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3D FINITE ELEMENT MODELLING IN CONTINUUM BIOMECHANICS

A considerable attention is given to a problem of influence of mechanical stresses on the structure and physiological properties of biological tissues. In particular, a broad application has been found by devices of mechanical vibrostimulation those give the positive influence onto increase of muscle force, increase of joints mobility and osseous tissue strength. However, the serious scientific substantiation of frequency selection for vibration effort is missing, as a rule. The main task of investigation was to study the vibrational properties of biological structures composing the inferior part of the human shank (Achilles' tendon, muscles, tibia and fibula) by using numerical tool ANSYS [1].

A three-dimensional (3D) model was made essentially from 5 cross sections of the leg (Fig.1). Between cross sections and at the extremities of the bone, spline extrapolations were made to match the shape of the leg. 119 areas and 32 volumes had composed the tibia. The fibula was created using the same method as the tibia. For fibula there were 107 areas and 27 volumes. After modeling tibia and fibula independently, the both models were joined and adjusted the positions of the bones.

Achilles' tendon appears on the two of five cross sections. It develops into the soleus muscle, and so we had to simulate the tendon in the same time as the muscles. Our first idea was to simulate muscles one by one but the geometry of muscles is very complex because muscles are mixed in the leg and ANSYS is not really adapted to design 3D complicated models. So we found another solution, easier and faster to develop: we created two muscular groups with more simple geometry: one for the back of the leg (Achilles' tendon, first part of the soleus muscle and gastrocnemius muscle), another for the part between the bones and the first muscular group. The last was composed of flexor hallucis longus, tibialis posterior and the second part of the soleus muscle. The volume created from these two muscular groups was equivalent to the volume occupied by the four muscles taken together (Fig.2).

The bones were assumed being composed of two materials [2]: an internal spongious tissue and an external compact tissue. The density of these materials was equal to 1850 kg/m^3 and 800 kg/m^3 correspondingly. In this study the materials were considered as isotropic, also in reality they are anisotropic. The following values for Young modulus (E) and shear modulus (G) were taken: $E_{compact}$ = 18700 MPa, $G_{spongious}$ = 6680 MPa; $E_{compact}$ = 500 MPa, $G_{spongious}$ = 200 MPa. The values of mechanical constants for soft tissues were E_{muscle} = 20 MPa, E_{tendon} = 1500 MPa, ρ_{soft} = 1000 kg/m^3. As tendon turns into muscle progressively, we had to create a new material between tendon and muscle with average material properties (E = 800 MPa).

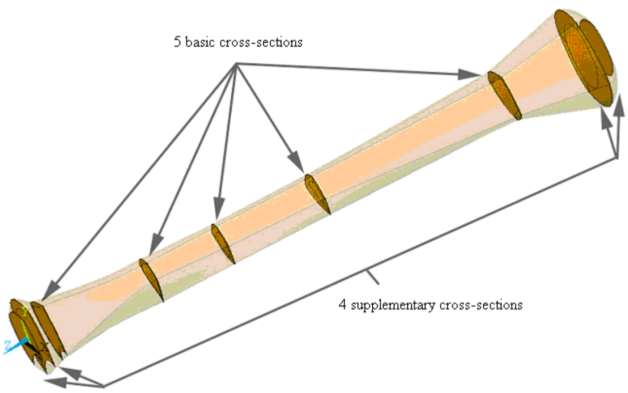

Fig.1. Cross-sections of tibia and fibula.

Finally, the two extreme surfaces of the tibia were submitted to the hinge support boundary conditions when only one central node from each side was embedded. After completing the geometry, a mesh was generated on the basis of the tetrahedral 10-nodes solid finite elements.

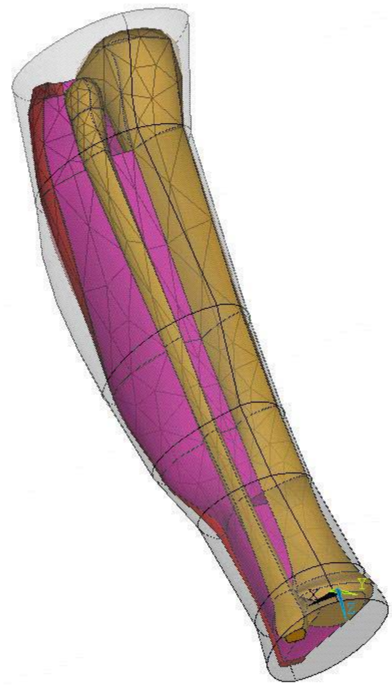

Fig.2. The full shank model.

A modal analysis of tibia only was made to find out eigen forms and eigen frequencies of the isolated bone with different material properties :

1. Compact tissue for the whole bone.
2. Compact tissue for bone diaphysis and spongious tissue for the heads of bone whilst no tissues for the tibia inside.
3. Compact tissue for bone diaphysis and spongious tissue for the heads, the marrow for inside bone with the following values: $E_{marrow} = 0.1$ MPa and $\rho_{marrow} = 1000$ kg/m^3.

The first two modes revealed by the finite element analysis were the bending modes in two planes, saggital and frontal ones corespondingly. The values of the first eigen frequency depending on the different material types and meshes are presented at the Tabl. 1.

The value of the second eigen frequency is larger than the first one because of the non-symmetric geometry of tibia and equal to 225 Hz for the material type 3 and the mesh with 2241 elements.

Table 1. Eigen frequencies of the isolated tibia.

	Material type 1	Material type 2	Material type 3
Mesh 256 elements	226 Hz	219 Hz	185 Hz
Mesh 2241 elements	222 Hz	216 Hz	182 Hz
Mesh 6681 elements	239 Hz	207 Hz	190 Hz

The full model of the shank was considered after inserting fibula, muscles and Achilles' tendon into the model (Fig.2). Unfortunately we could not use the skin envelope we had created because we were not able to operate with ANSYS the Boolean subtraction needed. So there were no materials surrounding muscles and bones.

Materials for the tibia and fibula were as explained for type 3, for the soft tissues were as mentioned above. Additionally to the nodes fixed at each extremity for each bone, bottom area of the tendon and top area of gastrocnemius muscle were also fixed. Mesh was composed of the 6341tetraedral elements.

The results of the enlarged vibration analysis are presented at the Tabl. 2.

Table 2. Eigen frequencies of the shank.

	1st mode	2nd mode	3rd mode
Frequency (Hz)	75	135	163

The first mode is almost a twisting mode around the longitudinal axis. Second mode is a bending mode in the saggital plane.

As a conclusion, it is necessary to mention that the results obtained are the first theoretical outcomes for the full shank. The finite element model developed is simulating the vibration properties of the inner biological structures very precisely. The numerical values of eigen frequencies and 3D images of the vibration modes can be used in combination with experimental methods and equipment for testing and studying the vibration properties of the human tissues.

REFERENCES:

1. ANSYS Basic Analysis Procedures Guide. 1998.
2. Yanson H.A. Biomechanics of the human lower limb (in Russian). Zinatne, Riga (1975).