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STRUCTURE OF THE HUMAN INTERVERTEBRAL DISC MAXIMIZES ITS STIFFNESS
STRUKTURA LIDSKÉ MEZIOBRATLOVÉ PLOTÉNKY MAXIMALIZUJE JEJÍ TUHOST

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Mathematical model of the human intervertebral disc was developed. The annulus fibrosus was modelled as a multilayer composite ply, while the nucleus pulposus was taken to behave hydrostatically. Using the optimization approach the design of the nucleus pulposus that maximizes the stiffness of intervertebral disc was determined. It was shown that the theoretically obtained structure is in almost perfect accordance with the physiological structure of the disc.

Keywords *intervertebral disc, optimization, composite tube*

Klíčová slova *meziobratlová ploténka, optimalizace, vrstevnatá trubka*

Introduction

The lower part of the spine, the lumbar spine, provides support for the upper body and protects the spinal cord [1]. The bony structures of the lumbar spine, vertebrae, are separated from each other by the intervertebral discs. Intervertebral discs softens impacts caused by the movement of the body and absorb the stress and strain transmitted to the vertebral column. The intervertebral disc is a structure composed of the annulus fibrosus, the nucleus pulposus and the end plates [1]. The annulus fibrosus is a collagen-fibre composite structure surrounding the nucleus pulposus. The annulus fibrosus consists of 10-20 sheets of collagen, called lamellae, tightly packed together in a circumferential fashion around the perifery of the disc [1]. Each lamella of the annulus fibrosus consists of the collagen fibres arranged in parallel [2]. They pass obliquely from one vertebral body to the next, at an angle about 60^{o} to the sagittal plane. However, as a rule, the fibres in each successive lamella are oriented in opposite sense, with one layer inclined to the left, the next layer inclined to the right and so on. While packed tightly together, these lamellae are stiff and can sustain considerably compression loads. Nevertheless, the annulus fibrosus is sufficiently pliable so that it can deform and thereby enables bending movement between the vertebral bodies. If it is buckled it loses its original stiffness which results in its lower bearing

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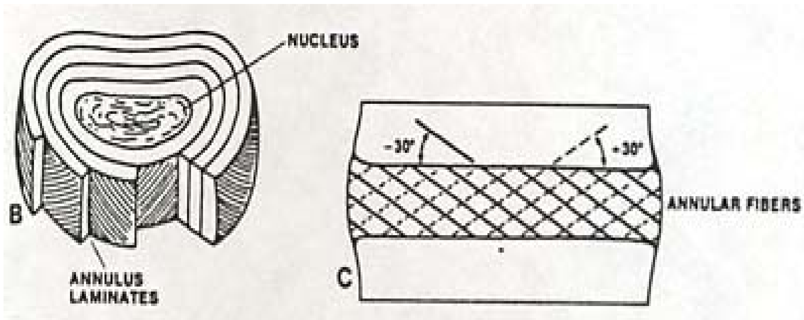
capacity. To prevent this, the annulus fibrosus requires the second component of the intervertebral disc - the nucleus pulposus.



Nucleus pulposus is the inner gel-like (proteoglycan-laden gel), highly hydrated core. The gel-like nature of the nucleus pulposus, constrained by the annulus, ensures its high water content and cushioning properties [1]. When compressed, this gel-like structure expands in the radial direction, braces the nucleus fibrosus from inside, thereby preventing it from buckling inwards and losing its stiffness.

The human intervertebral disc presents a composite-like part which structure certainly influences its function. This study was intended to design an anisotropic model of the human intervertebral spine and to test whether a structure of the disk, predicted theoretically to be an optimum one, corresponds to its physiological structure.

Mathematical model of the human intervertebral disc

The intervertebral disc was modelled as multilayer laminate tube. Each layer was considered orthotropic, the ply thickness was taken to be negligible with respect to the radius of the tube, and no buckling was considered. The mechanical properties of the composite were defined by its moduli of elasticity for the tube major a minor directions, and by the shear modulus of elasticity (E_1,E_2,G, respectively). Using the generalised Hook's law for the laminate ply, the constitutive laws for each ply were derived. Mechanical properties of each ply can be derived as a function of the winding angle α (between the fibres and the longitudinal axis of a ply). The derivation of the mathematical model extends the range of this article and has been already published [3]. Using the superposition method, the properties of a multilayer tube can be derived. The mechanical properties of the whole tube hence can be described by a set of values of angles $\alpha_1,...,\alpha_N$, where N is the number of layers and corresponds to the winding angle of the i-th layer. In our model, five layers were used (N=5) to form the multilayer tube.

The intervertebral disc loading

Based on the survey of literature we have found following types and magnitudes for load of the intervertebral disc.

Axial force acting on the intervertebral disc has a value of 8000 N, approximately [2]. The axial force is borne by nucleus pulposus and annulus fibrosus. The compressive load of the annulus can be estimated if standard dimensions of the intervertebral disc (the lateral diameter of 50 mm, the saggital diameter of 35 mm) are taken into account, i.e.,

annulus compressive load [N] = axial load [N] - 180.6 * hydrostatic press in nucleus [MPa]

In our calculations, the magnitude of the axial force transmitted through the hip joint was estimated to be 6000 N.

Shearing force can be neglected, because the most of the shearing force is transmitted through the posterior element of the intervertebral connections (zygapophysial joints).

Internal pressure of the nucleus pulposus that prevents buckling of the annulus fibrosus was determined using the invasive measurements by an instrumented needle [1]. The following relation was found between the compressive load and the hydrostatic stress in the nucleus, i.e.,

hydrostatic stress in nucleus [MPa] = 1.5 * axial compression [kN]

Bending moment. A typical bending moment, acting in the intervertebral disc when walking, was estimated to be 19.4 Nm [2]. According to the theory of elasticity, the bending moment causes compression of the anterior part of the nucleus fibrosus and tension of the posterior part of the annulus fibrosus. Therefore, the bending moment, acting in the posterior part of the annulus fibrosus, can be modelled by an additional axial force. Its magnitude was estimated from the beams theory to be 4000 N.

Torque is small, because in the lumbar spine, the angle of twist between adjacent elements, is limited by the zygapophysial joints [1].

Optimisation criterion

It is widely accepted that structures in the human body are optimised to sustain mechanical load. The bone is a typical example of the relationship between its structure and function. Unfortunately, we do not know a priori a criterion according which the structure of the intervertebral disc is to be optimised. Therefore, we chose a simple criterion stating that an optimum design of the intervertebral disc maximizes its stiffness [3].

The optimisation algorithm is a mathematical approach searching for an optimum design of the intervertebral disc ($\alpha_1,...,\alpha_N$) for a specific load. The optimum design is defined as a design yielding the maximum stiffness of the disc. In our work we applied the nonlinear programming optimisation.

Results and Conclusions

For the specific load and anulus fibrosus with five layers (N=5), the optimum solution is: $\alpha_1=-64.93^\circ$, $\alpha_2=64.71^\circ$, $\alpha_3=-64.49^\circ$, $\alpha_4=64.28^\circ$, $\alpha_5=-64.07^\circ$. The main conclusions are:

- The alternate signs indicate that the optimum design of the intervertebral disc has alternate directions of the collagen bundles, which is in a good accordance with reality observed
- As well as the angle of the fibres (approximately 64˚) correspond well to observed values.

From our results it can be concluded that the human intervertebral disc has a structure which maximize its stiffness with respect to its loading

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