Standing Up Right

ANSYS Multiphysics sheds light on the wonders of the human spine and how to fix it.

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The human spine is a wonder of engineering work, one that is heavily used in daily activities. An important part of it, the intervertebral disc (IVD), is one of the most sophisticated suspension and shock absorption systems ever found. When disorders arise, back pain quickly can become a nightmare. The National Technical University of Athens (NTUA) in Greece conducted a study using ANSYS Multiphysics software that revealed some secrets of how this precious structure works, as well as ways to fix it efficiently when it malfunctions.

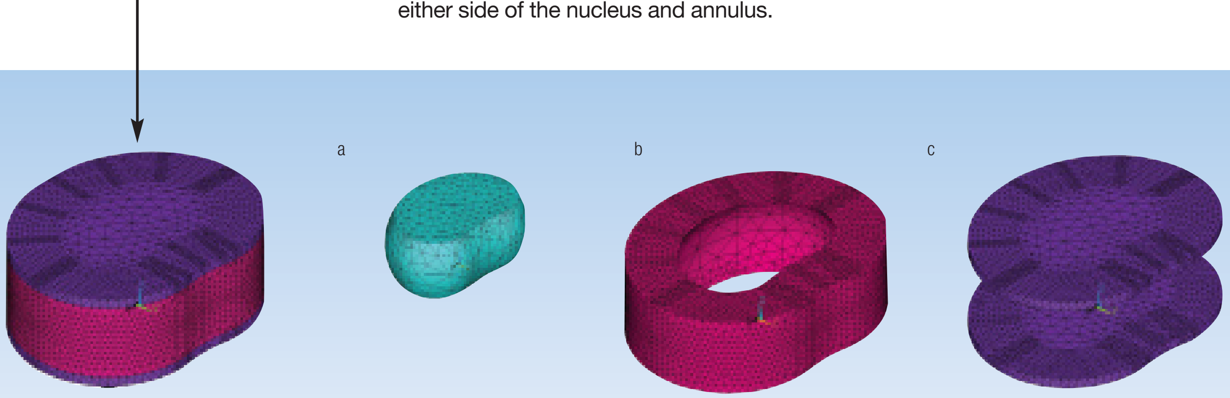
The spine's intervertebral disc is exposed to a combination of compression, bending and torsion stresses.

Simulating the Intervertebral Disc

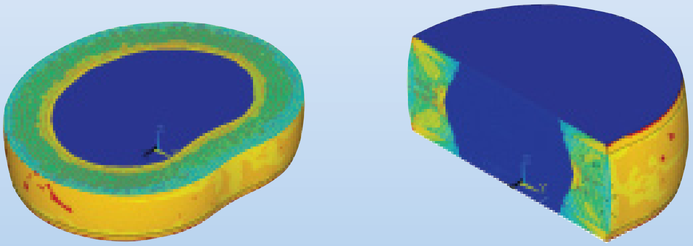
The IVD is located between the vertebrae in the spine. In performing daily activities, it acts as a cushion and therefore is exposed to a combination of compression, bending and torsion stresses. Each disc consists of the nucleus pulposus, a gel-like inner portion of the disc; the annulus fibrosus, the outer portion made of about 20 lamellae of coarse collagen fibers; and the two cartilaginous endplates, composed of hyaline cartilage, located on either side of the nucleus and annulus.

The IVD simulation model comprised four distinct volumes corresponding to the disc's regions: The nucleus was modeled as a nonlinear viscoelastic material in a kidney-like cross section; the two cartilaginous vertebral endplates were considered linear elastic bodies; and the annulus surrounding the nucleus was simulated as dual laminated shell elements whose outer surfaces were viscoelastic in nature. The study analyzed various scenarios in order to determine the contribution of each section of the IVD to the viscous character of the entire structure.

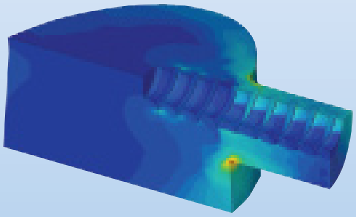
The numerical model revealed that the maximum stresses appeared in the fibers of the intermediate volumes of the annulus, in the vicinities of the endplates. The nucleus was almost stress-free, as expected due to its gel-like nature. The NTUA study also investigated the behavior of the IVD during daily activities; the results found that the reduction of disc height related to a person's 24-hour daily cycle was in very good agreement with the respective experimental data by Tyrell et al (L3–L4 discs) [1].



The numerical model of the intervertebral disc: a) nucleus pulposus, b) annulus fibrosus and c) cartilaginous vertebral endplates



The von Mises stress distribution through the center of the disc horizontally (left) and at the point of minimum vertical cross-sectional area (right)



The distribution of the Mises equivalent stress in a typical vertebra for a pull-out displacement of 0.02 mm

Studying the Surgical Remedy

Spinal stabilization using pedicle screws and rods (or plates) is one of the most common invasive treatments for spinal disorders and injuries. In this procedure, the surgical team implants screws posteriorly into a number of vertebrae and bolts them to a rod or plate. This assembly actively fixes the vertebra in place, with respect to each other, and thus stabilizes that section of the spine. After such a procedure, some serious problems can still exist. Pain in the IVD adjacent to the fixed vertebrae can occur due to failure of the spinal instrumentation, from either a fracture in structural elements or a loosening of the screws. Experimental and clinical studies alone cannot provide a complete view of the mechanical behavior of such complex structures. Numerical simulations introduce a unique tool for the thorough and parametric study of such systems.

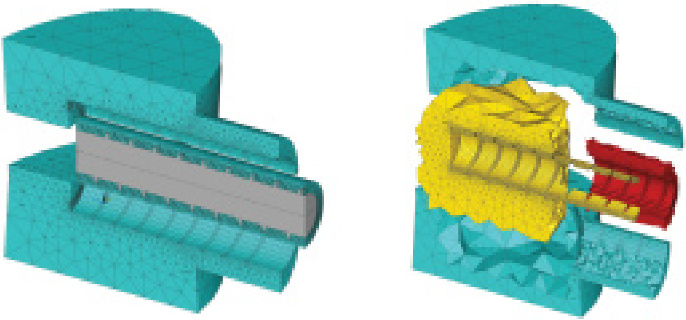
From the moment a pedicle screw is implanted into the vertebra, the bone begins to regrow around the screw. This regrowth leads to the eventual complete unification of the bone and the implant, which occurs about two years postoperatively. A fundamental requirement for the success of this procedure is the stability of the screw's fit into the bone. NTUA used mechanical simulation to investigate the influence of the vertebra structure and screw specifications — such as depth of implantation, pitch and inclination of the thread — on the value of the force required to loosen the screw from the spine.

The parametric study assumed that the vertebra consisted of cortical, subcortical and cancellous bone as suggested by measurements of bone mineral density of typical human lumbar vertebrae. The simulations estimated the force required to produce a pull-out displacement of 0.02 mm, the stress distribution onto the bone, and the contact pressure on the bone–screw interface. The results indicated that the pull-out resistance could be amplified significantly by ensuring that the screw was anchored into the regions of stronger materials located near the cortical shell. Furthermore, the parameter found to have the strongest influence on the pull-out force was the screw pitch. For pitch values varying from 2 to 5 mm, the pull-out force increased linearly by approximately 30 percent. The variation of the screw depth and the thread inclination had limited impact on the pull-out force. A comparison of the numerical results with the experimental results found them to be in very good agreement, within the tolerance of experimental error.

The main advantage of the numerical models lies in the accurate simulation of both the structure and the shape of the various portions of the biological disc or vertebra as well as of the constitutive behavior of the different materials. In order to further improve the accuracy of these numerical analyses, researchers must develop studies using models of increasing sophistication adapted to specific groups of people with morphology and properties varying with age, sex, type of activities, degenerations and other factors. ■

References

[1] Tyrell, A; Reilly, T; Troup, J., Circadian Variation in Stature and the Effects of Spinal Loading, *Spine*, 1985, 10(2), pp. 161-164.



The two phases of model construction: (left) the screw and surrounding bone implanted into the vertebra and (right) the regions of the vertebra (yellow: cancellous bone; red: subcortical bone; blue: cortical shell)