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EXPERIMENTAL PROCEDURES FOR EVALUATION OF RELATIONSHIP BETWEEN MECHANICAL PROPERTIES OF CANCELLOUS BONE AND ITS APPARENT DENSITY

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Finite element models of parts of human skeletal system are nowadays constructed on basis of data obtained from Computed Tomography or Magnetic Resonance images. Material properties of cancellous bone have been found to be strongly dependent on apparent density of the tissue. Experimental procedures used for evaluation of mechanical properties of cancellous bone using small samples of cylindrical shape will be described and relationship between the apparent density and Young's modulus of elasticity as well as ultimate strength are proposed. Compressive and tensile specimens are used while for the strains are measured using an optical method utilizing CCD camera of high resolution.

Experimentální zjišťování mechanických vlastností spongiózní kosti pomocí malých vzorků a optické identifikace deformace na povrchu vzorku je předmětem tohoto příspěvku. Použité vzorky jsou tahové i tlakové vzorky malých rozměrů. Deformace na povrchu vzorku jsou měřeny optickou metodou vysokorychlostní CCD kamerou s vysokým rozlišením. Matematický vztah mezi hustotou kostní tkáně a materiálovými vlastnosti (Youngovým modulem pružnosti a napětím na mezi kluzu) je odvozen pro případ kvazistatického zatěžování.

Keywords *mechanical properties, cancellous bone, apparent density, computer tomography, Hounsfield units, optical identification*

Klíčová slova *materiálové vlastnosti spongiózní kosti, hustota tkáně, počítačová tomografie, Hounsfieldovy jednotky, optická identifikace*

Introduction

For the needs of finite element models constructed using medical imaging data, relationship between the mechanical properties of every element and apparent density of the tissue at the same location is needed. The geometry of an organ can be realistically modeled with the help of the same medical imaging data. Marching Cubes Algorithm is used to detect the surface of the bones, surface mesh decimation; shape optimization algorithms create the outer and inner surface of the bone using triangular mesh. The surface mesh is expanded into 3-D using Delaunay triangulation (tetrahedralization) and finally the shape of the tetrahedra is optimized for the FE analysis. The algorithms work in general for any organ and any medical imaging technique, but special emphasis has been given to construction of parts of the skeletal system. It is convenient to use CT images as the source data because the hard tissues are clearly distinguishable using the X-ray radiation.

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Apart from the problem of defining the geometry in finite element modeling of the living tissues here is a problem of material properties of the selected tissue. The medical imaging systems give us not only the information about the geometry, but also some information about the density of the represented tissue is given. This information is given by the attenuation of the radiation by the respective tissue and can be different for every imaged pixel. Apparent density of the tissue is dependent on the attenuation of the radiation used. It has been shown by several authors that material properties of the bone tissue are proportional to relative density and thus information about the apparent density extracted from the CT scans can be used for material properties assessment.

Methods

Fig.1 Compressive and tensile specimens with surface markers

Cylindrical samples of cancellous bone are obtained from fresh proximal porcine femurs. Prior the mechanical testing, every sample is scanned using Somatom Plus CT scanner to enable later three-dimensional reconstruction of FE models and assessment of spatial distribution of material density obtained directly from the CT scans in Hounsfield units. Specimens for compressive testing are 10 mm in diameter and of the same height and are drilled out using a slow-rotation micro-drill cooled with water and cut using a low-speed, water-cooled saw. The ends of the specimen are then machined using wet sandpaper with the specimen fixed in a special device ensuring that the ends remain perfectly parallel. The diameter of the tensile specimens is only 5 mm while their length varies between 20 and 40 mm. Cyanoacrylate adhesive or two-component epoxy is used to fix the ends of the specimen in metal tubes. Complete stress-strain relationships were obtained for each individual sample. The strains on the surface of the specimen are evaluated using an optical identification method and a fast CCD camera.

3 Results and conclusions

Mechanical testing of 44 samples from 38 porcine proximal femurs was used to evaluate material properties of cancellous bone. Both tensile and compressive specimens from the femoral neck regions of porcine bone were used in the experiments. The specimens were drilled in the direction aligned with the principal trabecular orientation.
The yield strain was found to be dependent both on the anatomic site and strain rate applied. Mean compressive yield strains ranged from 0.91 ± 0.09%; mean tensile yield strain in the same

region was found to be 0.61 ± 0.03%. The yield stresses were found to be less reliable (18.54 ± 6.30% in compression and 12.15 ± 2.80% in tension) as well as the moduli of elasticity (672 ± 110 MPa for compression and 602 ± 52 MPa for tension). From the experimental measurement of material properties of cancellous bone using the small samples and optical identification method it is clear, that:

- yield strains could be considered uniform within the region of proximal femur
- better correlation between the apparent density and mechanical properties is for the *tensile* loading; however the reason for this might be explained by better experimental set-up of the tensile tests
- *power-law relationship* between the yield stress and apparent density can be formulated both for compression and tension

Our results showed strong correlation between the yield stress and apparent density, which is consistent with the results of previous studies [1, 2] however, the yield strains were found to be of little higher values particularly in tension. The small distance between the markers on the specimen surface might cause this. Strains are thus evaluated using smaller base length and because the failure of the trabecular bone is of local nature, our optical measurement gives better results.

A least-square regression analysis was used to test this power-law fit between Young's modulus and effective density. It was found, that for small strain rates (0.05 s^{-1}) the Young's modulus of elasticity of cancellous bone of porcine proximal femurs can be expressed in terms of the effective density of the bone tissue as follows:

$$E = 2615\rho^{2}_{eff}$$

where ρ_{eff} is the effective density in [$g.cm^{-3}$], which can be computed from the apparent density (given in Hounsfield units) obtained directly from the CT scans. The relationship between these two densities has the form:

$$\rho_{eff} = 0.523HU + 1000$$

Ultimate stress of cancellous bone is determined from:

$$\sigma_{ult} = 38.2\rho_{eff}^{1.5}$$

Conclusion

Power-law relationship between the material properties of cancellous bone and its apparent density obtained from CT scans was proposed. The power law exponent in the relationship between the modulus of elasticity and apparent density (1) is same as determined by [3]. However, our relationship gives a bit higher values of the modulus in the region of proximal femur. On the other hand, stronger correlation was found between the apparent density and yield strain, which gives a good argument for the strain-based measurements of failure. The failure criteria for the cancellous bone should also be expressed in terms of strain rather than stress. More references about the stress-based or strain-based failure criteria for cancellous bone can be found e.g. in [4].

It should be stressed, that these results are valid only for small strain rates. For greater values the strain rate influences the response of the bone and the strain rate has to be taken into account. This has been a subject of several investigations (i.e. [5, 6]), but the results differ substantially. For the construction of finite element models of whole bones material properties based on apparent density values of individual elements appears to be the most suitable procedure to account for individual variations in bone structural properties. It has been shown that for small ranges of strain rate the material properties of cancellous bone are proportional to the apparent density of bone tissue and the strain rate to the power of 0.06 [6]. However, viscoelastic properties of cancellous bone with a correlation to apparent density for higher values of strain rate have not been described up to now. No correlation with bone density has been shown for tensile or torsional strength of cancellous bone or Poisson's ratio.

Using the described method we are able to assess the material properties of cancellous bone in relationship with the apparent density in Hounsfield units for both in compression and tension. This procedure is used to validate finite element models of whole bones used in our computational analyzes.

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