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Biomechanical study of the bone tissue with dental implants interaction

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Abstract

The article deals with the stress-strain analysis of human mandible in the physiological state and after the dental implant application. The evaluation is focused on assessing of the cancellous bone tissue modeling-level. Three cancellous bone model-types are assessed: Non-trabecular model with homogenous isotropic material, non-trabecular model with inhomogeneous material obtained from computer tomography data using CT Data Analysis software, and trabecular model built from mandible section image. Computational modeling was chosen as the most suitable solution method and the solution on two-dimensional level was carried out. The results show that strain is more preferable value than stress in case of evaluation of mechanical response in cancellous bone. The non-trabecular model with CT-obtained material model is not acceptable for stress-strain analysis of the cancellous bone for singularities occurring on interfaces of regions with different values of modulus of elasticity.

Keywords: dental implant, trabecular bone, finite elements method, stress and strain analysis, modeling level

1. Introduction

Since 1960's when Brånemark and Linkow defined the direction of modern dental implantology, this medical field developed into a large extent and today it provides very effective solution to many dental problems: Starting with restoring the natural function of masticatory system and ending with dental aesthetic improvements. In 2003, there were more than 220 different types of implants manufactured by about 80 producers [12]. New materials such as technically clean titanium, nanostructural titanium or titanium alloys etc. as well as deepening understanding of the implant-living tissue interaction are emphasized nowadays. Despite the reliability of dental implants which is nowadays around 95 % [18, 27], it would be mistake to underestimate influences of other factors on successful treatment. Therefore, it is necessary to continue in efforts to improve quality of dental implants.

Application of a dental implant which is essentially a technical object is not only a medical procedure but an interdisciplinary process. It is therefore necessary to solve the dental implantology problems together with technical specialists, i.a. biomechanicians whose task is to assess the mechanical interaction of the system components, including living tissues as well as technical materials. In this respect, a very effective tool is computational modeling. Implant failures depend on many various factors as, for instance, mechanical ones. These factors are

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expressed by mechanical quantities stress and strain. In biomechanics computational models basically consists of models of geometry, material, loading and boundary conditions.

2. Material and methods

The paper deals with the interaction of a tooth or a dental implant with bone tissue regarding various modeling levels of the bone model. As the most suitable solution method was chosen the finite element method (FEM) which is used very often in such biomechanical problems like this. Thanks to latest technologies it is possible to build models on a quite high modeling-level. An example of building of such model is given in this article as well. In our case ANSYS 11.0 (Ansys Inc., Canonsburg, PA, USA) was used.

Prior to calculations, suitable geometry model is needed. The model of trabecular model of cancellous bone is obtained from the image of the mandible section. Therefore, 2-D geometry level is used throughout this study. This approach is sufficient enough for the comparison of the three proposed material models of mandibular bone. 3-D level of the same case is also possible but the model of trabecular structure would require data obtained directly from micro-CT [21].

In this study, the solution is divided into three parts:

1) An assessment of modeling level of bone tissue material.

2) Stress-strain analysis of mandible in the physiological state.

3) Stress-strain analysis of mandible with an applied screw implant.

2.1. An assessment of modeling level of bone tissue material

There are two types of bone tissue: Hard outer cortical bone and inner trabecular structure, so-called cancellous bone. All bones are inhomogeneous anisotropic biomaterials. Both these types should be incorporated into the model.

In our study, three general modeling-levels of cancellous bone material are assessed: Non-trabecular model (the lowest level), trabecular model (considering the trabecular architecture of the real bone) and CT-obtained model (non-trabecular but inhomogeneous material). Furthermore, these general models are divided into "sub-levels" according to the bone quality as will be explained below. Cortical bone is modeled in all cases as homogenous material with no special architecture.

The shape of bone was obtained based on the image of mandibular cross section [15] and also by using the computer tomography. Using CAD software SolidWorks and Rhinoceros, 2-D geometry model was created, specifically the outer shape corresponding to the 1st premolar region as well as the trabecular architecture of cancellous bone (see Fig. 1).

Linear isotropic material model is used for all parts of the system, i.e. two material characteristics are needed, specifically Young's modulus E [MPa] and Poisson's Ratio μ [–].

At the lowest level, bone is modeled as non-trabecular homogenous material with apparent material characteristics of cancellous bone (no cortical bone is incorporated, see Fig. 1a). Sensitivity study is performed to obtain proper value of the Young's modulus which is changed ranging from 150 to 750 MPa. The changing value refer to varying bone quality, specifically the lower Young's modulus value means lower bone quality and therefore lower bone density (e.g. in osteoporotic bones [29]). As for the interaction of an implant with bone, the main disadvantage of bone with lower density is lower bone support of applied implant.

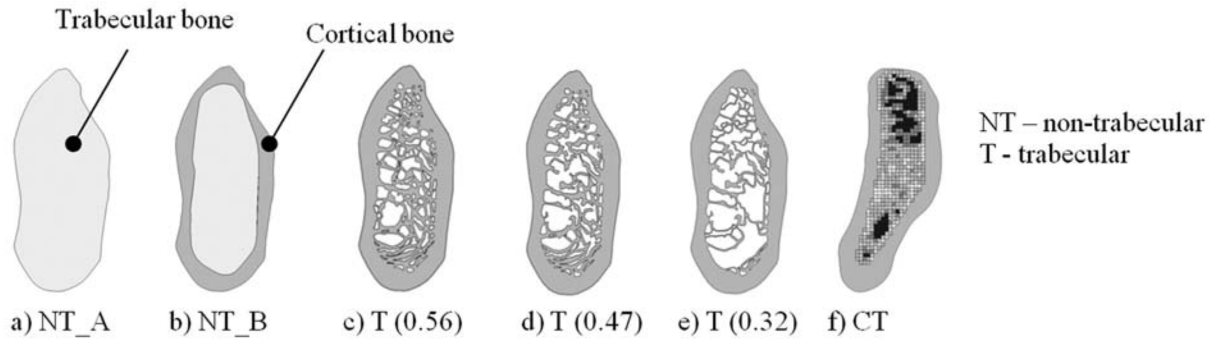

Fig. 1. Model of geometry and analyzed material modeling levels overview: a) non-trabecular model (only cancellous bone) – NT_A; b) non-trabecular model (cancellous as well as cortical bone) – NT_B; c) trabecular bone of good quality (BA/TA – 0.56); d) trabecular bone of normal quality (BA/TA – 0.47); e) trabecular bone of low quality (BA/TA – 0.32); f) CT-obtained model

Next modeling-level used in the study and which is very often used by other researchers ([4, 7, 19]) is non-trabecular homogenous model with incorporated cortical layer (see Fig. 1b). In this case, Young's modulus of cortical bone is of 13 700 MPa [10, 31] and similar sensitivity study as in previous modeling-level is performed in case of cancellous bone, i.e. Young's modulus ranged from 150 to 750 MPa.

Contrary to the previous models, model shown in Fig. 1c includes trabecular structure of real cancellous bone. At the micro-level trabeculae has the same material properties as cortical bone [25, 32] and therefore the Young's modulus of such cancellous bone model is of 13 700 MPa. In such model, lower bone quality can be modeled by using less dense structure and with thinner trabeculae (see Fig. 1d,e). The bone quality is here identified by a special characteristics often used in these cases, i.e. by so-called bone area fraction BA/TA which is defined as the area of bone tissue per total area (in 2-D analysis) [33].

The last modeling-level used in the study is non-trabecular inhomogeneous model. This model takes into account the distribution of bone density which is in the model characterized by varying value of the Young's modulus. This material property values can be obtained directly from CT images in the following way.

Prior to dental implant application, densitometry investigation is often performed by using CT [28, 34]. From CT images, CT numbers (which signify pixel intensity of the image) can be read. CT numbers can be converted to Hounsfield units (HU) [34] by which individual tissues are identified. There are observed correlation between HU and bone density or Young's modulus of that (mainly cancellous bone) tissue [16,23,24]. This correlation is the basement for material model. For purpose of its creation, new software CT Data Analysis [35] was developed at Institute of Solid Mechanics, Mechatronics and Biomechanics, Brno University of Technology. This software allows the user to load CT images and after defining a desired region to export CT numbers (HU units) matrix. This matrix is then converted into the Young's moduli matrix which can be exported into Ansys program as CT-obtained material model. It should be noted that two correlations can be used:

1) Linear correlation: The reference value is the CT number of cortical bone which has known Young's modulus of 13 700 MPa. According to the known formulas, Young's moduli of other tissues (cancellous bone in various positions within the region) can be calculated (see Fig. 2a)

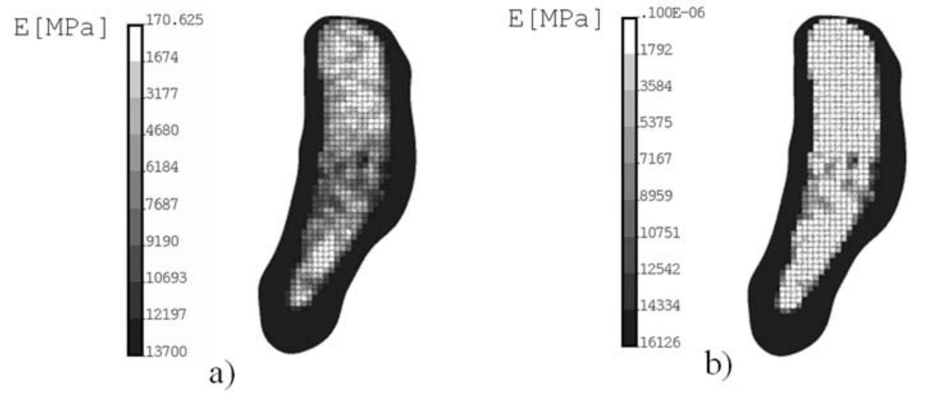

Fig. 2. CT-obtained material model: a) linear correlation used – CTlin, b) nonlinear correlation used – CTnonlin

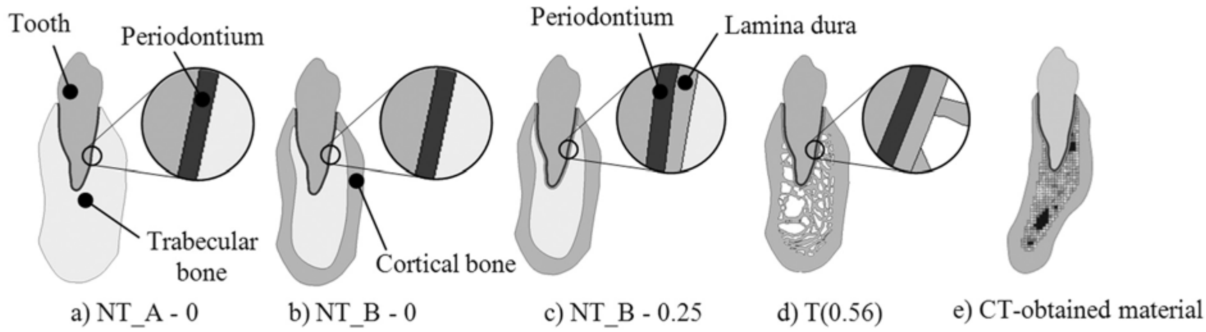

Fig. 3. Model of geometry: a) case 1A, b) case 1B, c) case 1B, d) case 1B, e) case 1B

2) Nonlinear correlation: Relation between bone density and Young's modulus is given by formulae (1) [23,24] (See Fig. 2b and note that the bone shape is different to that in Fig. 1 since it is obtained from different mandible)

$$\rho = 1.205 \cdot HU + 139, \qquad E = 2.349 \cdot \rho^{2.15}. \tag{1}$$

Material characteristics used for all models with the exception of non-trabecular inhomogeneous model of cancellous bone are presented in Table 1.

Table 1. Material characteristics: Young's modulus and Poisson's ratio

	E [MPa]	μ [–]	Reference
Cortical bone	13 700	0.3	[10, 31]
Cancellous bone	150–750	0.3	[8, 9]
Dentin	17 600	0.25	[17]
PDL	10	0.45	[14, 30]
Titanium	110 000	0.33	[36]

2.2. Stress-strain analysis of mandible in the physiological state

For the analysis of the physiological state geometry model is modified in alveolar region so as 2-D tooth model (1st premolar) including periodontal layer could be embodied. The layer is of 0.25 mm in thickness. In case of NT_A model (see Fig. 1a) the tooth with periodontium (PDL) is embodied directly into cancellous bone (see Fig. 3a). In case of NT_B model (see Fig. 1b)

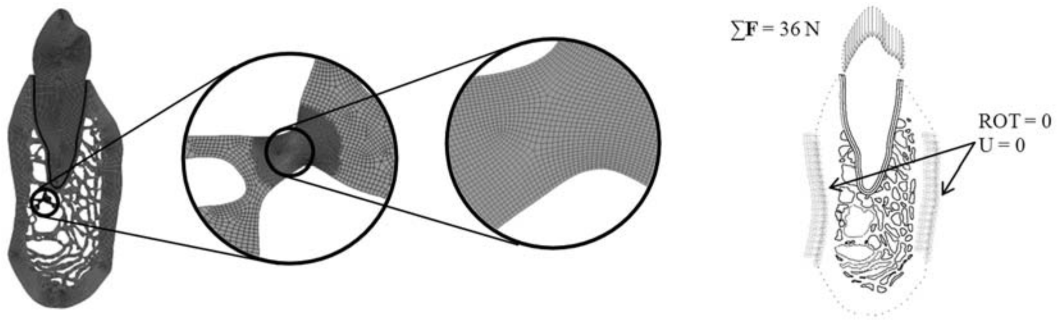

Fig. 4. FE mesh and the boundary condition

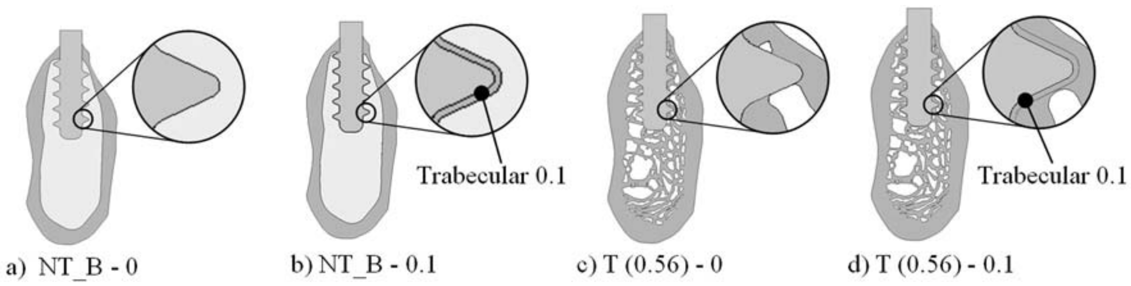

Fig. 5. Implant-Bone interface: Cases overview

two other variants are modeled: Model without Lamina dura layer (see Fig. 3b) and model with Lamina dura layer of 0.25 mm in thickness (see Fig. 3c). In case of all trabecular cancellous bone models ($T(0.56)$, $T(0.47)$ and $T(0.32)$ – see Fig. 3d) as well as in case of non-trabecular inhomogeneous model (see Fig. 3e) Lamina dura of the same thickness is included as well.

All models are discretized with 8-node quadratic element PLANE 182 with global size of 0.02 mm. Since periodontium, which is largely deformable soft tissue, is part of the model, the finite strain theory was selected for the analysis, i.e. the finite strain tensor is enlarged by higher order derivatives which are negligible in infinitesimal strain theory.

In order to carry out the FEM solution, it is inevitable to have boundary conditions. In our case, the model is in all cases constrained in the middle of buccal as well as lingual cortical bone boundary (see Fig. 4). The model is loaded by the force applied in coronoapical direction on the tooth crown; specifically the force of 36 N is applied. This value is equivalent to the loading force of 200 N applied in similar 3-D model [11].

2.3. *Stress-strain analysis of mandible with an applied screw implant*

The same cases as in the previous section are modified so as the screw implant could be inserted into the presented models. Two specific cases are furthermore analyzed. Either there is no occurrence of special bony structure similar to lamina dura (see Fig. 5a,c) or there is. If the structure occurs, the layer of this special bone is of 0.1 mm in thickness [1, 13, 22]. In case of $T(0.47)$, $T(0.32)$ and CTmat only cases with the special bony structure are analyzed.

Implants are osseointegrated [1, 5]. Three stages of the osseointegration are analyzed:

A) implant is osseointegrated by its whole surface (see Fig. 6a),

B) implant neck region is not osseointegrated with cortical bone (see Fig. 6b),

C) implant is not osseointagrated at all (unacceptable situation, see Fig. 6c).

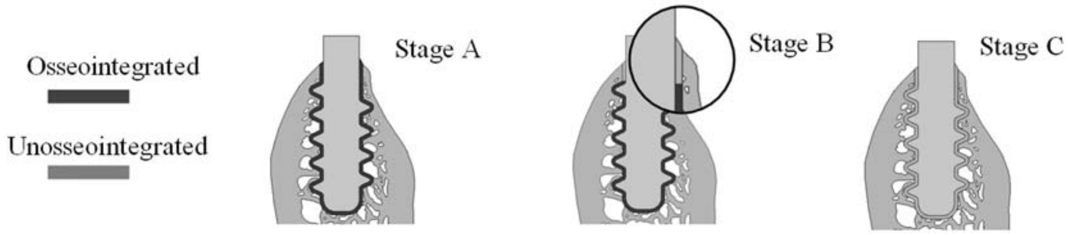

Fig. 6. Stages of osseointegration

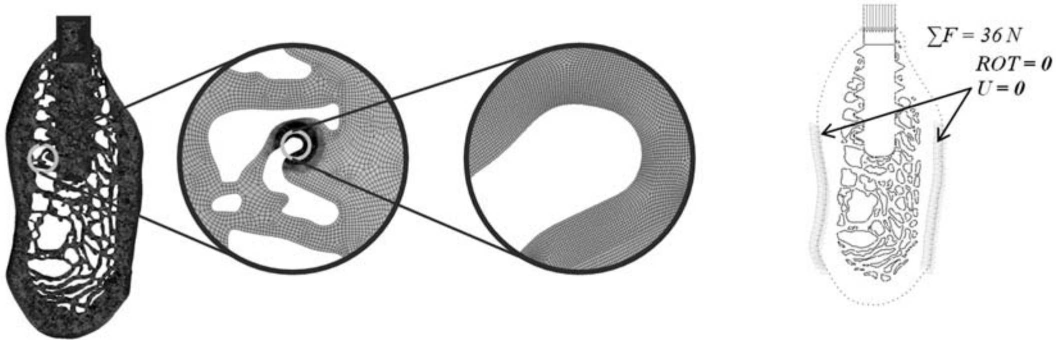

Fig. 7. FE mesh and the boundary conditions (model with the implant)

The osseointegration is modeled in ANSYS by rigid connection of osseointegrated parts, i.e. implant and bone have common FE nodes. In the un-osseointegrated regions (stages B and C), the implant bone connection is modeled by using contact elements CONTA172 and TARGE169 (pure penalty algorithm, standard contact, friction coefficient $f = 0$, normal contact stiffnes $FKN = 1$).

Model discretisation is similar as in the previous section. The same are also the boundary condition as well as the loading (see Fig. 7). Implant is made of technically pure titanium and it is modeled using linear isotropic model (see Table 1).

A total number of 35 computational models are created. Intel Core 4 Duo inside 2GHz 8GB RAM processor, PCG iterative solver and Full Newton-Raphson procedure was used. Unless specified otherwise all solver options were left default.

3. Results

3.1. Stress-strain analysis of mandible in the physiological state

Strain intensity and stress intensity are analyzed specifically their maximum values which occur in various locations of the system. Besides, maximum 1^{st} and 3^{rd} principal stresses (S1, S3) are analyzed as well. Representative strain intensity distribution for NT_B-0.25 and $T(0.56)$ cases is shown in Fig. 8. Results of all cases are shown in bar graphs in Fig. 9 and 10. These graphs show significant difference in stress and strain results.

By comparing the maximum stresses in cancellous bone, it is obvious that non-trabecular model gives significantly lower values that trabecular model. In case of non-trabecular model, the significant effect of lamina dura layer is also observed (NT_B-0.25). This layer is a part of load-bearing structure consisting mainly of cortical bone. Thus, this makes the cancellous bone less stressed than in case without the layer (NT_B-0). The highest stresses are found in trabecular cancellous bone models, especially with the trabeculae of low quality ($T(0.32)$).

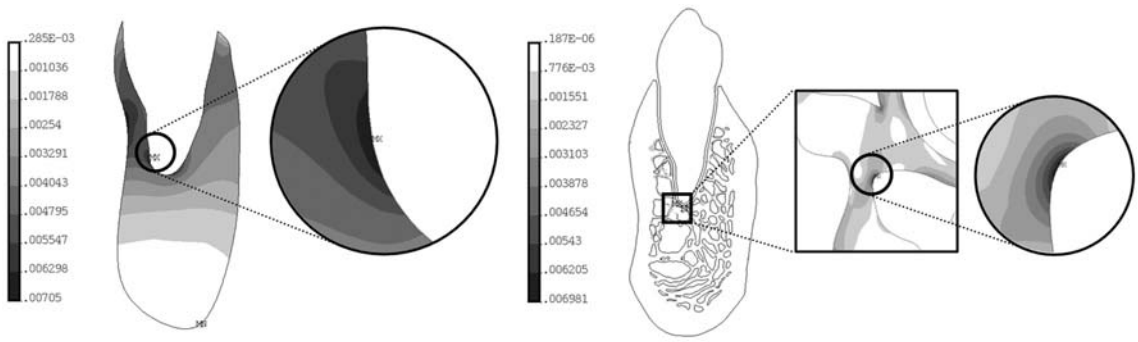

Fig. 8. Strain intensity in cancellous bone with the tooth. Comparison of cases NT_B-0.25, $T(0.56)$

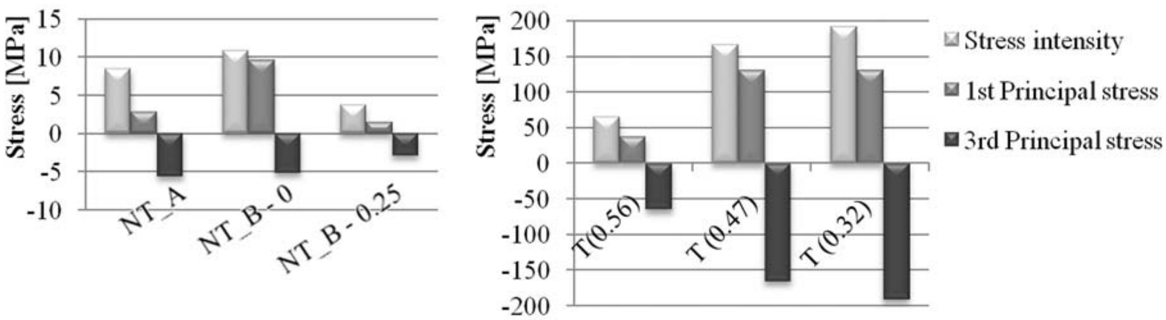

Fig. 9. Maximum stresses

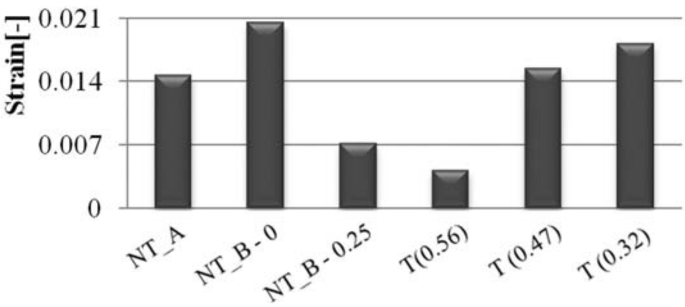

Fig. 10. Maximum strain intensities

On the other hand, by comparing the maximum strains in cancellous bone, the highest values are found in non-trabecular cancellous bone models without lamina dura (NT_A and NT_B-0) and, on the contrary, the lowest values are in trabecular cancellous bone models with trabeculae of low quality ($T(0.32)$) (see Fig. 10). From a quantitative point of view, the best accordance can be observed between the non-trabecular model including lamina dura (NT_B-25) and the trabecular model $T(0.56)$. Even the maximum values position is similar in these two cases (see Fig. 8). Therefore, it is obvious from the presented graphs that there is significant difference between stress and strain assessment. Stresses can be of tens to hundreds MPa in trabecular cancellous bone models, increasing with lowering the quality of trabeculae, whereas in non-trabecular cancellous bone stresses are much more lower, decreasing with lowering quality of bone (lowering its Young's modulus).

Neither stresses nor strains can be analyzed in models with CT-obtained material properties because of singularities occurring at interfaces of too many regions of different Young's modulus.

3.2. Stress-strain analysis of mandible with an applied screw implant

Results of the three analyzed stages of osseointegration are shown in Fig. 11 through Fig. 13. The maximum values of stress and strain intensities occurred always in different locations. It is found that not-surprisingly the best case is the fully osseointegrated implant. Two representative modeling-levels are presented. Firstly, model without the special bone layer around the implant ($T(0.56) - 0$), and secondly, model with the special bone layer ($T(0.56) - 0.1$). It is found that the layer reduces stresses and strains in cancellous bone and it also changes their distribution. Fig. 13 shows 1st principal stress distribution in models with lower quality of trabeculae ($T(0.45) - 0.1$ and $T(0.32) - 0.1$).

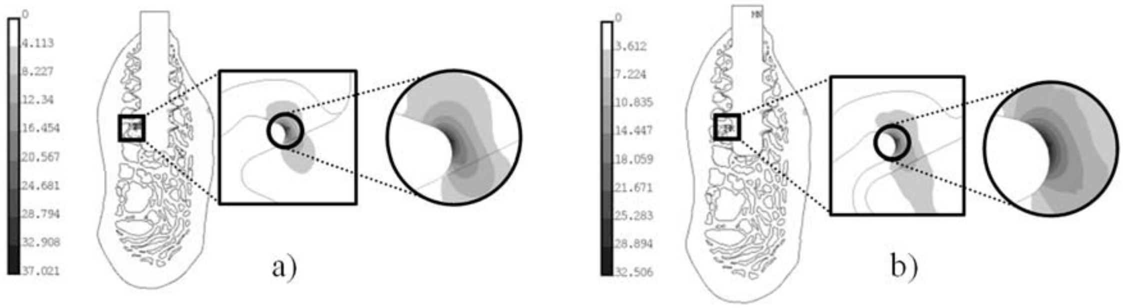

Fig. 11. 1st Principal stress. Stage A: a) $T(0.56) - 0$, b) $T(0.56) - 0.1$

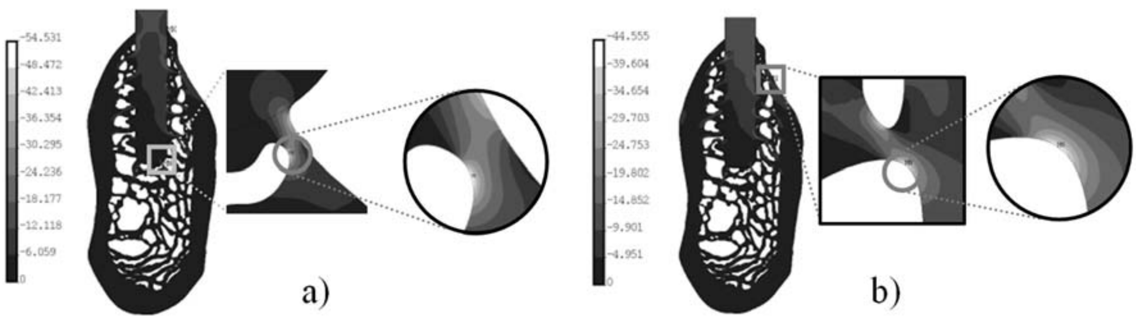

Fig. 12. 1st Principal stress. Stage B: a) $T(0.56) - 0$, b) $T(0.56) - 0.1$

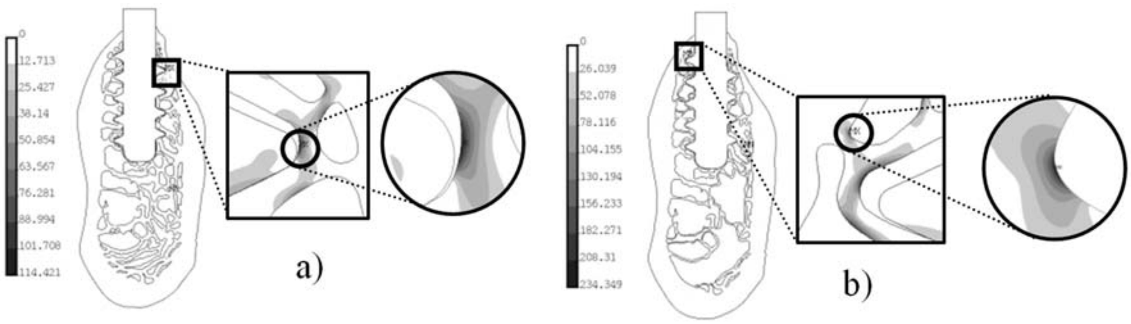

Fig. 13. 1st Principal stress. Stage C: a) $T(0.47) - 0.1$, b) $T(0.32) - 0.1$

As in physiological state analysis, results are presented in bar graphs again (see Fig. 14 and Fig. 15). The series of three bars (each for one stage of osseointegration) are presented for each material used in the model. Only stress and strain intensities are presented. From the graphs, significant difference between stress and strain results is obvious in all analyzed cases. The

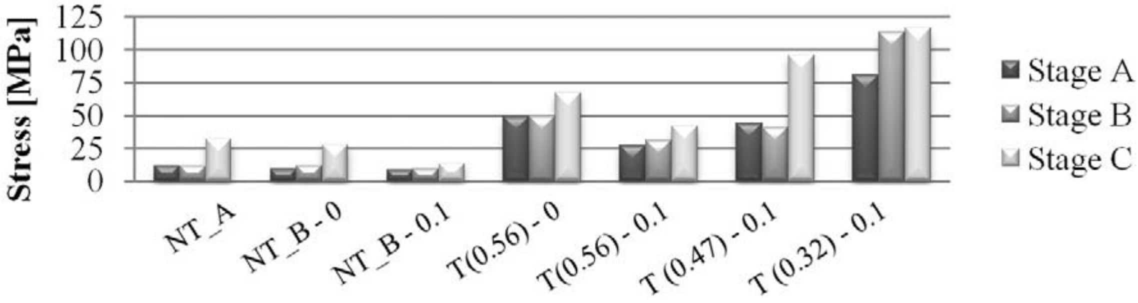

Fig. 14. Maximum stress intensities in cancellous bone

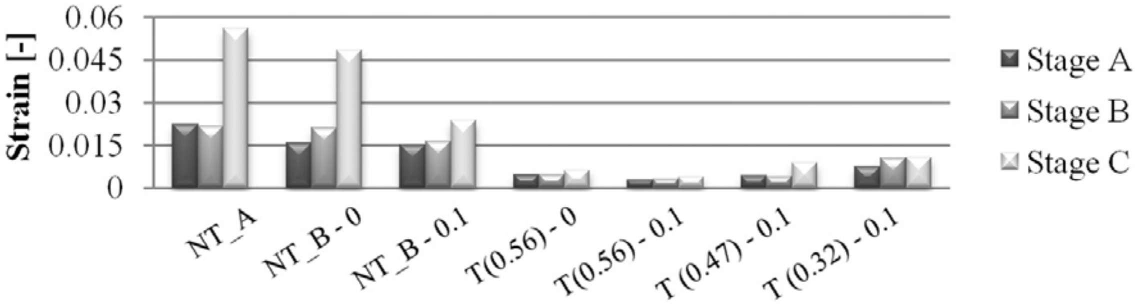

Fig. 15. Maximum strain intensities in cancellous bone

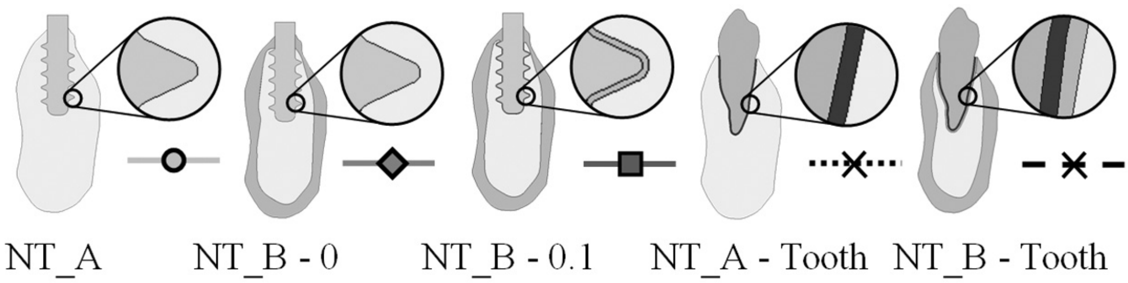

Fig. 16. Non-trabecular material models: Analyzed cases overview

stress intensity is of the highest value in non-trabecular cancellous bone model ($T(0.32) - 0.1$), whereas the strain values are, on the contrary, of the highest value in NT_A model (see Fig. 15). As stated in the previous section, neither stress nor strain analysis are applicable in model with CT-obtained material properties.

3.3. Stress-strain analysis of non-trabecular cancellous bone model

Results presented in the previous section are related to the trabecular model whose lower density (quality) is modeled by assuming thinner trabeculae. However, in most publications considering osteoporotic bone tissue non-trabecular cancellous bone model is prevailing and lower bone quality is modeled with decreasing apparent Young's modulus (see Table 1). Results obtained from such model are presented in this section.

Maximum values of stress intensity and strain intensity were analyzed again. Two states were compared: The physiological state on the one hand, and after implantation on the other (see Fig. 16). The maximum values of stresses change their position as Young's modulus of cancellous bone changes. On the contrary, the position of maximum strain values does not

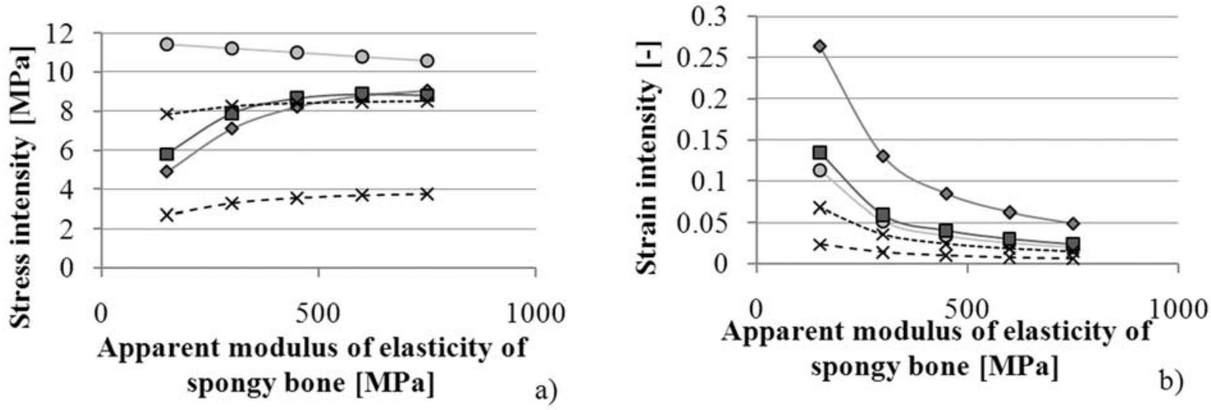

Fig. 17. Maximum stress and strain intensities. Non-trabecular models comparison (for graph legend see Fig. 16)

change (no strain redistribution occurs). As in the previous section, three osseointegration stages are analyzed. Fig. 17 shows results of fully osseointegrated stage. Each graph shows also the comparison with physiological state in two variants (dashed line).

4. Discussion

The loading of real cancellous bone of lower density (i.e. with lower BA/TA value) causes increasing stresses and strains in this tissue. It depends on the trabeculae distribution within the bone, their number and thickness. The lower number and thickness, the higher stresses occur (it is similar to loading of a beam in mechanical engineering). By comparing stresses in Fig. 9 and strains in Fig. 10 it is clear that a significant difference occurs in various material models of cancellous bone. This comparison is not possible in case of CT-obtained material model since no acceptable stresses and strains are calculated due to above mentioned singularities.

As for the models with the implant, a significant difference in maximum stresses and strains occurs in case of various material models. Much higher stresses occur in trabecular model of cancellous bone than in non-trabecular one. Quite the opposite result gives the strain evaluation; the highest values are obtained from non-trabecular model of cancellous bone while the lowest are obtained from trabecular one. Therefore, one should be aware of these differences between both cases (trabecular/non-trabecular). It should be seriously considered which of the two models is suitable for the analysis that one would like to perform. Our study shows that non-trabecular model is no longer suitable for analysis of interaction bone-tooth/implant. Model at higher modeling-level (i.e. trabecular model) should be used instead. To these days, cancellous bone is usually modeled as non-trabecular mass with no complicated structure of trabeculae [3, 6, 26]. An apparent Young's modulus obtained from experiment or from CT is prescribed to this structure. Stresses obtained from such models are inconsistent with reality because with decreasing bone quality stresses should increase, not decrease as shown by non-trabecular model results presented in this study. This inconsistency does not appear in strain evaluation. With decreasing bone quality strains increase (see Fig. 17a). The reason why maximum stresses in cancellous bone decrease as strains increase can be explained by the presence of cortical bone which plays significant role of the load bearing structure. This is obvious from Fig. 17a which shows that stresses in the model without the cortical bone (NT_A) are almost independent on Young's modulus change while stresses in the model with cortical bone (NT_B)

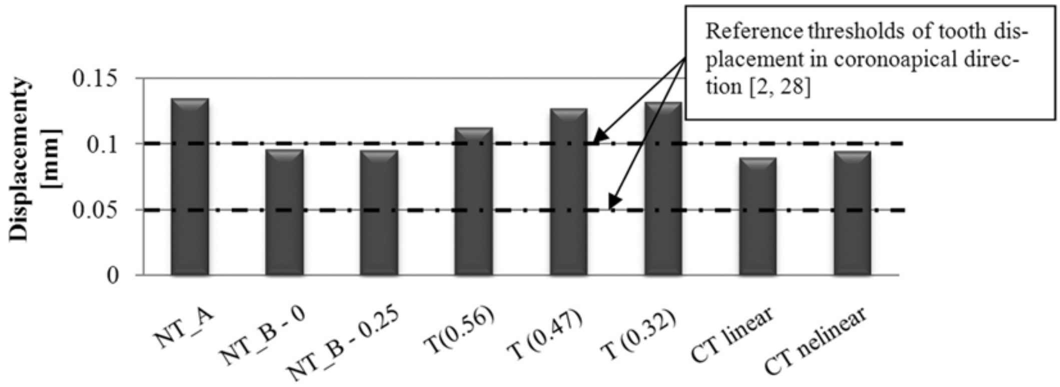

Fig. 18. Coronoapical tooth displacements

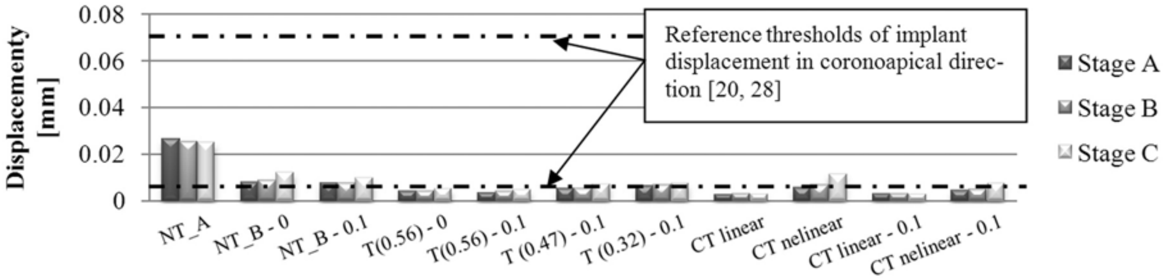

Fig. 19. Coronoapical implant displacements

decrease with the changing Young's modulus. This is because the load is carried via the cortical bone and the cancellous bone load is reduced. The study shows that strains are more appropriate mechanical quantity for the evaluation of mechanical interaction.

Verification of model quality, and thus quality of calculation results, is quite difficult in biomechanics. In case of dental biomechanics there is a possibility to utilize known values of tooth movement and implant movement. Specifically, we can compare calculated tooth and implant displacements in the coronoapical direction (i.e. in direction of the applied force) with that of obtained from literature. The displacement, in case of a tooth embedded in a bone of normal quality (see model $T(0.56)$) and loaded by force of 200 N, is of 0.092 2 mm. This value falls within the interval 0.05–0.1 mm which is valid for the same loading [2, 28]. Displacement results for all models are shown in Fig. 18. Maximum calculated value of implant displacement ranges from 0.004 to 0.027 mm (see Fig. 19). These results are also in agreement with values obtained from literature (0.005–0.073 mm; [20, 28]).

5. Conclusion

This biomechanical study is focused on assessment of the modeling-level of cancellous bone and its interaction with tooth or dental implant. 39 computational models are created and analyzed. Maximum values of stress and strains are evaluated and for better clarity shown in several graphs. Following conclusion can be stated:

1. It is more suitable to evaluate strains than stresses in an assessment of mechanical response of cancellous bone on its loading.

2. CT-obtained material model of cancellous bone is not acceptable for stress-strain analysis because of singularities occurring at interfaces of too many regions with different Young's modulus. However, this model can be used for stress evaluation in implants.

3. Trabecular model of cancellous bone is more suitable for analysis of interaction of bone with the embodied tooth/implant. Further improvement of modeling-level should be researched. One possible direction of this research could be using micro CT, which can be helpful for creating 3-D trabecular model of cancellous bone.

Acknowledgements

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