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Biomechanical analysis of functionally graded biomaterial disc in terms of motion and stress distribution in lumbar spine

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ABSTRACT

In recent decades, the development of new biomaterials for medical applications has been one of the challenging tasks for biomaterial scientists. Functionally graded biomaterials (FGBM) have been receiving an increasing attention due to their unique advantage, being able to satisfy the requirements of both mechanical and biocompatibility properties simultaneously. This paper evaluates the motion range and stress distribution of FGBM and non-FGBM artificial discs in response to different loading conditions i.e. compression, bending moment and torsion. In order to ensure the accuracy of analytical solution, the numerical solution was performed using finite element method and good agreement was found between the analytical and finite element results. In addition, the experimental data reported in the previous literature were used to predict the optimal model of artificial FGBM disc using the proposed analytical solution. The results of this study suggest that FGBM parameters can play an important role in achieving the goal of mechanical function optimization.

1. Introduction

Low back pain is one of the most common spine diseases which may cause different kinds of aches in patients. Disc degeneration is one of the major causes of lower back pain which is an inevitable natural procedure of ageing and appears as a result of changes in the structure and essence of the disc (Adams, Burton, Dolan, & Bogduk, 2007; Zhang & Teo, 2008). In this phenomenon, disc loses its flexibility and functionality which affects the function of other segmental structures. Therefore, many efforts have been devoted on studies related to the relationships between degeneration and motion range of intervertebral disc (Huang et al., 2006; Rohlmann, Zander, Schmidt, Wilke, & Bergmann, 2006; Tanaka et al., 2001).

Surgical treatment for lower back pain is mainly divided into fusion and disc replacement branches. Fusion and artificial disc replacement will be used for severe cases that fusion procedure is more prevalent surgical technique in the procedure of treating low back pain in relation to degenerative disc disease. Spinal fusion is recognized to result in some losses in motion, stiffness increment, and may even leads to the process of adjacent level degeneration (Bastian, Lange, Knop, Tusch, & Blauth, 2001; Bono & Lee, 2004; Kumar, Jacquot, & Hall, 2001). Clinical studies have reported the incidence of complications following arthrodesis or fusion in range of 6% to 58% (Chen, Zhong, Chen, Chen, & Hung, 2009; Kuslich et al., 2000; Rahm & Hall, 1996). On the other hand, it is believed that total disc replacement, as an alternative surgical treatment for degenerative disc

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Nomenclature

Variable	definition
a	inner radius
b	outer radius
$E\ (r)$	elasticity modulus dependent on r
E_0, E_1, E_{out}	inner, middle and outer layers elasticity modulus
E_n, E_a	nucleus and annulus elasticity modulus
F, F_n, F_a	total, nucleus and annulus axial load
$G\ (r)$	shear modulus dependent on r
G_0, G_1, G_{out}	inner, middle and outer layers shear modulus
G_n, G_a	nucleus and annulus shear modulus
I_n, I_a, I_{Total}	nucleus, annulus and total moment of inertia
J_n, J_a, J_{Total}	nucleus, annulus and total polar moment of inertia
L	length
M	bending moment
n, n_1, n_2	material parameters
$n_n n_a$	ratio of elasticity modulus of nucleus and annulus
r	radial coordinate
T, T_n, T_a	total, nucleus and annulus torsion
u_z, u_r	axial and radial displacement
$u_{z,n}$, $u_{z,a}$	axial displacement of nucleus and annulus
$v\ (z)$	elastic curve dependent on z
y	distance from the neutral axis
z	longitudinal axis
$\alpha(z)$	slope dependent on z
β, β_1, β_2	material parameters
ε_z, ε_r	axial and radial strains
$\varepsilon_{z,n}$, $\varepsilon_{z,a}$	axial strains of nucleus and annulus
φ	angle of twist
$\gamma_{r\theta}$	shear strain
$\upsilon(r)$	Poisson's ratio dependent on r
v_0, v_1, v_{out}	inner, middle and outer layers Poisson's ratio
v_n, v_a	Poisson's ratio of nucleus and annulus
ρ	radius of curvature
σ_z	normal stress
$\sigma_{z,n}$, $\sigma_{z,a}$	normal stresses of nucleus and annulus
$\tau_{r\theta}$	shear stress
$\tau_{r\theta,n}$, $\tau_{r\theta,a}$	shear stresses of nucleus and annulus

disease, can maintain the restoring and motion of the normal kinematics of the spine (Galbusera et al., 2008; Wang, Zhang, Sadeghipour, & Baran, 2013). In other words, an artificial disc can bring the ability of preserving motion and performance, similar to normal discs. The normal intervertebral disc can supply the compressive load transfer between two adjacent vertebrae and the result would be the intervertebral mobility and flexibility at the same time. Besides the flexibility and mobility of spinal disc, the stress distribution on disc is also important due to the point that intervertebral discs have a lower stiffness based on the structural nature of them. Hence, studies of stress distribution as mechanical performance of intervertebral discs have been carried out in vivo (Adams, McNally, & Dolan, 1996; Gay et al., 2008) and in vitro (Adams & Dolan, 2005; Green, Allvey, & Adams, 1994). Also, researches conducted on human spine illustrate that various parameters such as posture (Adams, Freeman, Morrison, Nelson, & Dolan, 2000; Edwards et al., 2001; Steffen, Baramki, Rubin, Antoniou, & Aebi, 1998), spinal load (McNally & Adams, 1992; Ranu, 1990), muscle force (Wilke, Krischak, & Claes, 1996; Wilke, Wolf, Claes, Arand, & Wiesend, 1996) and time (Adams et al., 1996; McMillan, Garbutt, & Adams, 1996) are significant parameters, influencing the stress distribution within the intervertebral disc.

In terms of anatomy, the intervertebral disc consists of annulus ground substance and nucleus pulposus, which embeds collagen fibers in the ground substance. The arrangement of the collagen fibers in the annulus fibrosus is optimal to bearing the stresses in response to different loading conditions. Many researchers reported that in the radial direction of disc, there are a certain number of fiber layers which mechanical properties of them, such as elasticity Modulus, increase from the innermost layer to the outermost one (Chen et al., 2009; Lee et al., 2004; Polikeit, Ferguson, Nolte, & Orr, 2003; Shirazi-Adl, Ahmed, & Shrivastava, 1986a; White & Panjabi, 1990). These variations in the mechanical properties of disc attracted the attention of some researchers to functionally graded biomaterials (FGBM). A functionally graded biomaterial is a nonhomogeneous biomaterial which its properties such as elasticity modulus, Poisson's ratio, mass density and thermal