BIOMECHANICAL FEATURES AND THE THREE-DIMENSIONAL MODELLING OF THE BONE STIMULATED BY MICRO-CT –XRAY AND BY THE FINITE ELEMENT METHOD

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Summary

Biomechanics is a multidisciplinary field focused on the analysis of biological materials, i.e., cellular or tissue fragments. In general, little is known about the mechanics of the processes acting upon biological materials, since it should be noted that chemical, mechanical, remodelling and adhesional interactions exist at vivid tissues cellular level. In order to monitor, with the help of ultrasounds, the biomechanical behaviour of the 45-day-deposited callus after tibial ostectomy (oste(o)- <New Latin from Greek osteon, bone - + -ectomy < New Latin ectomia, to cut out) as compared with a normal bone, an algorithm was put forward to determine the biomechanical features of the bone in question. This algorithm is based on the method of the finite element. The bony model could be submitted to compression and shearing with the help of the VCAT programme packages, demonstrating the recovery of the bony tissue under the influence of ultrasounds in a percentage of 90% after 45 days since the ostectomy.

Key words: bony tissue, biomechanics, the method of the finite element, micro-CT X-Ra

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Introduction

As structure, material and biological systems, bone has represented the topic of numerous biomechanical studies, with applicability in medicine, due to its being considered a system of high complexity, and a multifunctional tissue [Weiner and Traub, 1992]. Statically, the bone provides the sustaining of the body; dynamically, it represents the levelling-element of the system of locomotion, whose role is to transmit the muscular forces during instances of movement. Long bones are particularly submitted to static and dynamic stresses, the forces acting on different directions and with different intensities [Katz, 1979].

When stresses exceed the elasticity limits fractures occur. To determine the biomechanical behaviour of a bone, its mechanical features are determined, under the circumstances of traction, compressing and shearing stresses, assuming that its structure is transversally isotropic and three-dimensionally orthotropic [Sasaki N et al, 1989]. Taking into account static and dynamic stresses, the biomechanical characterization of bone is achieved within a framework of complex mechanical trials which are similar to the natural stress conditions, up to the limit of the bone fracture [Currey, 1970]. It should be considered that the internal organization expresses the functional adaptation.
A system of reference where the bone with its main axes of the stresses (x, y, z) will be placed should be defined.

Material and method

To monitor the biomechanical behaviour of the 45-day-old callus with the help of the ultrasounds after the tibial ostectomy, as compared to the normal bone, an algorithm determining biomechanical features based on the finite element method was put forward. The finite element method allows for the analysis of the physical phenomena which may be described with the help of mathematical models represented by systems of differential equations with initial conditions and with limits (big programmes of structural analysis added some phenomena which may be calculated through modelling by means of other types of simpler linear or non-linear non-differential equations). [Crolet and Aubiza, 1993] Nowadays, it is considered that due to the evolution of the calculation accuracy of the finite element numerical modelling programmes, the results obtained through the simulation of the mechanical trials based on the modelling with the finite element method, are similar to all those obtained in the experimental trials intended to detect the biomechanical behaviour of bones. [Kimura et al, 2005].

To determine the biomechanical behaviour of the stimulated bone, the following work protocol was applied:
1. the sample taking and processing
2. micro-CT X-Ray scanning
3. 3D-VCAT software reconstruction
4. numerical simulation with the finite element method
5. determining of the mechanical characteristics

The sample scanning, reconstruction and modelling were performed with the help of the research team members at the VCAD Integrated Research Program department, the RIKEN Institute of Physical and Chemical Research, Japan. The Micro-CT X-Ray scanning technique as well as the VCAT and VSTRUCT software which were used are now being developed within the research programmes performed by the above-mentioned team.

Results and discussions

Although the material the bone is made of is anisotropic and non-homogeneous, the bone was considered to manifest itself in a stress area which does not exceed certain limits since it is homogenous and isotropic. This supports the hypothesis of physical linearity and Hooke’s law validity, which states that for a certain stress, within proportionality limits the developed stresses are directly proportional with the specific deformations, the proportionality coefficient being a certain material-depending constant, i.e., the longitudinal elasticity module, or Young’s modulus, whose measuring unit is MPa. 1 MPa represents the pressure created by a force of 1N, which acts on a surface of 1mm. Young’s module may be expressed as the reverse of the elasticity coefficient and it depends upon the nature of the body, this one being peculiar to each body [Black and Mattson, 1974]. The bone has an insufficiently elastic structure. Accepting this hypothesis made it possible for the application of the programmes underlying the finite element method [Ascenzi and Benvenuti, 1986].

1, 2 and 3E (G, respectively) are longitudinal elasticity modules or the Young’s modulus (the transversal elasticity module or the shearing module), and ν is Poisson’s ratio. These values are expressed in GPa.

The modelling of the tibial diaphyses through the finite element method enables a complete study of the bony tissue behaviour from the point of view of the stresses and deformations which develop when different stresses are applied. This method shows considerably superior advantages as related to the classic methods provided by the theory of elasticity which are based on simplifying hypotheses such as:
-stresses are constant in case of compression and stretch wherever they may be applied.

-normal stresses vary linearly on the height of a section, from the 0 value in the neutral fibre of the section up to maximal values in the external fibres of the section [Rüegsegger et al, 1996]

The biomechanical characterization of the two samples lies in the determining of the elastic constants when calculating sample stress in conditions of longitudinal compression, volume compression and transversal shearing (figure 1).

The schemata of the mechanical trials simulated through the modelling with the finite element are presented in figure 2. The same set of trials was performed both for the stimulated bone and for the normal one in order the have the possibility to compare the two samples value of the elastic constants (the elasticity module). Table 1 presents the results of the numerical simulation.

The results highlight the fact that the stimulated bone recovered in two weeks’ time the capacity of taking over the effort in a percentage of 85% in compressions and of 95% in shearing stresses. These values show that the bony structure recovered itself in a percentage of 90%.

In the compact bone the collagen fibres are responsible for the shearing resistance. The values of the module of elasticity in shearing forces, are in the perspective of our study, very similar in the bone stimulated by the normal bone (17/16). Therefore, the collagen fibres may be concluded to be mature, which also results from the study of osteons in polarised light where the collagen is shown to be birefringent, looking like the Cross of Malta. The difference appears because of the process of remodelling which leads to the deviation of local stresses from the reference value. The adaptation of the form and configuration is accompanied by an adaptation of the internal structure responsible for the elastic properties.

Figure 1. 3D reconstruction of the stimulated bone and of the normal bone with an end to performing the analysis through numeric modelling with the finite element method of the mechanical behaviour under compression, traction and shearing stresses.
The crystals of hydroxyapatite are responsible for compression. The differences which appear in the trials performed through longitudinal compression are due to the insufficient sediments of calcium in the newly-formed osteons.

The increase of the number of Haversian and Volkmann canals could be another cause, which results in an increase of the blood flux with the bone depriving of calcium ions.

![Figure 2. Schemata of mechanical trials simulated with the finite element method](image)

a) longitudinal compression  b) volume compression  c) shearing

Table I. Comparison of the values of elasticity modules obtained in the case of numeric simulation of mechanical trials applied to the normal and to the stimulated bones

<table>
<thead>
<tr>
<th>Trial type</th>
<th>Elasticity module</th>
<th>Average values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stimulated bone</td>
</tr>
<tr>
<td>Longitudinal compression</td>
<td>E3 [GPa]</td>
<td>16.5</td>
</tr>
<tr>
<td>Volumic compression</td>
<td>B11 [GPa]</td>
<td>17</td>
</tr>
<tr>
<td>Shearing in the xy plan</td>
<td>G12 [GPa]</td>
<td>16</td>
</tr>
</tbody>
</table>

The bone can bear diverse stresses, its resistance being induced by the symmetry of the different composing elements. In the case of the compact bone, the osteons are arranged with their long axis in the bone axis. This arrangement results in the existence of some major differences in the bony behaviour depending on the direction of the applied force (in the long axis of the bone or in other axes).

Currey considers that the different mechanic properties are given by the two bone components: the collagen fibers for traction and shearing, the hydroxyapatite being responsible for compression [Feldkamp *et al.,* 1984]. In the case of the long bone, all of the studies test the stress and shearing resistance, compression being determined in the case of spongy bone. The collagen fibers responsible for shearing
resistance are mature, the small difference appearing because of the remodeling process necessary for the adapting of the form and configuration of the bony internal structure which is responsible for the elastic properties. This recovery after shearing was also highlighted in the fractures stimulated with continuous current [Mehedinti et al, 2004]. Submitting the continuous current post-stimulated callus fragments to compression produced by the EDZ apparatus, the resistance of the newly-formed bony tissue was noticed to be very close to that of the normal bone, the breaking force of the callus submitted to electrical stimulation having the value of 4.4kN/mm². This difference suggests that the metabolic process involved in the reorganization of the newly-formed bony tissue at the level of callus, under the influence of electrical current and of ultrasounds, undergoes some morphological and architectural changes as well as modifications of the shearing resistance [Parfitt, 1987]. The neo-formation process may, in its evolution, affect the bone crystalloid network, the newly-formed bone being incompletely recovered, the longitudinal compression resistance being reduced with 25% and the volume compression with 15%.

Conclusions
The use of the micro-CT-X-Ray to cross-cut the bone, which is necessary for the discretization process, enhances bony built models degree of fidelity and demonstrates the full recovery of the fractured bone from the perspective of image radiology.

The three-dimensional model of the tibial dia physis could be constructed through the finite element method. With the help of the VCAT programme packages the bony model could be submitted to compression and shearing, thus showing the recovery of the bony tissue under the influence of ultrasounds in a percentage of 90% , 45 days since the ostectomy.

Our results are comparable to those obtained in the stimulation of the fractures with continuous current, the method we used having the advantage of non-invasiveness.

The computer simulation essentially contributes to the construction optimizing of the would-be spare parts intended to replace bones. More than any other type of image, the medical image is the carrier of an impressive amount of information, which is very important in the determining of the medical diagnosis, and last but not least, in the medical research. The structural message of the medical image has definite functional implications, being measurable and describable mathematically.

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