Effects of intervertebral disk behavior on the load distribution and fracture risk of the vertebral body

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EFFECTS OF INTERVERTEBRAL DISK BEHAVIOR ON THE LOAD DISTRIBUTION AND FRACTURE RISK OF THE VERTEBRAL BODY

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Abstract: Osteoporosis is characterized by low bone mass and an increased fracture risk. Measurements of bone mass alone, however, will not provide adequate information about the fracture risk, because the trabecular architecture or spatial distribution of the bone density has an important effect on the strength. We have developed a method to estimate the tissue strength of trabecular bone directly from three dimensionaly reconstructed axial CT-scans in combination with a finite element model. The method provides the stress distribution throughout the structure which can be used as a measure for the strength and fracture risk of the bone. A matter of concern with this method are the external loading conditions placed on the vertebral body, which might be strongly affected by the behavior of the intervertebral disk. In this study we have tested the effects of various intervertebral disk models on the load distribution through the vertebral body.

A three dimensional model of a vertebral body was developed based on serial axial CT-scans which were converted to a 3-D Finite Element model. The model was augmented with intervertebral disks at the upper and lower endplates. The disks contained a nucleus and an annulus region. The properties of the nucleus were varied to study the effects of a healthy disk with a functional nucleus pulposus and a degenerated disk with virtually no load bearing of the nucleus pulposus. In all cases the cortical shell carried most of the load. For the model with the load bearing nucleus the cortical shell transferred appr. twice as much load than the cancellous bone. With an external load of 2000 N, the stresses in the cortex in the mid-transverse cross-section of the examined_ vertebral body were plm. 30 MPa for the load bearing nucleus model and plm. 40 MPa for the degenerated nucleus model. In both cases this value is high relative to the failure stress, indicating a high fracture risk for the examined vertebral body. The methods introduced in this study can be used to estimate load transfer through the vertebral body directly from CT-scans and, thereby, assessing the fracture risk of the bone and thus the status of osteoporosis.

Introduction: Osteoporosis can be characterized by an increased bone fracture risk predominantly occurring in trabecular bone regions such as the spine (vertebral bodies) and the proximal femur. Assessment of osteoporosis is usually done by means of a Bone Mineral Density (BMD) measurement. Although it is known that BMD correllates with fracture risk, BMD measurements omit the three dimensional topology of the trabecular architecture which also has an important effect on the mechanical behavior of trabecular bone. Therefore, grading of the fracture risk needs more refined measurements, taking mechanical aspects and the three dimensional distribution of the trabecular bone into account. It can be accomplished with a 3-D finite element model where the attenuation levels from CT imaging is transferred into a 3D distribution of material properties (elastic moduli)[2,3,4]. This provides information about the stresses and potential deformations in the entire structure. However, the load distribution through the spinal segment depends on the behavior of the entire functional spinal unit, including the intervertebral disk. Thus, an important question for the evaluation of fracture risk of a vertebral body is how mechanical behavior of the intervertebral disk affects the load distribution and failure risk (maximal stress) in the vertebral body. A healthy disk is very hydrophilic and behaves as a visco-elastic material. Therefore, the effective stiffness is time dependent and the material behaves relatively stiff for a short term response. After a longer loading period, water is expressed and the disk becomes more flexible. The central (nucleus) region contains more water than the peripheral (annulus fibrosus) region. Thus, the ratio between the effective stiffnesses of the annulus and nucleus is greater than 1 for short term and less than 1 for a long term response. The nucleus region of a degenerated disk is dehydrated and the stiffness of this region is considerably lower. The mechanical behavior of the disk can potentially affect the load distribution through the vertebral body and might, thereby, influence the fracture risk.

The aim of this study was to assess the load transfer and fracture risk in a vertebral body using various alternative mechanical characteristics of the intervertebral disk.

Methods: A human cadaver specimen of a lumbar vertebral body (L 3) was scanned in continuous axial slices of 1 mm thickness on a CT scanner (Somatom Plus S, Siemens AG). The resolution was 182 x 182 microns per pixel. In a computer model the bone was 3D reconstructed and a Finite Element Model with brick elements of 910*910*1000 microns was produced. The apparent density assigned to every element in the model was linearly related to the CT attenuation level of the CT pixels within the element (25 pixels in this case). The elastic modulus of every element was dependent on the local density value and taken in accordance with Carter and Hayes[5]: $E=2610\rho^3$, where E is the elastic modulus in MPa and ρ the apparent bone density in g/cm^3.

An artificial intervertebral disk was placed at the upper and lower endplate portions. Both disks had the same size brick elements. The intervertebral disks contained two types of material, representing the nucleus pulposus and the annulus fibrosus. Both were modeled as linear elastic materials. The Young's modulus of the annulus fibrosus was fixed at E=10 MPa and three moduli for the nucleus were tested: E=1 MPa, E=10 MPa and E=100 MPa. A load of 2000 N was applied by a uniform displacement in the longitudinal direction of the top plane relative to the bottom plane. Altogether, the model consisted of 100.867 brick elements (Figure 1) and could be adequately analysed using the Finite Element code developed by Van Rietbergen et al.[6,7,8], based on an element by element, conjugate gradient iterative solver.

Results: The stress, strain, and strain energy distributions throughout the vertebral body were evaluated in a three part analysis. The analyses resulted in relatively high loading of the vertebral body's cortical shell, in particular, in the mid-transverse sections as seen in the coronal plane. The model

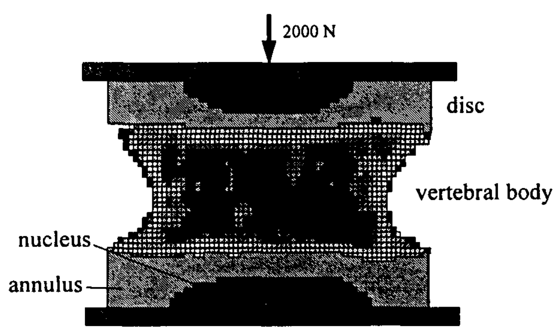

Figure 1 Coronal plane of finite element model. Density distribution in the vertebral body as indicated (white = high dense, black = low dense). The annulus fibrosus had a fixed modulus of 10 MPa and the modulus of the nucleus pulposus was varied (1, 10 and 100 MPa)

with the low modulus for the nucleus pulposus and the model with the uniform disk modulus behaved almost the same. The maximal stress levels in the cortical shell and the stress distribution throughout the segment were very similar (Figure 2). At the region of the endplate, the model with the stiff nucleus resulted in a higher stress level in the central

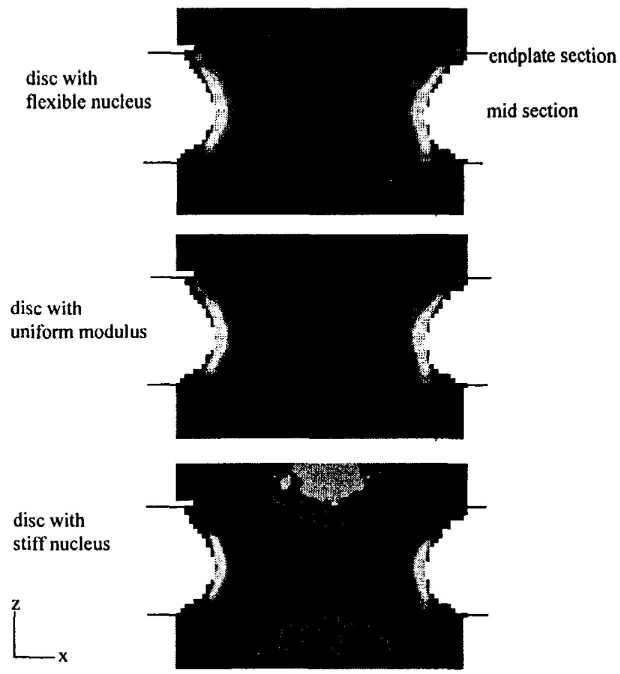

Figure 2 *Load distribution throughout the vertebral body (mid-coronal section) in the three models indicated by the normal stress in the longitudinal direction (σ_{zz}). White indicates high stress and black indicates low stress. The maximal stress occurs in the cortex of the mid- transverse cross-section and the magnitude was appr. 30 MPa in the model with the stiff nucleus and appr. 40 MPa in the model with the flexible nucleus or the uniform disk.*

region of the endplate, but this effect diminished completely in the region of the midsection of the vertebral body, where again a high proportion of the load was transferred through the cortical shell (Fig. 2 and 3).

We have determined the ratio of the total load (integrated longitudinal stress) through the cortex (σ_{co}) relative to the load through the spongiosa (σ_{sp}) for the mid-transverse section of the vertebral body at the mid-coronal level, see Table I. This ratio was approximately the same in the low modulus nucleus model and the uniform disk model, but was lower in the stiff nucleus model. However, the latter model still transfers about twice as much load through the cortical shell than through the spongiosa. This indicates that support of the trabecular bone inside the vertebral body is relatively low in all cases. In fact, the results show that whatever loading is placed on the vertebra, it will always result in predominantly cortical load transfer in the center axial region as seen in the mid-coronal section of the vertebra (Fig. 3).

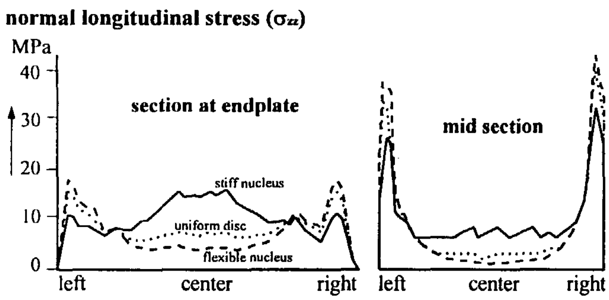

Figure 3 From the mid-coronal slice of the model of the vertebral body transverse cross-sections were taken at the location of upper endplate and the mid-section (see Fig. 2) and the normal stresses in the longitudinal direction were plotted. The model with the stiff nucleus gave elevated stresses in the central region of the endplate (left). At the mid-section all three analyses showed peak stresses in the cortical shell (right).

$E_{annulus}$ (Mpa)	1 (flexible)	10 (uniform)	100 (stiff)
ratio: σ_{co}/σ_{sp}	5.5	5.0	1.96

Table I: Ratio of cortical load (integrated stress given in N) vs spongious load (in N) in the mid-transverse cross-sectional region of the three models.

Discussion: Although the disk clearly consists of viscous material containing more phases (water and solid fibers), we have modeled it as a linear elastic material. Instead of a true time dependent behavior, we have modeled the *effective* modulus of elasticity of the disk materials which characterizes the effective elastic response of a healthy disk or a degenerated disk at a specific time after loading. The model with the stiff nucleus probably overestimates the actual situation since the annulus fibrosus also contains water. Hence, a stiffness ratio of 1:10 (10 Mpa vs. 100 Mpa) might exaggerate the actual situation. In that sense it is surprising that the stiff nucleus model transfers most of the load through the cortical shell. This must be due to the bone density distribution inside the vertebral body. The three dimensional morphology and subsequent stiffness distribution is such that a load which is more or less uniform at the endplates (Fig. 3, left, stiff nucleus), is directed to the cortical shell, resulting in a peak stress in the cortex at the mid-transverse cross-section (Fig. 3, right). Thus, the vertebral body behaves more or less as a box with rigid edges. The model with virtually no nucleus (E=1 MPa) behaves similar to the uniform disk model, both having appr. a peak stress of 40 MPa in the cortical shell (Fig. 2 and 3). This indicates that the load distribution in the examined vertebral body is rather insensitive to disk degeneration. We speculate that this is due to the fact that the vertebra was from an old person with probably degenerated disks and the bone probably was adapted to this situation. Therefore, the cortical shell and the endplates appear thick in the examined vertebral body (Fig. 1). The stress peaks (Fig. 2 and Fig. 3, right) are amplified by the concave shape of the cortical shell, which led to bending as shown in the mid coronal cross-section (Fig. 1).

We have developed a method where we can analyse the mechanical status of a vertebral body directly from 3D CT reconstructions. Several quantities related to the stress distribution and overall strength of the structure can be evaluated. The examined vertebral body seems to be adapted to a situation with a high loading through the cortical shell. Although we have chosen extreme values for the effective stiffness of the disk, the differences between the maximal stresses found in the cortical shell were relatively moderate (30 MPa vs. 40 MPa, see Fig. 3). These values are high in the context of the applied loading of 2000 N and it can be expected that the examined vertebral body is at risk for failure. In order to make a better judgement of the present findings, it is required that more vertebral bodies from various patients and controls are being analysed. The method and the evaluation prospects as demonstrated in this study may improve radiological evaluation of osteoporotic suspects.

References:

1. Stewart et al., Br. J. Radiol. 68:614-620, 1996.
2. Faulkner et al., Radiology. 179(3): 669-74, 1991
3. Keyak et al. J. Biomed. Eng. 12:389-397, 1990
4. Huiskes et al. Clin. Orthop. 274: 124-134, 1992
5. Carter and Hayes, J.Bone Jt. Surg., 59-A:954-962, year?
6. Van Rietbergen et al., J Biomech 28:69-81, year?
7. Van Rietbergen et al. J. Num. Meth. Eng. 39:2743-2767, 1996.
8. Weinans and Sumner, in "Bone Research in Biomechanics" ed. Lowet, Ruegsegger, Weinans, Meunier, p. 3-16, IOS press, Amsterdam, 1997.

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