FEM-BASED ESTIMATION OF MECHANICAL STRENGTH OF HUMAN VERTEBRAE AS NEW INDICATOR OF BONE DISEASE AND FRACTURE

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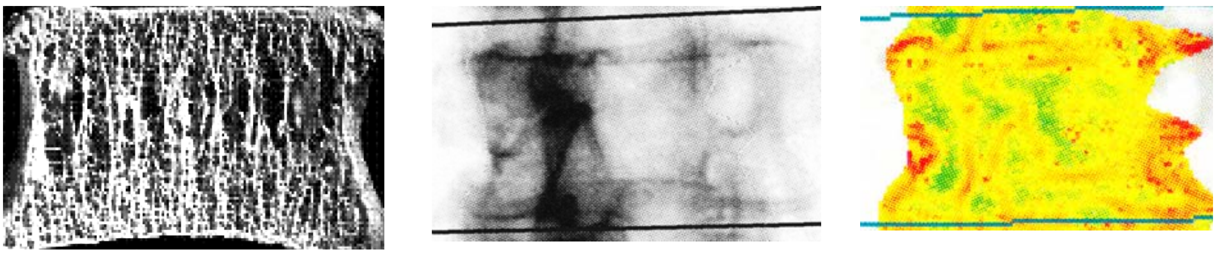
1. Introduction

Bone osteoporosis is a severe disease leading to gradual increase of the bone porosity, decrease of bone strength and to the bone fracture in elderly. The osteoporotic bone might be weaken to such a degree that a break may occur at minor stretch or torque. The fracture of the femur neck and the long bones has been intensively studied, while the vertebrae (fig.1a) that are mostly composed by the spongy (cancellous) bone and experienced poroelastic compression rather than crack formation and development, is not well studied.

The fracture of the bone as a hard material is the solid dynamics problem while in the commonly approved Fracture Risk Assessment Tool (FRAX) no quantitative index of mechanical properties of the affected bone is included. Among the risk factors the bone mineral density (BMD) determined by densitometer and trabecular-bone score (TBS) are used. TBS is a textural parameter that quantifies the local variations in the porosity averaged over one dimension [1]. When the X-ray image of the bone (fig.1b) is digitized in grayscale, the colors of pixels correspond to the amount of mineralized bone in the orthogonal direction. The TBS index is derived from evaluation of the experimental variograms (fig.1c) and characterizes the bone microarchitecture, i.e. clear presence of trabeculae in the bone structure. This paper is dedicated to biomechanical interpretation of the variograms and TBS index from the point of view of mechanical criteria of fracture.



a b c

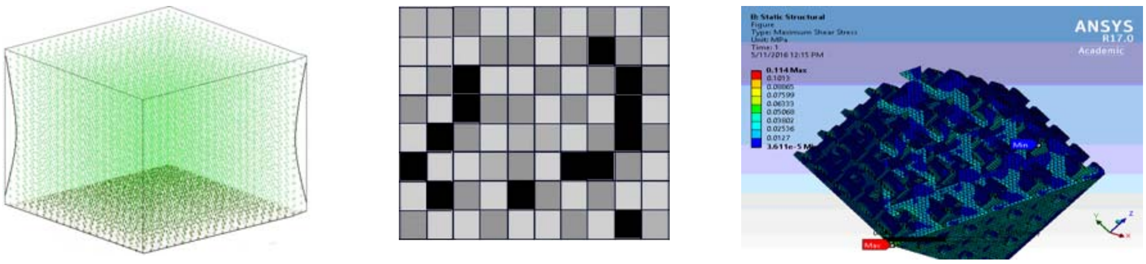
Fig.1. Cross-section view (a), X-ray image (b) and the TBS computations (c) of L3 vertebra.

2. Materials and methods

The trabecular micrositucture of human vertebrae has been generated according to the algorithms based on the analysis of microtomography data [2] and saved as 3D matrixes composed by 0 (pores) and 1 (mineral tissue) (fig.2a). The typical shape of the vertebra as cylinder (d=3 cm, h=3 cm) with a ‘waist’ of d=2-2.8 cm in the middle (h/2) and thing cortical shell has been used. Different porosity distributions have been obtained by random location of the neighboring holes in (x0y), (x0z) and (y0z) planes. As a result the porous structures with clear chains of ‘1’ (bone trabeculae) in the vertical (longitudinal trabeculae) and horizontal (transverse ones) directions that proper to the structure of vertebrae (fig.1a) have been obtained.

The 2D matrixes containing the number of non-zero voxels in the 3D structure (fig.2a) normalized by the length of the row (longer in the central area and shorter at the periphery of the structure) have been computed in arbitrary direction perpendicular to the vertical axis of the structure. The 2D matrixes correspond to X-ray images of the 3D structures computed *in silico*. The values in the matrixes have been ranged in 4 groups and replaced by 4 shades in grayscale (fig.2b). Based on the 4-color images, the BMD and TBS values have been computed for each 3D structure.

The finite element mesh for the generated porous structures from porescale to mesoscale has been built using the home developed software [3]. The mesh files have been converted into the AnSys format and the corresponding structures has been submerged to static (1 kN) and dynamic (sin-type) loads. The Young modules E=10-20 GPa typical for the spongy bones of different mineralization have been tested (fig.3a).



a b c

Fig.2. X-ray image of a L3 vertebra (a) and the TBS computations (b).

3. Results and discussion

Comparative analysis of the computed BMD and TBS values with stress distributions carried out on 40 generated structures revealed no correlation to the max/min von Mises stress values/locations, but a very good correspondence to the max/min stresses averaged over horizontal cross sections. Therefore, the relative number of 'weak voxels' experienced stresses $\sigma > \sigma^*$ in each raw well correlates with both FRAX indexes. Here σ^* is critical stress which is different for compression and torque loads and known in experimental biomechanics. TBS was found a better predictor of bone fracture; because at the same averaged porosity the size of the pores could be different that influences the bone strength for both static and dynamic loads.

4. Conclusions

The presented results give a biomechanical interpretation of the TBS parameter and its importance for the FRAX calculator. While the density-based BMD parameter is intuitively clear, the TBS index is more complex; it displays not only the textural connectivity but also mechanical strength factor, as it was proved by our FEM results. The developed approach will be applied to the X-ray and CT images of the vertebrae of the patients with high fracture risk indexes.

6. References

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