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ACCURATE FINITE ELEMENT MODEL OF HUMAN VERTEBRA

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ABSTRACT
The most frequent occupational deseases are ones regarding different disorders of spine caused by inadequate design solutions of operator’s seat, vibration absorbers etc. Ergonomic analysis of designe solutions of machine and its subsystems, conducted when design is still going on, could prevent mentioned consequencies of inadequate design solutions. This analysis is based on results retreived from finite element analysis of human spine in different postures and different working regimes. Finite element model of human spine involves finite element models of vertebrae, ligaments, intervertebral disks etc. This paper deals with development of an accurate finite element model of human vertebra. Geometric and mechanical properties of finite element model of human vertebra are obtained by quantitative computed tomography. Quantitative computed tomography is state of the art in finite element modeling of parts of human skeleton.
Keywords: finite element model, vertebra, ergonomics

1. INTRODUCTION
Low back disorders represent the most common and most costly musculoskeletal problem. Up to 80% of adults will eventually experience back pain at some time during their life and 4÷5% of the population has an acute low back episode every year. Much of this low back disorders are associated with occupational factors and significantly increases workers compensation costs. For example, low back disorders account for 16÷19% of all workers compensation claims, but 33÷41% of the total cost of all work compensation costs in the USA. Estimates of annual costs for low back disorders have been as high as 100 billion US$ [7].

Epidemiologic methods have been used to identify occupationally related physical risk factors in a variety of industries. Most epidemiologic studies have investigated the risk contribution of: (1) heavy physical work, (2) lifting and forceful movements, (3) bending and twisting, (4) whole-body vibration and (5) static work posture. Some critical reviews based on many of these studies have found strong evidence of low back disorders risk association for the lifting and forceful movements, bending and twisting, as well as the whole-body vibration. More moderate evidence or risk association was identified for heavy physical work and none evidence was identified for static work posture [7].

Ergonomic design of machine and its subsystems could prevent influence of physical risk factors on low back disorders. Adequate shape and position of operator's seat as well as adequate arrangements of controls on console could prevent operetor's awkward postures while machine operates and reduce bending and twisting of his spine. Choice of adequate characteristics of vibration absorbers could reduce load of operator's spine caused by whole-body vibrations. Therefore, ergonomic analysis of designe solutions of machine and its subsystems have to be conducted while design is still going on in order to prevent influence of physical risk factors on low back disorders. This analysis is based on results retreived from finite element analysis of spine in different postures and different working regimes. This paper is focused on development of an accurate finite element model of vertebra that represents a part of finite element model of spine.

2. METHODS

2.1. Object of finite element modeling

Spine is consisted of: seven cervical, twelve thoracic, five lumbar and one sacral vertebra. Low back disorders come from degenerative changes in lumbar spine, the most frequently caused by mechanical loading of spine. The most loaded part of lumbar spine is L_5 or fifth lumbar vertebra which is chosen as a representative vertebra for finite element modeling. A typical L_5 vertebra is shown in Figure 1.

Figure 1. Fifth lumbar vertebra

2.2. Research equipment

Equipment used for this research, CT scanner Aura 1.3, shown in Figure 2, is manufactured by Philips Medical Systems. Some characteristics of this CT scanner:

-x-ray energy [keV]: 100, 120, 130, 140
-slice thickness [mm]: 1, 2, 3, 5, 7, 10
-mA settings [mA]: from 15 to 50 each 5 mA
from 50 to 100 each 10 mA
-image resolution: 512x512.

CT scans are conducted in Clinical Center of Montenegro in Podgorica.

Figure 2. CT scanner Aura 1.3

2.3. Computed tomography

Computed tomography is widely accepted non-destructive method of examining the interiors of human body. Scanned human body is placed on the table inside a stationary ring with x-rays detectors and x-rays tube that rotates along the ring. To produce tomographic image, x-rays pass through human body along several different paths in several different directions, resulting in an image that displays differences in density at each of several thousands point in two-dimensional slice through the body. Each slice represents certain finite thickness, so by stacking up a series of contiguous equidistant slices, one can construct a continuous three-dimensional map of the density variations in the body that is expressed in terms of the linear attenuation coefficient. Tomographic images involve geometric data on scanned body and CT numbers of each image pixel. CT number or Hounsfield unit measures x-ray linear attenuation of human tissue inside three-dimensional pixel, so called voxel, whose third dimension is slice thickness. CT number is obtained by the following equation [3]:

$$HU = 1000 \cdot \left(\frac{\mu}{\mu_{H_2O}} - 1 \right) \tag{1}$$

in which μ is a linear attenuation coefficient of human tissue inside the voxel and μ_{H2O} is a linear attenuation coefficient of water.

CT scan of vertebra was taken on healthy middle-aged mail subject. This scan was taken on Aura 1.3 scanner (130 keV, 80 mA) with a pixel resolution of 0.5 mm/pixel, 512x512 pixels array, 1 mm slice thickness. Partial series of obtained CT images of vertebra is shown in Figure 3.

Figure 3. CT images of vertebra

A liquid potassium phosphate (K_2HPO_4) calibration phantom was used to establish the correlation between the CT number and bone mineral density of trabecular bone tissue ρ_{QCT} in g/cm^3 [2,3,6]. A few samples of calibration phantom corresponding to different bone mineral densities of trabecular bone tissue were scanned simultaneously with vertebra. Based on densities of calibration phantoms and equivalent CT numbers retrieved from CT scan data a linear correlation between the CT number and bone mineral density of trabecular bone tissue was established [8,9].

2.4. Finite element modeling

An anatomically correct three-dimensional geometric model of vertebra was created from the contours retrieved from CT images and meshed into 8-noded linear solid isoparametric finite elements. The vertebral shell and endplates from cortical bone tissue were generically modeled as an isotropic continuum with Poisson ratio of 0.3 and elastic modulus of 779 MPa [2], and a constant thickness of 0.35 mm based on the average thickness of the shell and endplates [10]. The trabecular centrum of vertebra was also modeled as an isotropic continuum with Poisson ratio of 0.2 [5] and elastic modulus assigned to finite elements that is based on the following regresion model [4]:

$$E = -34.7 + 3230 \cdot \rho_{QCT} \tag{2}$$

in which ρ_{QCT} [g/cm^3] is a bone mineral density and E [MPa] is an elastic modulus of trabecular bone.

3. RESULTS

3.1. Reconstruction of geometric properties

CT images were downloaded in DICOM image format and exported to DicomWorks 1.3.5 software in order to adjust image contrast and to extract contour of vertebra. Series of CT images with properly adjusted contrast were saved as a BMP files, and read into Mechanical Desktop software where the anatomically correct two-dimensional geometry of vertebral contours was created. Based on analysis of vertebral shape a boundary surface of vertebra was decomposed to a number of patches. A number of points laying on the edges of these patches were found on vertebral contours, and boundary curves of the patches were fitted to these points. Boundary curves were used to create all the patches of the geometric model of vertebra that is shown in Figure 4.

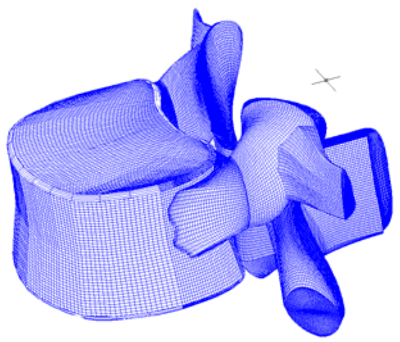

Figure 4. Geometric model of vertebra

3.2. Reconstruction of material properties

Quantitative CT measurement of bone mineral density of trabecular bone tissue ρ_{QCT} was conducted by means of a liquid K_2HPO_4 calibration phantom. K_2HPO_4 concentration of calibration phantom samples was under 300 mg/ml because above this concentration a linear relationship between CT numbers and bone mineral density of trabecular bone can not be expected [8,9]. Figure 5 shows an example of processing data retrieved from CT scan of calibration phantoms. The densities of calibration phantoms are plotted in relation to the CT number. A regresion line was fitted to seven calibration values and expressed by the following equation:

$$\rho_{QCT} = -0.0829 + 0.0026 \cdot HU \tag{3}$$

Correlation coefficient of this releationship was r=0.999.

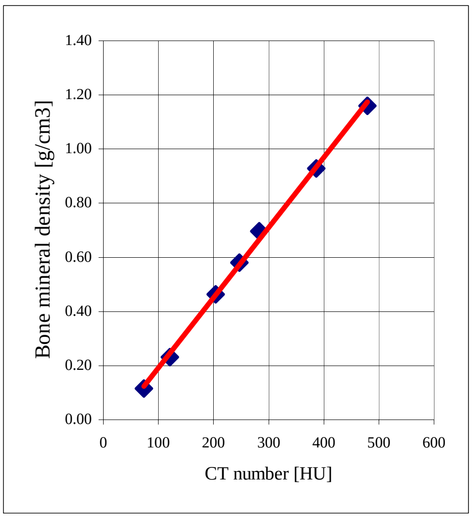

Figure 5. Correlation between the CT number and bone mineral density of trabecular bone

Geometric model of vertebra was saved as an IGES file, and read into ALGOR finite element softvare where the model was mashed into 8-noded linear solid isoparametric finite elements as it is shown in Figure 6. Programme, developed by the author of this paper, was used to identify the voxels belonging to each finite element or vice versa, regarding to finite element size and to assign elastic modulus of trabecular bone tissue determined after the equations (3) and (2). Reconstructed distribution of elastic modulus for one scanned vertebral slice is shown in Figure 7.

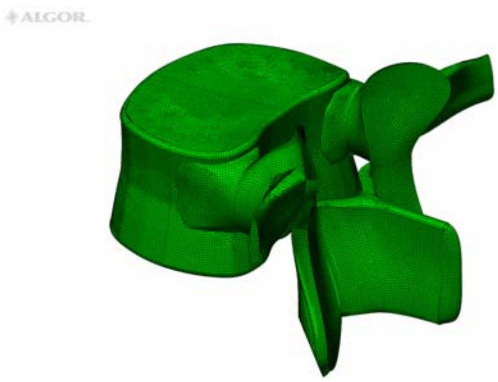

Figure 6. FE model of vertebra

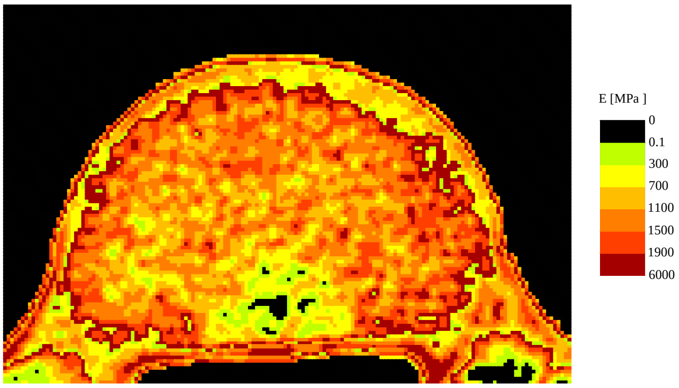

Figure 7. Distribution of elastic modulus

4. CONCLUSION

Introduced method for development of finite element model of human vertebra enables development of highly accurate finite element model regarding its geometric and material properties. Finite element models of human vertebrae developed in this way represent basic structure of finite element model of human spine that also involves finite element models of ligaments, muscles and intervertebral disks. This model is to provide data on stress and strain state of each spinal parts of machine operator in different postures and different working regimes of machine that are necessary for risk evaluation of influence of occupationally related physical factors on spinal disorders. Results of this evaluation represent basis for ergonomic design of machine.

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