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FEM analysis of compression screws used for small bone treatment

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Analysis and modelling

ABSTRACT

Purpose: The paper presents results of numerical analysis in metatarsal bone „I" - compression screws system. The aim of the work was determined stresses, strain and displacement in the inserted screws.
Design/methodology/approach: Metatarsal bone „I" was selected to researches. The analysis was carried out on the metatarsal bone „I" - compression screws system. The influence of the loads and displacements on the bone - screws system on the results of numerical analyses was analyzed. In order to carry out calculations, 2 models of diverse mechanical properties of screw - Ti-6Al-4V alloy - model 1, stainless steel (Cr-Ni-Mo) - model 2 and two load steps were selected.
Findings: The analyses showed the difference in displacements, strains and stresses depending on the selected mechanical properties screws and the way of loads.
Research limitations/implications: The limitations were connected with simplification of numerical model of femur as well as with the selected boundary conditions. Two difference way of loads metatarsal bone „I" - compression screws system: 1_force F = 500 N, 2_ displacement l = 1 mm were applied.
Practical implications: The obtained results can be useful in clinical practice. They can be applied in selection of stabilization methods or rehabilitation as well as in describing the biomechanical conditions connected with type of bone fracture obtained from medical imaging.
Originality/value: Stress-strain-displacement characteristics of metatarsal bone „I" - compression screws system, obtained from the numerical analysis were presented in the work.
Keywords: Numerical techniques; Biomechanical analysis; Biomaterials

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1. Introduction

Nowadays the canullated compression screws are used for small bone treatment such as scaphoid fractures, intercarpal arthrodesis, finger joint arthrodesis and corrective osteotomy of hallux valgus. Application of this kind of surgery implants make fast healing of bone fractures possible [1-5].

Implantation technique consists: first drill and screw guide. The Kirschner wire is inserted using the drill and screw guide. Second, checking the position of the K-wire in 4 planes under image intensifier control. After that the surgeon determining screw length, drilling through drill and screw guide. Next the compression screws are inserted - Figs. 1 and 2. At the end of implantation procedure the position of screws are being checked in 4 planes under image intensifier control - Fig. 1 [1].

From the biomechanical point of view, determination of hard tissues structure is crucial. Knowledge of the properties is essential, both in diagnosis of bone system illnesses as well as in selection of implants' mechanical properties. Stiffness of a bone - implant system is particularly important [6-25].

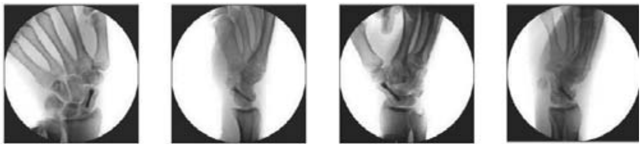


Fig. 1. Checking the position of the screw in 4 planes: axial, Lateran, 45° pronation, 45° supination [1]

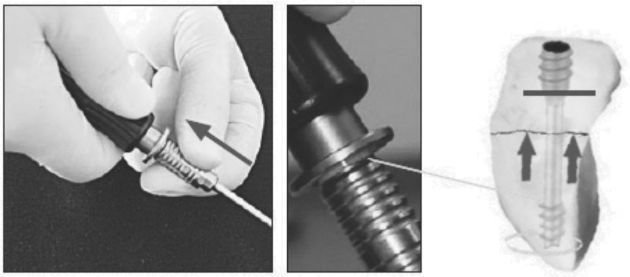


Fig. 2. Insertion of the screw [1]

2. Materials and methods

The bones of foot includes tarsal bones, metatarsals (bones) [I-V], phalanges, and sesamoid bones. Metatarsal bone "I" was applied in the analysis. This is the longest, the thickness and the most loaded bone of foot - Fig. 3. In order to carry out the numerical analysis the following material properities of bone were set: Young modulus E = 18600 MPa and Poisson's ratio $\nu = 0.3$.

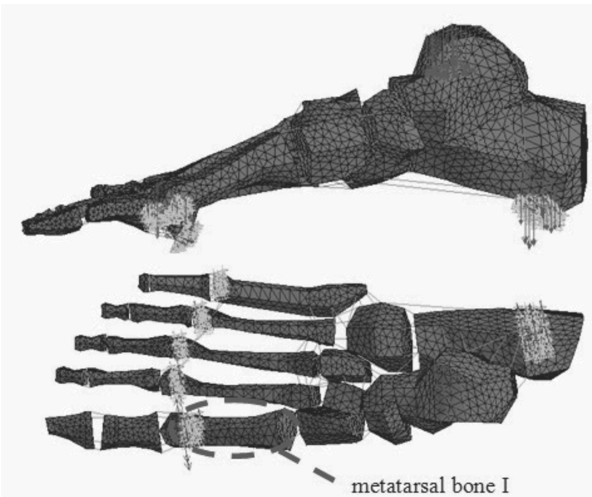


Fig. 3. Geometrical model of human foot and metatarsal bone "I" choose for numerical analysis

Geometrical model of compression screws was carried out in ANSYS software on the basis of technical documentation - Fig. 4. The following material properties were set:

- model 1:
- titanium alloy - Ti-Al-4V ELI [27]:
  - Young modulus E = 110000 MPa
  - Poisson's ratio $\nu = 0.33$
- model 2:
- stainless steel Cr-Ni-Mo [26]:
  - Young modulus E = 200000 MPa
  - Poisson's ratio $\nu = 0.33$

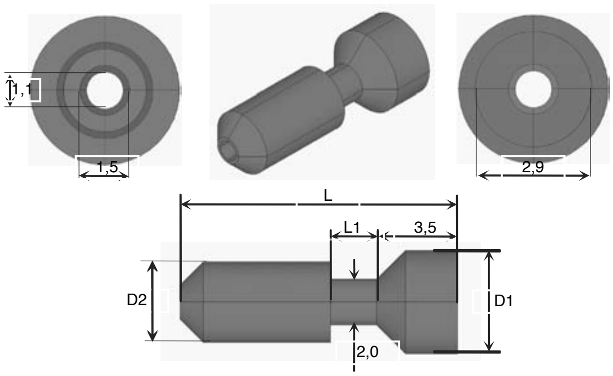
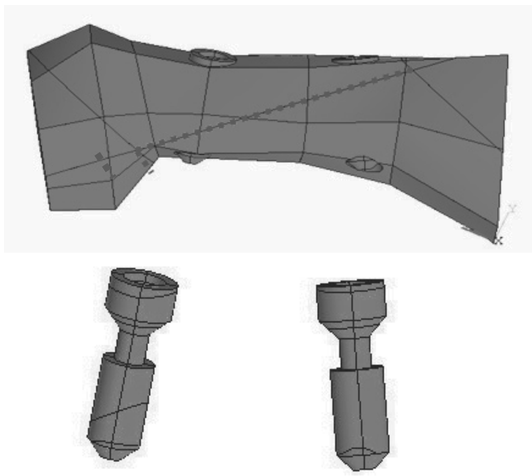


Fig. 4. Geometrical model of compression screw

Geometrical model of metatarsal bone "I" - compression screws system take into considerations operation technique was presented in Figure 5.

a)



b)

Fig. 5. Geometrical model of metatarsal bone "I" - compression screws system: a) general view of metatarsal bone "I" with fracture gap, b) compression screws

On the basis of the geometrical models a finite element mesh was generated. The meshing was realized with the use of the SOLID95 element - Fig. 6. This type of element is used for the three-dimensional modeling of solid structures. The element is defined by 20 nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions - Fig. 7.

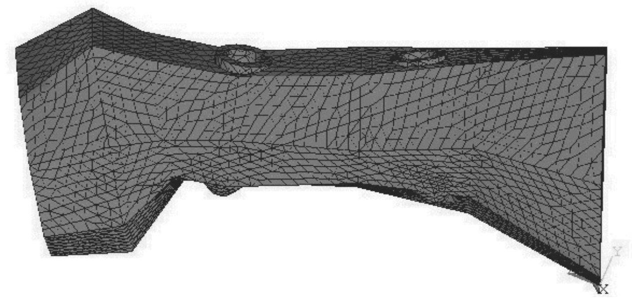


Fig. 6. Discrete model of the metatarsal bone "I" - compression screw system

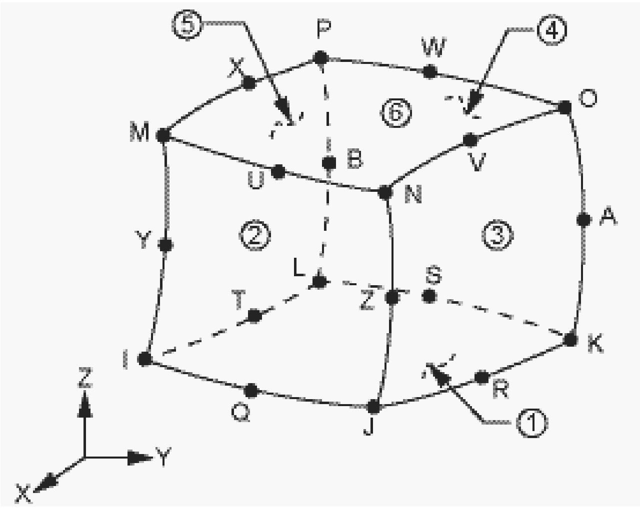


Fig. 7. The SOLID 95 finite element

In the course of the work, displacements, strains and stresses, depending on the screws mechanical properties, were calculated.

In order to carry out the calculations, appropriate initial and boundary conditions reflecting phenomena in real system were determined - Fig. 8.

The following assumptions were set:

- lower part of the metatarsal bone "I" was immobilized (all degrees of freedom of nodes on external surfaces of condyles were taken away),
- bone was loaded according to the scheme presented in Fig. 4. There were perform two stages of solution: 1 – displacement 1 mm was established at the basis of metatarsal bone "I", 2 - force F = 500 N was applied at the basis of metatarsal bone "I"

The range of analysis consisted of determination of displacements, strains and stresses:

- in elements of the metatarsal bone "I" - compression screws made of stainless steel,
- in elements of the metatarsal bone "I" - compression screws made of Ti-6Al-4V alloy.

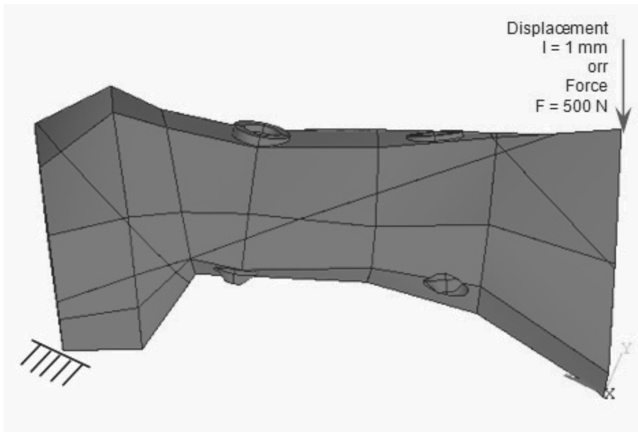


Fig. 8. Loading scheme of model

Table 1.
Results of the FEM analysis of the metatarsal bone "I" - compression screws system

Load steps			Displacement, mm				Strain ε, %	Stress σ, MPa
			x	y	z	Σ		
			Metatarsal bone "I" - compression screws system (Ti-6Al-4V alloy)					
1	Displacement 1 mm	System	0.32	0.05	0.17	1.02	0.32	4704
		Compression screws			—			870
2	Force F = 500 N	System	0.007	0.006	0.053	0.544	0.44	4525
		Compression screws			—			385
			Metatarsal bone "I" - compression screws system (Cr-Ni-Mo stainless steel)					
1	Displacement 1 mm	System	0.30	0.03	0.16	1.069	0.32	4762
		Compression screws			—			1389
2	Force F = 500 N	System	0.006	0.005	0.05	0.529	0.44	4525
		Compression screws			—			541

3. Results

The obtained maximal displacements, strains and stresses for the metatarsal bone "I" - compression screws system for both metallic biomaterials (Ti-6Al-4V alloy and Cr-Ni-Mo stainless steel) and two load steps are the reduced values according to the Huber-Mises-Henck hypothesis. The obtained results were presented in table as well as in the graphic form.

The results for the given boundary conditions were presented in Table 1 and Figures 11 to 22.

The obtained results allowed to draw graphs representing relation between the global and axial displacements and stresses depending on the applied boundary conditions - Fig. 9 and 10. On the basis of the analysis it was concluded that maximum equivalent stresses were localized the fixation site of the model and in the point of the applied loading. Lower values of both displacements and stresses were presented in the models loaded with the force of 500 N for the screws made of Ti-6Al-4V alloy.

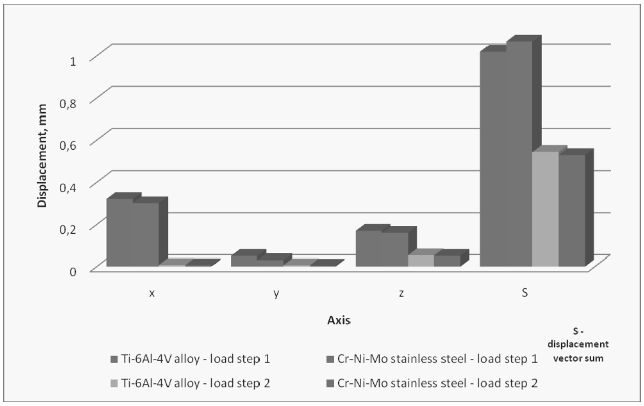


Fig. 9. Comparison of maximum displacement for all analyzed models

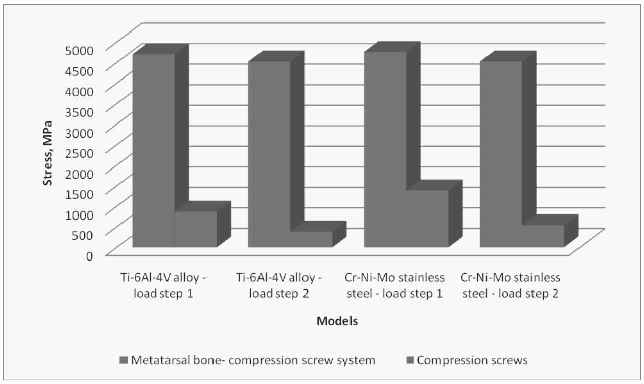


Fig. 10. Comparison of stress value for all analyzed models

Maximum stresses in the screws were localized in the transition zone between threads for the displacement equal to 1 mm. For the Ti-alloy and stainless steel screws and for the applied boundary conditions, maximum stresses were equal to 870 MPa and 1389 MPa, respectively. However, the stresses on the whole surface, for both the applied force 500 N and the displacement equal to 1 mm, did not exceed 400 MPa for the Ti-alloy screws and 500 MPa for the steel screws.

3.1. FEM analysis of the bone - compression screws system - compression screw made of Ti-6Al-4V alloy - load step 1

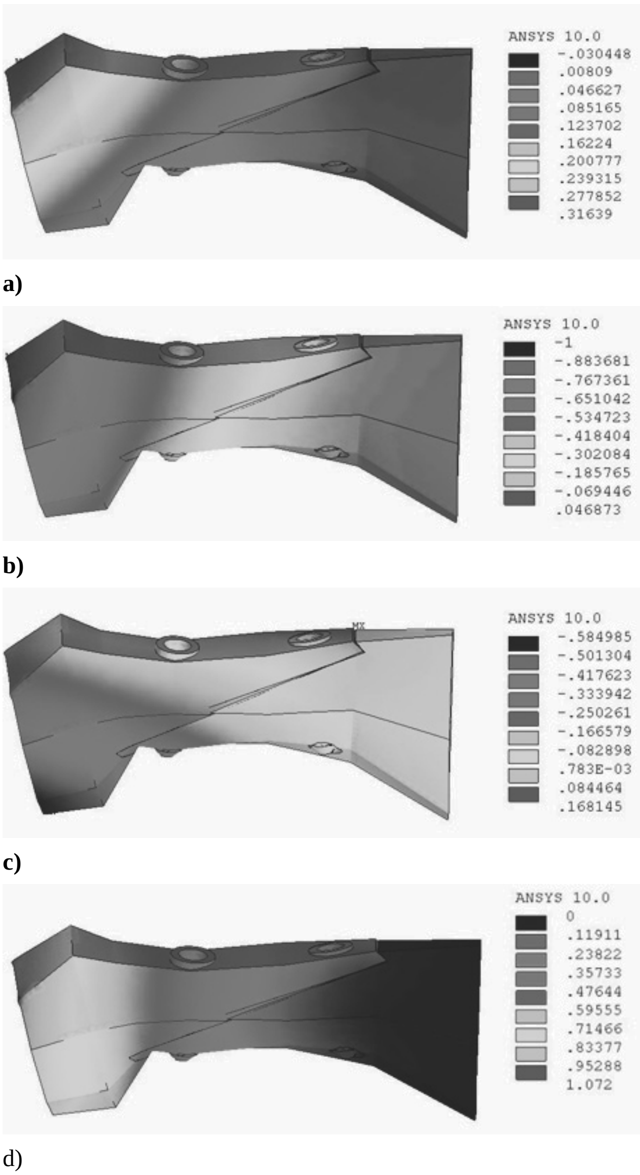


Fig. 11. Displacement distribution in bone - compression screws system: a) axis OX, b) axis OY, c) axis OZ, d) displacement vector sum - Ti-6Al-4V alloy, load step 1

Fig. 12. Strain distribution in bone - compression screws system x100% - Ti-6Al-4V alloy, load step 1

a)

b)

Fig. 13. Stress distribution in bone : a) compression screws system, b) crews, MPa (screws - Ti-6Al-4V, load step 1)

3.2. FEM analysis of the bone - compression screws system - compression screws made of Ti-6Al-4V alloy - load step 2

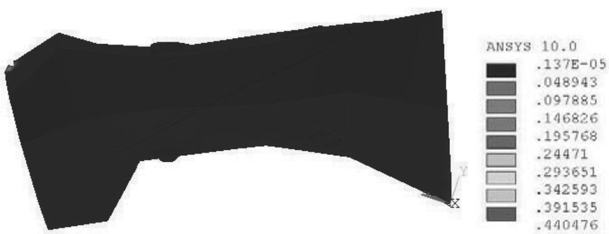
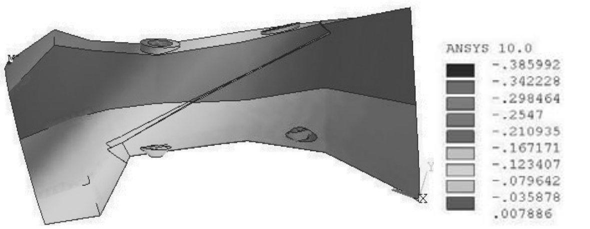


Fig. 14. Strain distribution in bone - compression screw systems x100% - Ti-6Al-4V alloy, load step 2



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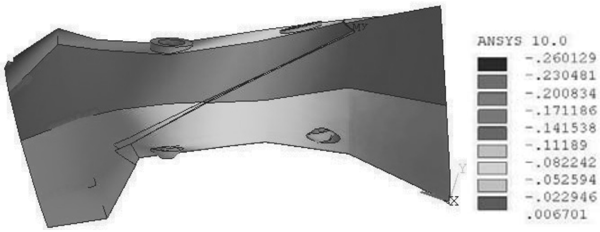

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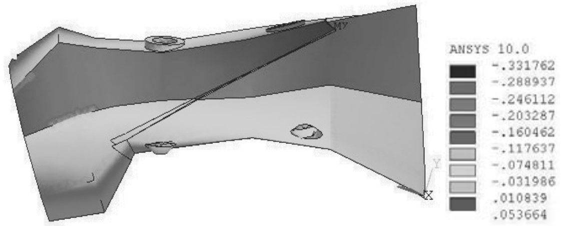
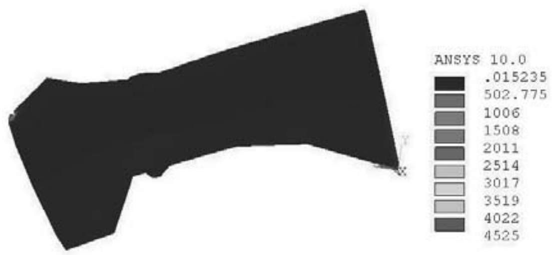


c)

d)

Fig. 15. Displacement distribution in bone - compression screws system: a) axis OX, b) axis OY, c) axis OZ, d) displacement vector sum - Ti-6Al-4V alloy, load step 2



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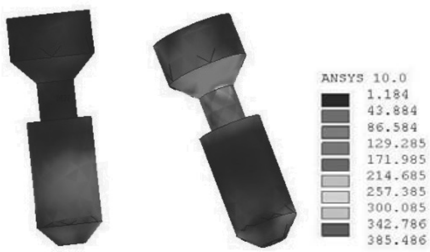
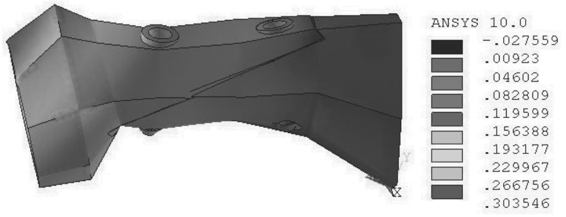


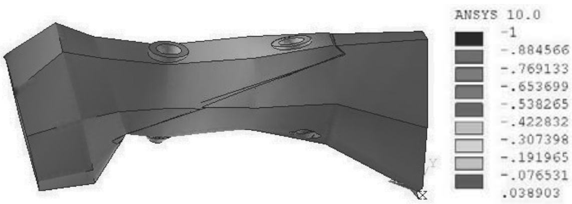
b)

Fig. 16. Stress distribution in bone: a) compression screws system, b) crews, MPa (screws - Ti-6Al-4V, load step 2)

3.3. FEM analysis of the bone - compression screws system - compression screw made of Cr-Ni-Mo stainless steel - load step 1



a)



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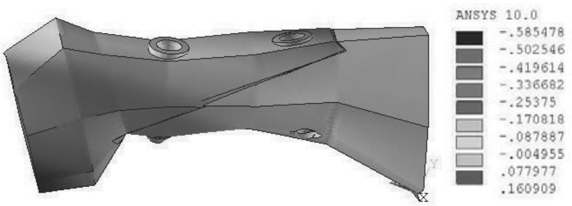
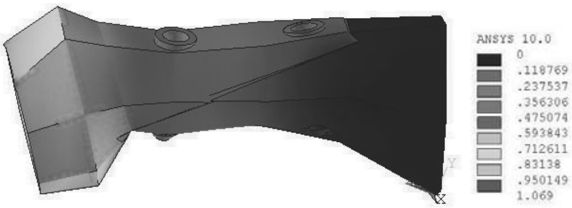


c)



d)

Fig. 17. Displacement distribution in bone - compression screws system: a) axis OX, b) axis OY, c) axis OZ, d) displacement vector sum - Cr-Ni-Mo stainless steel, load step 1

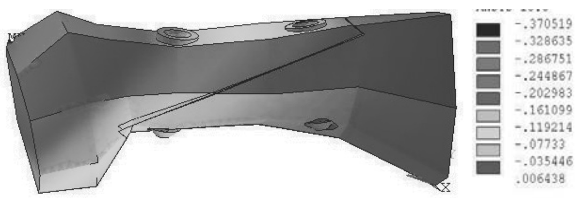
Fig. 18. Strain distribution in bone - compression screws system x100% - Cr-Ni-Mo stainless steel, load step 1

a)

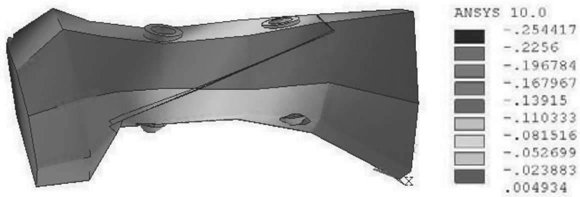
b)

Fig. 19. Stress distribution in bone: a) compression screws system, b) crews, MPa (screws - Cr-Ni-Mo stainless steel, load step 1)

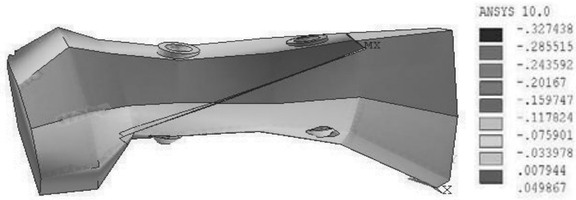
3.4. FEM analysis of the bone - compression screws system - compression screw made of Cr-Ni-Mo stainless steel - load step 2



a).



b)



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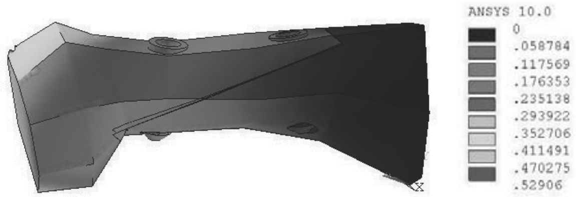

d)

Fig. 20. Displacement distribution in bone - compression screws system: a) axis OX, b) axis OY, c) axis OZ, d) displacement vector sum - Cr-Ni-Mo stainless steel, load step 1

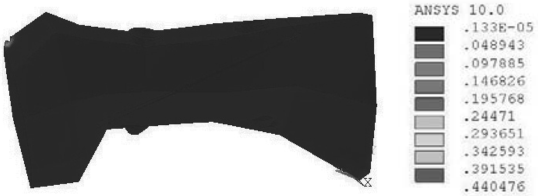

Fig. 21. Strain distribution in bone - compression screws system x100% - Cr-Ni-Mo stainless steel, load step 2

a)

b)

Fig. 22. Stress distribution in bone: a) compression screws system, b) crews, MPa (screws - Cr-Ni-Mo stainless steel, load step 2)

4. Conclusions

The preliminary numerical analysis of the metatarsal bone “I” - compression screws system for the applied different metallic biomaterials allowed to indicate dangerous areas of the compressive screws and is starting point for the geometry optimization. The analysis of the obtained results showed that for the given way of loading, the damage of the screws is highly probable in the most vulnerable area ei. the transition zone between threads. The initial research carried out on the simplified model, taking into consideration only the metatarsal bone "I", will be continued with the use of the complete model presented in Fig. 1. Further research of compressive screws will be focused on experimental tests in order to verify the results of the numerical analysis.

Acknowledgements

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