FEM BASED FRACTURE RISK ASSESSMENT IN PATIENT SPECIFIC OSTEOPOROTIC LUMBAR VERTEBRA L1

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1. Introduction

The ability of fracture risk assessment is a useful diagnostic tool for analysing the state of osteoporotic bone. There are several developed methods which employ bone mineral density (BMD) in order to predict the long-term fracture risk. BMD is usually assessed by dual energy X-ray absorptiometry (DXA) and some studies have shown that decrease of standard deviation in BMD is associated with a higher risk for future fracture [1–3]. Modern techniques of medical diagnostics also dispose computer-based algorithms, such as FRAX [4], which calculate fracture probability from obtainable clinical risk factors like age, body mass index(BMI), and dichotomized risk factors comprising prior fragility fracture, parental history of hip fracture, current tobacco smoking, long-term oral glucocorticoid use, rheumatoid arthritis, other causes of secondary osteoporosis, alcohol consumption and others [5]. On the other hand, these methods don't verify the complexed relation between such important parameters as trabecular bone score (TBS), thickness of cortical shell and the value of external load.

The finite element method (FEM) based continuum models can supply the additional patient specific data in order to define the risk of fracture by additionally applying the reliability theory. This work proposes the new method of fracture risk calculation, based on statistically processed results obtained by numerical investigation of strength properties of lumbar vertebral L1 body with various grades of osteoporotic degradation.

2. Methods and Materials

Bone tissue model. The bone tissue is modelled as elastoplastic continuum, so the Maxwell-Huber-Hencky-von Mises criterion is chosen to predict the fracture of the model. The selection of this criterion is based on mechanical properties of bone, which seems to behave as a ductile material [6]. The inhomogeneous lumbar vertebral body consists of two basic structural members - outer cortical shell fulfilled by inner bone tissue. In this study, the DICOM data of human CT was used for development of initial anatomical geometry of vertebral body. The geometry of trabecular tissue was obtained by boolean cut operation of initial anatomical geometry model of vertebra by regular shifted cylinder system. The Maxwell-Huber-Hencky-von Mises yield criterion is applied on research of stresses, which occur on cortical shell and on trabecular tissue of the model. The Ramberg-Osgood equation mathematical model of the stress σ strain rate ε behaviour of bone was applied [7]. Finally, the model was meshed with tetrahedral grid due to its curvature and finite element method was applied for solving differential momentum equation of motion.

Model fitting. In risk evaluations we have used three degrees of freedom: external load P, cortical shell thickness of lumbar vertebra Δ and bone volume to total volume ratio β_{BVTV} which was obtained from trabecular bone score (TBS) interdependence. On other hand, TBS was obtained from 2D vertebra CT scan. These variables were used for solving finite element method for above proposed mechanical model strength of lumbar vertebra. Finally, the obtained set of points values for different combination of free variables were used for least square fitting by quadratic polynomial as follow

$$\sigma_s = \sum_{i,j,k=0}^{2} a_{ijk} \beta_{BVTV}^{i} \Delta^j P^k \tag{1}$$

Risk evaluation. Fracture risk of lumbar vertebra can by expressed in term of reliability $R = P(Z \leq 0)$, where $Z = X_\sigma - Y_{\sigma_Y}$ has the following CDF

$$R = P(Z \leq 0) = \int_{-\infty}^{0} \int_{-\infty}^{\infty} f_{X_\sigma}(\sigma + z) f_{Y_{\sigma_Y}}(\sigma) d\sigma dz \tag{2}$$

where f_{X_σ} and $f_{Y_{\sigma_Y}}$ are PDFs of the normal random variables X_σ and Y_{σ_Y} of the maximum stress caused by the external load P and the strength, respectively.

3. Numeric Results and Conclusion

The static failure reliability R, see Fig. 1, is evalueted by the Monte Carlo method. Our results show that the fracture risk is substantially higher at relatively low levels of apparent BV/TV ratio, and critical due to thinner cortical shell, and it suggests the high levels even during daily activities of typical distribution of external loads. In addition, this model could be used for determining of fracture risk of individual patient by applying of peculiar anatomical properties of lumbar vertebrae. The proposed method of fracture risk assessment based on cancellous bone and cortical shell in-silico finite element modelling includes basic principles of evaluation of fracture risk of mechanical system and should be used as supplementary method with other known fracture risk evaluation methods.

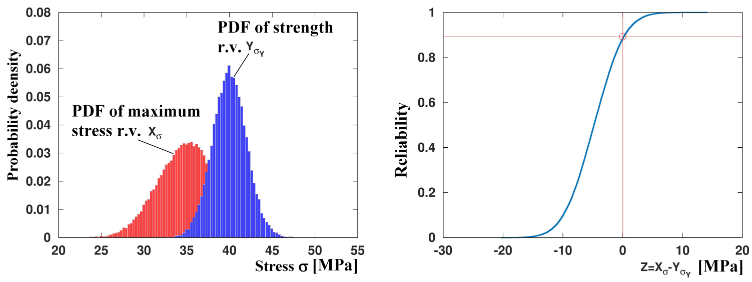

Figure 1: PDFs of the stress ($\mu = 35$ MPa) and the strength ($\mu = 40$ MPa) (left) and the reliability R (right).

4. References

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