While Galante[3] reported almost equally

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oriented criss-crossed fibres throughout the AF, Marchand and Ahmed[1] found strongly axially oriented fibres in the most external posterior layers. Cassidy et al[4] reported fibres 38% more transversal in the inner than in the outer AF. In change, Holzapfel et al[5] only found significant tangential angle variations with fibres 100% more transversal in the anterior than in the posterior AF.

To our knowledge, besides isolated studies on body-disc-body units[6,7], no thorough investigations about annulus fibre orientation effects on lumbar spine FE predictions were reported so far. Thus, the objective of this study was to test whether different non-pathological AF fibre-induced anisotropies could affect IVD biomechanics in a lumbar spine bi-segment model. Moreover, it was hypothesized that particular deformation modes require specific AF fibre organizations. For this, the ability of different fibre absolute angle distributions to limit local IVD deformations was investigated through a new parameter quantifying AF mechanical stability.

3. MATERIALS & METHODS

A previously developed L3-L5 lumbar spine FE model was used[8]. The AF collagen fibre-reinforced material was structurally modelled. 20 individual and mono-oriented fibre layers were radially distributed through the AF thickness over four layers (OUT, MIDout, MIDin, IN) of rebar elements superimposed to the GS elements (Fig. 1).

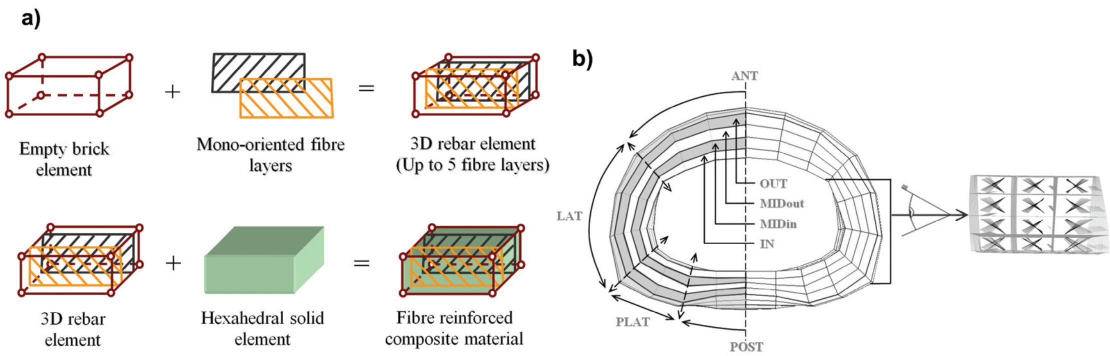


Fig. 1: AF composite structure modelling

In both the L3-L4 and L4-L5 AFs, the absolute fibre angles with the IVD axial direction potentially varied within each annulus area (Fig. 1b). Three fibre distribution models, i.e. the ISO, RAD, and TAN models were created from literature data. A fourth model, i.e. the ANI model, combined the angle variations from the RAD and TAN models (Table 1). Fibre orientation gradients were modelled with linear angle variations[4,5].

Table 1: Characteristics of the different annulus fibre-induced anisotropy models

Model			ISO	RAD	TAN	ANI
Criss-cross angle gradient			None[3]	Radial[4]	Tangential[7]	Radial, tangential
Criss-cross angle extrema (°)	ANT	OUT	60	62	67	77.6
		IN	60	45	67	56.4
	POST	OUT	60	62	32.7	38.4
		IN	60	45	32.7	28

AF material properties were summarized in Table 2. Collagen bundles were considered hypoelastic with tension-only stiffness. Based human procollagen properties[9], collagen II stiffness was assumed to be 0.77 times that of collagen I. Multiplication of 0.77 by collagen I to II measured contents [10] gave the apparent fibre stiffness through the AF thickness. GS material properties were varied among the different AF radial sections by fitting an incompressible Mooney-Rivlin model to experimental data[11]:

$$W = C_{10}^{GS}\left(\overline{I_1}-3\right)+C_{01}^{GS}\left(\overline{I_2}-3\right)+C_{11}^{GS}\left(\overline{I_1}-3\right)\left(\overline{I_2}-3\right) \quad (1)$$

where W is the GS strain energy density, $\overline{I_1}$ and $\overline{I_2}$ are the 1st and 2nd deviatoric invariants of the right Cauchy-Green tensor, respectively. C_X^{GS} are given in Table 2.

Table 2: AF material properties

Annulus radial section		OUT	MIDout	MIDin	IN
Collagen bundle apparent stiffness (*) (MPa)		$0.95k_I$	$0.91k_I$	$0.86k_I$	$0.85k_I$
GS Mooney-Rivlin parameters (MPa)	C_{10}^{GS}	0.0595	0.053	0.053	0.040
	C_{01}^{GS}	0.0002	0.001	0.001	0.006
	C_{11}^{GS}	0.0296	0.058	0.058	0.032

(*) Based on collagen I and II tangent stiffness, k_I and k_{II}, so that $k_{II}=0.77k_I$ with $k_I=BE^{(A-1)}$ in the toe part[12], $B=2.23\times10^6$ MPa, $A=3.15$, and $k_I=847.76$ MPa in the linear part[13].

10 N.m axial rotation (pure moment) and 1000 N axial compression (follower force) were simulated. Axial compression was applied on a L3-L4 reduced model. Loads were applied on the upper bony endplate of L3, while the lower bony endplate of L5 (L4 for the reduced model) was fixed in all directions. It was hypothesised that optimally oriented AF collagen bundles should (i) bear the largest amount of load as possible, (ii) distribute loads as well as possible through the AF thickness[5], and (iii) limit GS shear strains[14]. Conditions (i)-(iii) were quantified by user-defined parameters.

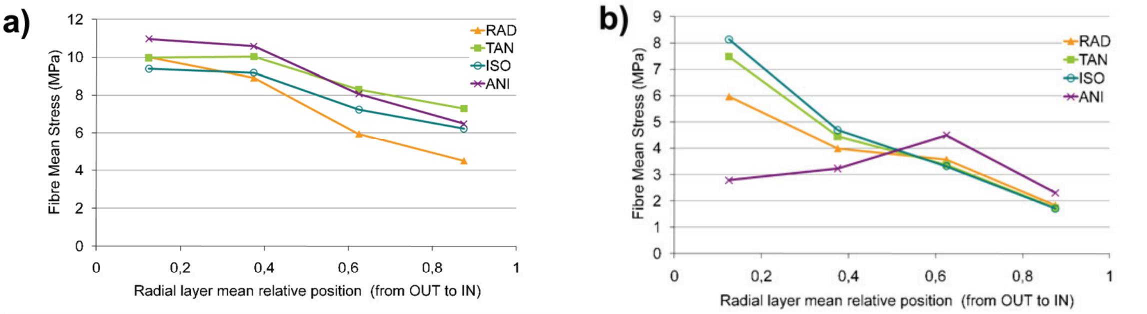
Related to (i), the Radial Mean Stress parameter (*RMS*), was the mean longitudinal fibre stress, calculated over the AF thickness in each tangential sector. According to (ii), the Radial Stress Distribution parameter (*RSD*), aimed to quantify the homogeneity of fibre loading through the AF thickness. Within each tangential quadrant, fibre mean stress was computed over each radial area and plotted against the mean relative position of the area along the AF thickness. Stress variations through the quadrant were interpolated quadratically, and *RSD* values were calculated as the norm of the vector formed by second and first order interpolation coefficients, divided by the quadrant mean fibre stress. Related to (iii), the third parameter was the Matrix Shear Strain parameter (*MSE*), defined in each tangential quadrant as the mean total shear strain value. Parameters were normalized and combined together to establish the *FCQ* parameter, whose values increased with the simultaneous fulfilment of conditions (i), (ii), and (iii):

$$\overline{FCQ}_{quadrant}^{segment} = A\ln\left(B+\frac{e^{\overline{RMS}_{quadrant}^{segment}}}{e^{\left(\overline{RSD}_{quadrant}^{segment}+\overline{MSE}_{quadrant}^{segment}\right)}}\right) \quad (2)$$

where A and B are normalizing parameters so that $\overline{FCQ}_{quadrant}^{segment}\in[0,1]$. In each AF tangential quadrant, stabilization by the collagen network was comparatively studied in terms of fibre loading and GS shear strains, and then related to the *FCQ* parameter values. All calculations were performed with MSC Marc Mentat.

4. RESULTS

Under axial compression, the RAD and ANI models, returned worse fibre stress radial distributions than the TAN and ISO models (Fig. 2a). In the anterior AF, the TAN model led to the highest $\overline{RMS}$ parameter, while maximum mean fibre stress was given by the ISO model in the rest of the tissue. Under axial rotation, the RAD model provided the most distributed fibre stresses and the lowest $\overline{RSD}$ value, in the anterior AF (Fig. 2b). In the postero-lateral quadrants, the ANI inner fibres led to the greatest $\overline{RMS}$ values and at the L3-L4 level, the TAN model gave the lowest $\overline{RSD}$ value.



Parameters	RAD	TAN	ISO	ANI
$\overline{RMS}^{L3-L4}_{ANT}$	0.70 (IV)	0.98 (II)	0.88 (III)	1 (I)
$\overline{RSD}^{L3-L4}_{ANT}$	0.90 (III)	0.89 (II)	0.77 (I)	1 (IV)

Parameters	RAD	TAN	ISO	ANI
$\overline{RMS}^{L4-L5}_{ANT}$	0.94 (III)	0.98 (II)	1 (I)	0.75 (IV)
$\overline{RSD}^{L4-L5}_{ANT}$	0.21 (I)	0.55 (II)	0.68 (III)	1 (IV)

Fig.2: Fibre stresses and related parameters in the anterior AF quadrants. a) axial compression (reduced model, L3-L4), b) axial rotation (L4-L5) - (I): best value - (IV): worst value

Under axial compression the RAD model led to the highest GS mean total shear strain values, in the anterior and lateral AF. Lowest values were given by the TAN model in the anterior quadrant, and by the ISO model in the other quadrants. Under axial rotation, annulus matrix mean total shear strains decreased from the anterior to the posterior AF. The RAD model led to the least mean shear deformations, except in the L3-L4 posterior AF where the lowest GS mean total shear strain value was given by the TAN model.

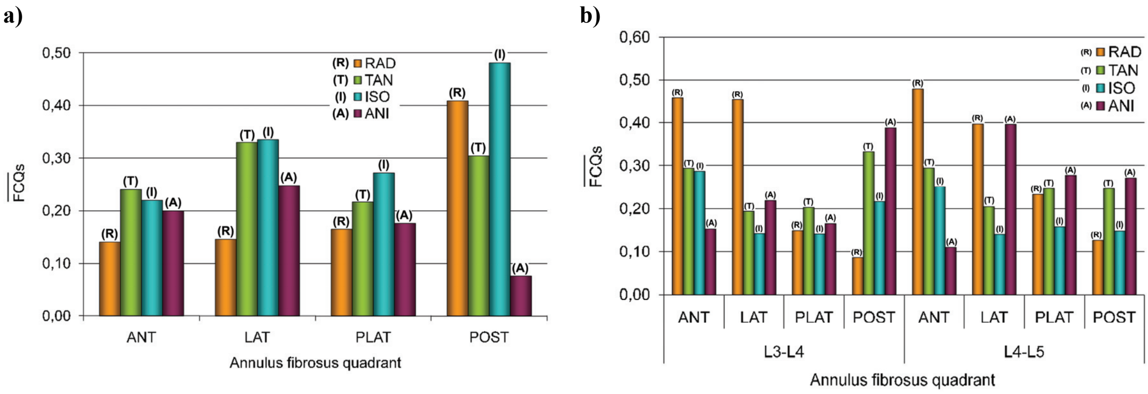


Fig. 3: FCQ parameter values computer in the different AF quadrants. a) axial compression (reduced model), b) axial rotation.

Under axial compression, highest $\overline{FCQ}$ values were given by the AF models without fibre orientation radial gradients (Fig. 3a). In the anterior quadrant, the TAN model offered the best compromise in terms of fibre load magnitude and distribution, and GS shear strains. In the other quadrants, this happened with the ISO model. Under axial rotation, $\overline{FCQ}$ parameter values suggested that the RAD fibre configuration would best stabilized the anterior and lateral AF (Fig. 3b). In the L3-L4 and L4-L5 postero-lateral AF, the TAN and ANI models respectively gave the best results.

5. DISCUSSION

Under axial compression, transversal orientation and stress bearing capacity of the AF fibres were positively correlated. Actually, direct axial compressive loading and simultaneous NP pressurization produce an outward biaxial bending of the fibre layers. This gave place to preferential activation of transversal fibres, since the AF is freer to expand laterally than axially. Such result was in accordance with early simulations[6]. In most AF quadrants, radial fibre orientation gradients led to the worst fibre stress distributions. Comparing the RAD and ANI with the ISO and TAN models, poor fibre stress radial distribution correlated with increased GS shear strains. Indeed, with the modelled radial orientation gradients, axial inner layers offered a limited relative resistance to the NP transversal expansion and displaced the loads to the outer layers. According to the computed $\overline{FCQ}$ values, it can be concluded that the transversal and distributed anterior fibres of the TAN model were the best one to locally stabilize the anterior quadrant, under compression. Similarly, the fibres of the ISO model gave the highest local $\overline{FCQ}$ values in the lateral, postero-lateral, and posterior quadrants.

Under axial rotation, the 45º and 62º oriented inner and outer fibres of the RAD model allowed AF deformations, while limiting both load concentrations and matrix shear strains, in the anterior and lateral AF. Such results was well quantified by the $\overline{FCQ}$ values, but was not only related to the main motion. A study of the coupled motions indicated that the whole AF underwent significant axial tractions. In the anterior AF, the extremely transversal outer fibres of the ANI model could not limit such local stretch, giving locally low $\overline{FCQ}$ values. Over the whole L3-L4 postero-lateral quadrant, the 44º oriented fibres of the TAN model were in average both the most axial ones and the closest ones to 45º. Thus, they were clearly the best to locally resist both main and coupled L3-L4 motions, as shown by the $\overline{FCQ}$ parameter value. Increased L4-L5 ranges of motion made unbalanced anterior and posterior fibre orientations to generate large additional extensive motions. Thus, fibre axial orientation and radial orientation gradient were appropriate to locally limit L4-L5 posterior AF deformations, in line with the ANI $\overline{FCQ}$ value, but not with the GS shear strain result, due to inter-quadrant interactions.

Depending on the chosen AF collagen organization, fibre stresses could locally vary by about 100% or more, and GS mean total shear strains could change by up to 50%. Thus, more knowledge about the functional distribution of collagen orientations should be acquired to truly assess the IVD biomechanics. Strong interactions were shown between optimal AF fibre configuration and local loadings, and the proposed $\overline{FCQ}$ parameter was able to quantitatively assess these interactions. The present model had clear limitations in terms of tissue and boundary condition modelling, but provided that these limitations can be overcome, the $\overline{FCQ}$ parameter could be used to explore patient-specific lumbar AF fibrous organizations. The $\overline{FCQ}$ parameter could also assist the design of artificial discs aiming to mimic the natural IVD structure.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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