SIMULATION OF TRABECULAR BONE ADAPTATION – CREATING THE OPTIMAL BIOLOGICAL STRUCTURE

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Summary In the paper the simulation of trabecular bone adaptation based on the micro-structure of the trabecular net is discussed. The assumption to the algorithm of bone remodeling stimulated by mechanical loading is presented. The basics of the own adaptive mesh generator are described. The results of computations, using specialized software, including parallel Finite Element Analysis are presented.

INTRODUTION

The Wolff's law, which has been stated in 19th century tells, that the bone is able to adapt to the mechanical stimulation. After many experiments it is clear, that the amount and organisation of the beams in trabecular bone tend to mechanical optimum. The research of the remodeling of trabecular bone is in the main area of many medical research centers, but the phenomena of bone mass losing is also very important during the space exploration. The mechanical stimulation is one of the most important factors of the normal bone functionality. There are many models of bone remodeling based on the strain energy density [1,2] and used for the adaptation simulations of the bone, treated as a continuum material. The main idea behind that is to prepare the model of the bone adaptation as a material of specific, changing properties depending on the loading history. The progress in computer hardware technology and parallel computations enable now modeling of the bone adaptation process using the real topology of the trabecular bone with use of a linear model of the trabecula. The latter is justified by experimental investigations stating that on the trabecular level the bone can be treated as an linear material [3].

Fig.1. Graphically rebuilt micro-CT slices – an input for the adaptive mesh generator

REMODELING SIMULATION

In the paper the assumption to the algorithm of bone remodeling stimulated by mechanical loading is presented. The beams of trabecular bone are assumed to be an isotropic linear material, where the marrow space is treated as voids. The simulation of the remodeling process needs both finite element mesh generation and evolution, and structural stress and strain analysis. To prepare an appropriate solid mesh an own adaptive mesh generator has been designed and is presented. The micro-CT slices are the input information about the bone topology, but the algorithm needs some graphical operations (Fig.1.).

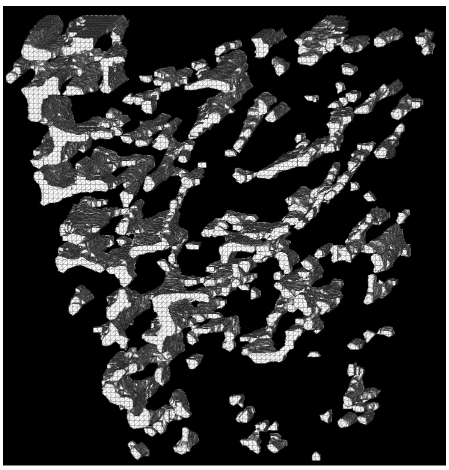

Fig.2. The solid mesh of the trabecular bone structure created by adaptive mesh generator

In contrary to other mesh generator of this type it works very robust. CT slices are converted to the specified format and the solid mesh is build layer by layer according to the topology of the trabecular bone (Fig.2.). The mesh generator enables generation of solid mesh, which can be adapted according the scenario of bone adaptation. It is possible to merge or split regions preserving proper finite elements shape. After applying constrains and loads the FEM computations are performed. The mesh is adapted according to the obtained from FEM strain rate. In the algorithm, exactly as in real trabecular bone the material in regions of low stress intensity is removed. In the healthy bone and in the algorithm this process is balanced by creation of new bone (finite elements in the computations) in the direction of dominant compression. In the algorithm there are two steps of mesh evolution. First the graphical information of each layer, corresponding to the CT-slice is changed. Then the new mesh is generated according to the element building rules. The sequence is repeated until there are no reason for the further adaptation, thus the structure is adapted to the load (Fig.3.a) and optimal. In Fig.3a it can be clearly seen that the structure follows the maximum principal stress trajectory and rebuilds adequately. While Fig.3a illustrates only the principle of the evolution in Fig. 3b the trabecular bone having 5x5x5mm dimension and subjected to compression is modeled. The computational model consists of 650000 elements.

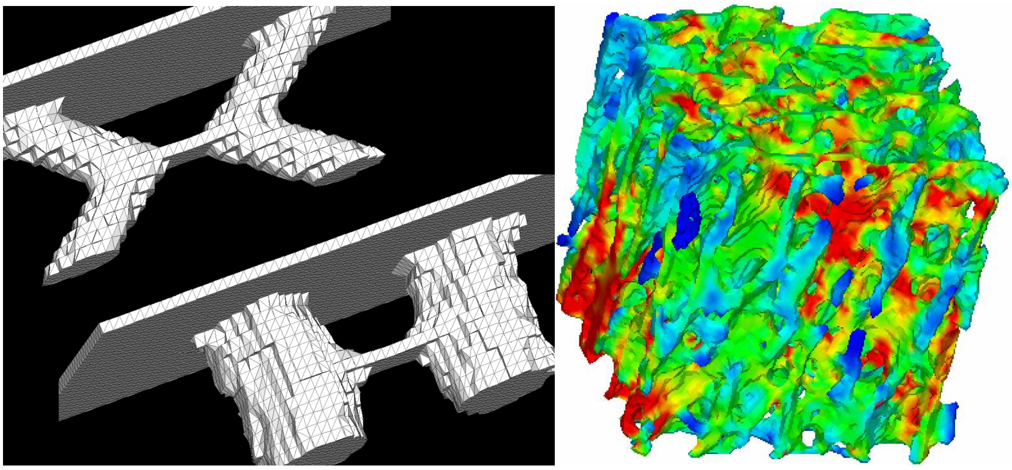

Fig.3. a) The adaptation of the simple test structure under compression – rebuild in the principal stress direction
b) Trabecular bone 5x5x5mm subjected to compression – equivalent stress Von Mises

CONCLUSIONS

The algorithm of building of optimal structure basing on biological principle of trabecular bone is presented. It consists of CT-data processing interface, robust 3D mesh generation tool, mesh evolution tool, remodeling scenario, and parallel FEM software and environment. With this program the trabecular bone remodeling is simulated and reproduced. The optimal structure following principal stresses is the result of the evolution. The used algorithm appeared to be very flexible. It is possible to test different scenarios of the bone remodeling. It is shown that linear material model combined with topological structure evolution is satisfactory for bone modeling and strictly follow the biological behavior. It will yield similar results as the nonlinear models based on the bone homogenization but is simpler and closer to the real trabecular bone properties.

Future investigations will include different scenarios including the ones appropriate for materials found in mechanical applications. The homogenization of bone properties based on microFEM model of the trabecula is considered. The parallel environment is being developed.

References

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