Composite mechanics of the multilayer structure of the annulus fibrosus

George Youssef*, Cesar Lopez**, J. Michael Kabo**

*Mechanical Engineering Department, San Diego State University, USA
**Mechanical Engineering Department, California State University Northridge, USA

Abstract
The degeneration of the intervertebral disc (IVD) rests on many factors, but some of the main ones are the absence of a blood vessel supply, excessive overloading, and cycling loadings. This deterioration may contribute to peripheral pain and neurological dysfunctions. When degeneration is severe or in some other cases when the annulus fibrosus (AF) ruptures, fusion surgery, disc arthroplasty, and disc discectomy have been used as clinical solutions. However, these solutions limit the range of motion, the material used does not reproduce the natural behavior, and more importantly, it weakens the overall mechanical response of the spinal column, which accelerates degeneration. Recent research indicates a new focus on the composite nature of the annulus. In this paper, a mathematical model is used to predict the mechanical behavior of the AF based on its anatomical structure. Previously published experimental data of AF are correlated with the mechanistic-based predictions and found to be in good agreement. The mathematical model shows that maximum strain occurs at the mid-to-outer region, which is consistent with published data from animal models. The results indicate that future motion preserving, total disc replacement devices and tissue restoration technology can be effectively designed using composite materials for synthetic AF.

Key terms: composite mechanics; intervertebral disc; annulus fibrosus; mechanical behavior of annulus; disc mechanics; disc degeneration

1 Introduction
There has been active interest in the investigation of the mechanical properties of the entire intervertebral disc (IVD) as well as each of its constituents, where the key objective is to create a new synthetic replacement in the case of severe degeneration. Currently, there exist three main surgical intervention solutions to remedy degenerated discs, which includes fusion of the motion segment, disc arthroplasty, and discectomy[1]-[4]. These treatments are usually recommended after other options such as medication, physical therapy, neuromodulation, and intradiscal electrophysical therapy are exhausted [5], [6]. In fusion surgery, the movement of a motion segment is constrained using bone graft and it may involve using screws, plates or rods to fix the vertebrae in place[1],[5]. Fusion surgery is currently considered as the gold standard, however, associated problems such as elongated recuperation time, adjacent segment degeneration, and pseudarthrosis have been documented [2]. On the other hand, in disc arthroplasty, the degenerated disc is completely removed and replaced by a synthetic structure that usually consists of metallic endplates and a polymer cage, i.e., metal-on-polymer device, or a completely metal structure, i.e. metal-on-metal [1],[2],[6]. As of 2011, in the United States, there were only two devices that were approved by the Food and Drug Administration, which are InMotion/Charité III from DePuy Spine and ProDisc from Synthes [2],[3]. Although, the devices are similar in structure, both are metal-on-polymer devices, they have significant biomechanical differences[3]. For instance, Charité devices allow anterior-posterior movement of the rotational axis, while it is fixed in ProDisc replacement technology[2].

*Corresponding Author: Dr. George Youssef
Email Address: gyoussef@mail.sdsu.edu
Tel: +16195466649
Other prosthetics such as nucleus pulposus, motion preserving, and dynamic stabilization devices are currently under different stages of investigation and development [2], [3]. Finally in disc disectomy, surgeons remove part of the AF due to herniation of the disc. As a result, the annulus gets sealed with synthetic material that does not reproduce the natural behavior and increases the risk of disc degeneration [3], [4], [7]. Thus in all, the available replacement discs and the materials used to alleviate the disc degeneration problem do not reproduce the mechanical and physiological functionality of the natural discs, which make them clinically deficient [3]-[5], [7]-[9]. Thus, it is important to explicate the significance of the anatomical structure of natural constituents of the intervertebral disc on the mechanical behavior in order to create the “ideal” synthetic IVD.

Despite the extensive experimental and clinical research published on this topic thus far [1]-[9], the quest for a biologically-inspired synthetic disc is impeded by the lack of fundamental understanding of the significance of the anatomical structure and the contribution of the IVD constituents, i.e. annulus fibrosus (AF), nucleus pulposus (NP) and endplates, to the load-bearing ability and the overall functionality of the disc. This quest is further complicated by the limitations imposed by available experimental mechanics techniques to separate the mechanical contribution of each element. In this paper, the anatomical structure of annulus fibrosus is the focus to understand the load-bearing abilities and contribution of the annulus from the perspective of mechanics of composite materials.

2 Annulus Fibrosus Background

The annulus fibrosus is a biological, ring-like structure that forms the outer part of the intervertebral disc, where its task is to keep the nucleus pulposus in place while resisting complex loadings from the vertebral bodies and the NP. The annulus fibrosus is made of approximately 20 lamellae, where each lamella consists of near 40 fiber bundles of proteoglycan and collagen [8], [10]. The proteoglycan bonds the lamellae structure together, while the collagen fibers serve as the load bearing members. Moreover, it was found that the annulus varies from a compliant material near the nuclear-annular region to a stiffer material at the outside boundary of the annulus [11]-[13]. The annulus fibrosus has been experimentally investigated as a homogenous isotropic material to determine the mechanical properties; nonetheless a few researchers have studied the annulus as a heterogeneous structure with anisotropic material properties [11]. Generally, these efforts focused either on the contribution of the annulus as part of the entire motion segment or only on the mechanical behavior of the extracted annulus with limited regard to the anatomical properties of the annulus based on its composite mechanics properties. Adams et al. suggested the annulus is more likely to collapse in the posterior region due to damage of the endplate [14]. They reported the posterior section of IVD experienced 25% higher stresses after the endplate was damaged [14]. Schmidt et al. numerically simulated the movement of the motion segment with and without the nucleus pulposus and compared the results with in-vitro experiments [15]. The in-silico results predicted the range of motion of the in-vitro studies with 95% accuracy; however, the properties used in the simulation were iterated to mimic the movement with disregard to the actual physical and mechanical properties of the intervertebral soft tissue [15]. On the other hand, Krismer et al. indicated that the structure of the annulus fibrosus contributes significantly to the mechanical behavior of the motion segment in addition to dampening cyclic loads [16]. Wagner et al., on the other hand, reported that the natural annulus is an uneven material with stiffer response when tested in tension (E\text{tension}=0.447\pm0.379MPa) than in unconfined compression (E\text{compression}=0.235\pm0.127MPa); an indication of dependence of the behavior of the constituents of annulus fibrosus on the loading direction [17]. Elucidating the sensitivity of the response to loading conditions, Pééri and coworkers measured the compressive modulus of the annulus fibrosus of bovine tails using confined compression stress-relaxation experiments and reported the effective compressive modulus to be 0.74MPa [18]. Alternatively, Fujita et al. described the variation in the tensile mechanical properties in the radial direction of AF sections harvested from the anterior and posterolateral quadrants from fifteen human discs [19]. The initial modulus showed a statistically insignificant increase in the inner, middle, and outer region. Meanwhile, the value of the tangent modulus of the middle section that consisted of multiple lamellae (0.64\pm0.46MPa) was statistically different from those reported for the inner and outer regions, 0.44\pm0.46MPa and 0.42\pm0.45MPa, respectively [19]. Anatomically, Fujita et al. argued that the dependence of the modulus is attributed to the radial location of each lamella. This argument is mechanically supported since the collagen fiber orientation varies between 25° and 45° from the outer to the inner diameters of the annulus, respectively [10]-[12]. Finally, Holzapfel et al. suggested that the native annulus can be considered as a composite material [11]. They harvested 11 human spines from cadavers, where single rectangular lamellae specimens were separated based on different regions of the annulus. A tensile load was then applied along the fibers of the lamellae and
the tensile modulus was measured. The results confirmed the fiber orientation of the annulus varies in the radial direction and the stiffness along the longitudinal and transverse fiber direction change accordingly. The material stiffness of the lamella was 78MPa in the longitudinal direction and 0.50MPa in the transverse direction [11]. Notably, these results of the elastic moduli of single lamella are significantly different from those reported by Wagner et al. of the effective modulus; highlighting the significance of the number of lamella and fiber orientation on the overall response of the annulus material [17].

Despite the extensive research on the annulus fibrosus, limited research has been conducted on the validity of the presumption that the annulus can be considered as an engineering composite material and that the fiber volume fraction and orientation are optimized to resist common physiologic loads. The assumption of applicability of mechanics of composite materials, which will be demonstrated in this paper, can be used to transform the development of prosthesis design. This is significant since researchers, on separate but not consistent bases, have identified the heterogeneity and anisotropy of the native annulus. The following section is a brief introduction to the mechanics of composites, which will be used to elucidate the mechanical behavior of the nature-optimized annulus fibrosus structure. Specifically, we will demonstrate the use of a mathematical model consisting of mechanics of composite materials to predict the elastic properties and mechanical failure behavior and compare it to experimentally measured and reported results.

3 Composite Mechanics

In the realm of mechanics of composite material, the mechanical properties in the 12-plane can be determined using testing of a single lamella in longitudinal (1-direction) and transverse (2-direction) [20]. These include the elastic modulus along the fiber direction ($E_1$), the modulus in the direction transverse to the fiber ($E_2$), the Poisson’s ratio ($\nu_{12}$), and the shear modulus ($G_{12}$). Once determined, these properties can be used to calculate the properties in xy-plane that is rotated at any arbitrary angle ($\theta$) defined positive counterclockwise from the 1-direction. Thus, the mathematical model used in this study consists of the transformation equations of composite mechanics, which are listed below.

$$E_x = \left[\frac{1}{E_1} \cos^4 \theta + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1}\right)\cos^2 \theta \sin^2 \theta + \frac{1}{E_2} \sin^4 \theta\right]^{-1}$$  (1)

$$E_y = \left[\frac{1}{E_1} \sin^4 \theta + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1}\right)\cos^2 \theta \sin^2 \theta + \frac{1}{E_2} \cos^4 \theta\right]^{-1}$$  (2)

$$G_{xy} = \left[\frac{1}{G_{12}}(\sin^4 \theta + \cos^4 \theta) + 2 \left(\frac{2}{E_1} + \frac{2}{E_2} + \frac{4\nu_{12}}{E_1} - \frac{1}{G_{12}}\right)\cos^2 \theta \sin^2 \theta\right]^{-1}$$  (3)

$$\nu_{xy} = \frac{\nu_{12}}{E_1} \left[\sin^4 \theta + \cos^4 \theta - \left(\frac{1}{E_1} + \frac{1}{E_2} - \frac{1}{G_{12}}\right)\cos^2 \theta \sin^2 \theta\right]$$  (4)

**Fig. 1 Transformation of lamella from 12-plane to xy-plane by angle $\theta$**
\[
\eta_{sx} = G_{xy} \left[ \left( \frac{2}{E_1} + \frac{2\nu_{12}}{E_1} - \frac{1}{G_{12}} \right) \sin^2 \theta \cos \theta - \left( \frac{2}{E_2} + \frac{2\nu_{12}}{E_2} - \frac{1}{G_{12}} \right) \cos^2 \theta \sin \theta \right]
\]  
\[
\eta_{xs} = E_x \left[ \left( \frac{2}{E_1} + \frac{2\nu_{12}}{E_1} - \frac{1}{G_{12}} \right) \cos^2 \theta \sin \theta - \left( \frac{2}{E_2} + \frac{2\nu_{12}}{E_2} - \frac{1}{G_{12}} \right) \sin^2 \theta \cos \theta \right]
\]

\(E_1\) is the modulus in the x-direction, \(E_y\) is the modulus in the y-direction, \(G_{xy}\) is the shear modulus in xy-plane, \(\nu_{xy}\) is the Poisson’s ratio, and \(\eta_{si}\) and \(\eta_{is}\) (\(i=x, y\) and \(s\) is a contracted notation corresponding to properties in x-y system of coordinates) are the shear coupling coefficients that define the dependency of the resulting normal and shear deformations on applied loads [20]. Eqs. (5) and (6) show that normal and shear deformations are coupled at any arbitrary fiber orientations except at 0\(^{\circ}\) and 90\(^{\circ}\). Such that, an application of a normal stress in either x- or y-direction will result in normal and shear strains and vice versa. These observations characterize orthotropic materials when loaded along the non-principal directions [20].

Equation (7) presents the linear constitutive relationship, which can be used in conjunction with Eqs(1)–(6) to calculate the strains \((\varepsilon_x, \varepsilon_y, \gamma_{xy})\) based on a given loading scenario \((\sigma_x, \sigma_y, \tau_{xy})\) [22]. The non-principal strains can then be used to resolve the strains in the lamella principal directions (i.e., second part of Eq. (7)). Thus, these equations collectively can be used to understand the reason that the fiber orientations range between 25\(^{\circ}\) and 45\(^{\circ}\) from the outer and normal principal behavior of each lamella in the annulus fibrosus under application of different levels of physiologic loads that are encountered. The applicability of these equations is shown in the next section with focus on time-independent behavior of the annulus fibrosus.

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix} = 
\begin{bmatrix}
1/E_x & -\nu_{yx}/E_y & \eta_{sx}/G_{xy} \\
-\nu_{xy}/E_x & 1/E_y & \eta_{sy}/G_{xy} \\
\eta_{sx}/E_x & \eta_{sy}/E_y & 1/G_{xy}
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix}, \quad 
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\gamma_{12}
\end{bmatrix} = [T]
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}
\]

\(\frac{[T]}{[T]} = \begin{bmatrix}
m^2 & n^2 & 2mn \\
m^2 & m^2 & -2mn \\
-mn & mn & m^2 - n^2
\end{bmatrix}\) and \(m = \cos \theta \) and \(n = \sin \theta\)

4 Results

The aforementioned mathematical model was applied using the material properties of single lamellae reported by Iatridis and coworkers [21], [22]. They collected the properties based on an uniaxial tension experiment, where \(E_1=136\text{MPa}, E_2=0.76\text{MPa}, G_{12}=0.30\text{MPa},\) and \(\nu_{12}=0.30\) [21], [22]. These properties were adopted with the focus on uncovering the underlying physical significance of the fiber orientation in the native annulus fibrosus.

Figure 2 shows the dependence of the mechanical properties on the fiber orientation based on Eqs. (1)-(6). As a result, the moduli in the x- and y-direction (Fig. 2.a), shear moduli in the xy-plane (Fig. 2.b), shear coupling coefficient between normal stress and shear strain (Fig. 2.c), and shear coupling coefficient between applied shear and normal deformation (Fig. 2.d) were calculated for every possible fiber orientation.

The results in Fig. 3 show a comparison between the predicted moduli using composite mechanics transformation equations (Eqs. (1)–(2)) and a priori results [19], [23]. However, the predicted values were higher than the average modulus reported by Iatridis et al., E=0.56 ± 0.21MPa [23]. In addition, Eq. (7) was used to predict the strain of the annulus based on two different applied loads, nominal torso weight (Fig. 4.a) and rotation (Fig. 4.b).
Fig. 2 Dependency of the mechanical properties on fiber orientation where a) represents the stiffness in the x-and-y direction, b) is the shear modulus, c) the shear coupling coefficient between normal stress and shear strain, while d) is the shear coupling coefficient between applied shear and normal deformation.
Fig. 3: Comparison of the elastic moduli based on Eqs. 1 and 2 with experimentally reported data.

Fig. 4: Three load case scenarios and predicted strain using macromechanics of composite lamina.

4.1 Discussion

In Fig. 2.a the moduli $E_x$ and $E_y$ at $\theta = 0^\circ$ assume the values of $E_1$ and $E_2$ as the $x$- and $y$-direction are aligned with the 1- and 2-direction, respectively. It can also be seen that at $\theta = 90^\circ$, the longitudinal direction of the fibers is aligned with the 2-direction, thus $E_y = E_1$. Notably, when $x$- and $y$-axis are aligned with the principal directions, the stiffness in the $x$-direction is nearly 200 times larger than in $y$-direction, which implies unrealistic physiological deformation. That is, the structure can resist deformation in the $x$-direction but it will collapse in the $y$-direction due to the lack of stiffness. Nonetheless, as mentioned in the previous section, the fiber orientation of the natural disc is bounded between $25^\circ$ at the most outer lamella and $45^\circ$ at inner lamella. With this range in mind, the difference between the moduli is less than twofold and the normal deformation resistance in $x$- and $y$-direction are comparable.

The shear modulus, $G_{xy}$, is shown in Fig. 2.b, where the lowest values are reported at 0° and 90°, at which the shear moduli are equal to the value of $G_{12}$ of a single lamella. As the fiber orientation changes, the resistance to shearing deformation increases monotonically from 1.55 $G_{12}$ at 25° to reach a maximum of 2.5 $G_{12}$ at 45°. In other words, the maximum shearing resistance is located at the inner diameter of the disc to prevent lamellae tearing or delamination due to axial rotation loading while annulus fibrosus is in contact with the gelatinous nucleus pulposus. This can be further discussed by considering the angle of twist ($\phi$) per unit applied torque (T), ($\psi = \phi \over T$), in axial rotation loading scenario, where $\psi_i = R_i \over G_i J$ with $R_i$ is the radial location of lamella, $G_i$ is the fiber orientation dependent shear modulus of $i$th lamella, and $J$ is polar moment of inertia (such that $J = 6\pi R_i^3 t$ where $t$ is the lamella thickness). Thus, $\psi_i$ is inversely proportional to the shear modulus and to the squared of the radial location of the corresponding lamella. This implies that the twisting per unit applied torque at the inner diameter of the annulus is nearly nine times higher than the outer lamella. This facilitates the strain transduction from the nucleus to the annulus while preventing the excessive deformation of the outer perimeter of the annulus to protect the spinal cord and surrounding nerves and tissues as the IVD reacts to common loading conditions.

Finally, Fig. 2c and 2d show the shear coupling coefficients between applied normal stress and shear strain ($\eta_{is}$) as well as between applied shear stress and normal deformation ($\eta_{si}$), respectively. The former (Fig. 2c) shows maximum coupling at fiber orientation with 0°<$\theta$<25°, which indicate that the natural annulus fibrosus is optimized to
reduce the shear deformation due to applied normal stress (e.g., \( \gamma_{xy} = \eta_{sy} \frac{\sigma_{xy}}{E_y} \)). It is worth noting, this is the most common loading scenario as the weight of the torso exerts normal compressive stresses on the annulus. On the other hand, the maximum coupling between applied shear stress and resulting normal deformation is reported at \( 25^\circ < \theta < 45^\circ \) as shown in Fig. 2d. This coupling is needed to transfer the load to the nucleus and the surrounding ligaments during axial rotation loading such that \( \varepsilon_y = \eta_{sy} \frac{\tau_{xy}}{G} \) where \( \eta_{sy} < 0 \). This means, the disc is axially compressed (\( \varepsilon_y < 0 \)) as shear stress due to torsion is applied based on axial rotation, which as a result gives a rise to the nucleus’s mechanical contribution as a load-bearing member. This is consistent with results reported in the literature [19].

In addition, the predicted elastic moduli in Fig. 3 is higher than the one reported by Iatridis et al. because they tested segments of the entire annulus as a homogenous material, i.e. they reported the effective modulus of the entire annulus wall-thickness [23]. It is important to note here that it is expected based on mechanics of composite laminates, where the stiffness of the multi-layer structure is less than the stiffness of single lamella depending on the fiber orientation and stacking sequence. Second, good agreement is shown between the predicted and the moduli reported by Fujita et al., where they measured the properties of sections of the annulus at outer, middle and inner locations [23]. To this end, not only the mechanics of composite materials is capable of predicting the properties at an arbitrary fiber orientation, but, and more importantly, it is also capable of explaining the physical and mechanical significance of the specific fiber orientation found in the natural disc. That is, the inner lamellae consist of soft material to facilitate the strain transduction from the expansion of the nucleus pulposus, while the outer lamellae tend to be stiffer [11]-[14]. Therefore, the fiber configuration of annulus is built to optimize its functionality.

Subsequently, we utilized the properties that were predicted using the transformation equations (Eqs. (1)-(6)) and the constitutive relationship (Eq. (7)) to consider the response of each lamella at different orientations to two specific and common loading scenarios. First, the mechanical deformation based on applied axial compression, \( \sigma_y = -1 \text{MPa} \), due to the weight of the torso, and lateral compression, \( \sigma_x = -1 \text{MPa} \), due to the hydrostatic pressure from the nucleus on the annulus is calculated along principal direction using Eq. (7) [24], [25]. The approximation for stress due to the weight of the upper torso with 1 MPa is considered reasonable based on the average weight of torso and surface area of the intervertebral disc [26]-[28]. Nonetheless, the variation of the stress level does not pose any contradictions in the results presented below since the models used herein are linear, where the increase or decrease in the stress level will result in change in the corresponding strain level without change in the overall behavior, respectively. In the second loading scenario, we consider the application of axial rotation in addition to the stated normal loads.

Figure 4.a shows the principal strains (in L-2 plane) based on axial and lateral compression only, from which we generate the following four observations. First, The strain along the fiber direction, \( \varepsilon_1 \), is positive, i.e. loading the fibers in tension, while the strain in the transverse direction is compressive, \( \varepsilon_2 < 0 \). Second, the magnitude of the transverse strain, \( \varepsilon_2 \), is nearly four times larger than the longitudinal strains because the fibers are stiffer as it is the load-bearing member of the lamella. Third, although there is no applied shear stress, shear strain is generated due to the shear coupling coefficient, \( \eta_{sy} \). Fourth, the magnitude of normal and shear strains is decreasing as the fiber orientation changes from \( 25^\circ \), where the maximum strains are reported, to \( 45^\circ \) where \( \varepsilon_1 \approx \gamma_{12} \approx 0 \). This generally justifies that disc herniation is due to bulging of the annulus based on the weakening of the middle to outer lamellae, where the maximum effective strains occur, in response to displacement of the fiber bundles because of the excessive transverse strains. These justifications correlated with the findings collected by Wade et al., where it was found that disc herniation initiates at the middle lamellae of the annulus[29]. In addition, Fig. 4.a shows that the predicted strains are in agreement with the tensile radial failure strains of reported by Fujita et al.[19].

Figure 4.b shows the predicted strains due to simultaneous application of normal and shear loadings. The values of the longitudinal strain, i.e. along the fiber, remain insensitive to the application of shear stress due to axial rotation when compared with the previous loading scenario. There is a slight increase in the shear strain, where the maximum was reported at \( 25^\circ \) in both loading scenarios but \( \gamma_{12} \approx 0.5 \) for normal loading while \( \gamma_{12} \approx 0.9 \) for combined normal and shear loading. The transverse strain has almost increased by twofold after application of shear stress because of the contribution of shear coupling coefficient, \( \eta_{si} \) in addition to the normal strain as shown in Fig. 4.a. Finally, the orientation-dependent strains in each lamella are significantly different from those experimentally
measured by Fujita et al., because the shear loading was not included in their experimental investigation [19]. Additionally, the two-dimensional model presented herein must be improved to better predict the 3-dimensional motions, nonetheless the promise of representing the annulus as composite of collagen fibers embedded in a compliant matrix proved to be reliable in predicting basic research measurements. Ongoing research in our group is exploiting the other IVD constituents.

5 Conclusions

In conclusion, the physical significance of the fiber orientation in the annulus fibrosus has been elucidated by mechanics of fiber-reinforced polymer matrix composite materials, where the transformation equations are used to predict the material properties of a single lamella in the x- and y-direction. It is important to note the aforementioned equations have been used extensively in the aerospace industry for the design and analysis of complex composite structures. Here, we recalled these equations in the sense of reverse engineering, where the predicted properties will reveal the connotations of the natural annulus composition. This in turn can be used to design robust biologically-inspired total disc displacement devices. While the model’s predictions were in good agreement with previously reported data, there are two important limitations that must be noted. First, the model does not account for any nonlinear mechanical behavior (e.g., no hyper-elasticity), nor it accounts for the time-dependent behavior (viscoelasticity is also absent). Second, the interaction between any adjacent lamellae is not included in the presented model. Thus, no conclusions can be made about the inter-lamella stresses.

In this study, the elastic moduli of a single lamella in x- and y-direction were found to have comparable values and it was in good agreement with experimentally reported results in the literature. The shear modulus was found to be maximum at 45°, which is required to minimize the shear deformation in the lamella adjacent to the nucleus pulposus. Additionally, the failure strains were calculated using orthotropic lamina constitutive relationship in each lamella based on the fiber orientation and common loading scenarios. The experimentally reported strain tends to agree with strains calculated using composite mechanics. In general, the discrepancy between the calculated and measured results are due to the limitation of the experimental techniques used to measure the properties as well as negligence of the effect of inter-laminar stresses in the theoretical models. Nonetheless, the outcomes of our research substantiate the necessity for the composite nature of the annulus fibrosus material. Finally, composite mechanics show a good explanation for the high stress and strain on the lateral side of the annulus fibrosus, which may be one cause for the high appearance of herniated intervertebral discs on the lateral side. The outcomes of this research can be used to design superior synthetic annuls fibrosus than their counterparts in existing total disc replacement technologies.

References


