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Biomechanical analysis of the femur-Dynamic Condylar Screw (DCS) system

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ABSTRACT

Purpose: The aim of this study was a biomechanical evaluation of the (Dynamic Condylar Screw - DCS) system after epicondyle fractures and a comparison of obtained results of the two alternative biomaterials for the stabilizer.

Design/methodology/approach: Models of stabilizer and femur were designed, the discretization was conducted and boundary conditions were set. Numerical analysis with the use of the finite element method was performed in the ANSYS Workbench 15 Software. Two models of system: M-316 LVM (stabilizer with properties CrNiMo steel - femur) and M-Ti64 (stabilizers with properties Ti6Al4V alloys – femur) were subjected to numerical analysis. As a reference point the state of displacement, strain and von Misses stresses by in helfy femur (M-HF) were determined.

Findings: For all of the analysed models, the values of assumed mechanical properties of cortical bone and cancellous bone were not exceeded. Simultaneously, it is possible to use alternative biomaterials, CrNiMo steel or Ti6Al4V alloy for DCS system.

Research limitations/implications: In order to perform more detailed characteristics of analysed DCS implant, in future research it is expected to carry out macro and microscopic observations for implants removed from the body and their electrochemical evaluation.

Practical implications: The analysis allows the determination of potentially dangerous areas, affected to damage due to overloading. Furthermore, the analysis identifies the areas of initiation and development of crevice, pitting and fatigue corrosion.

Originality/value: The presented work allows the selection of alternative metallic biomaterials for the manufacturing of the evaluated DCS system and indicates its potentially dangerous area. This work might be interesting for engineers and doctors dealing with the construction of a new forms of implants used in orthopedics.

Keywords: Dynamic Condylar Screw (DCS); Metallic biomaterials; AISI 316LVM; Ti6Al4V; FEM

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

First of all, the aim of surgical epicondyle fractures is to combine fractions in a stable way and restore proper limb functioning in short period of time. Therefore, the early admission by patient the vertical of body posture is important, because it protects against general and local complications. One of the methods used to join the broken parts of the femur lower extremity is DCS (Dynamic Condylar Screw) system. This method anticipates in joining the bone with angular plate which is fixed with screws with proper diameter and length. This stabilizer is most commonly made from corrosion resistant 316 LVM steel in cold worked state. The holes made in the angular plate enable fixing the cortical screws with 4.5 mm diameter on the proper angle that ensures the axial compression in the fracture area. There are 3 to 16 holes in the DCS plate and it is chosen depending on fracture type. The length of used bone screws for cortical and cancellous bones varies from 50 mm to 145 mm. Application of DCS system assures the minimal irritation of soft-tissue [1-3].

Numerical analysis preceding stabilizing system implantation, which was carried out to obtain displacement and stresses states that occur in implant during stabilization, in bones fractions and on the interface of implant-osseous tissue is important because of biomechanical features of the stabilizer and metallic biomaterial type [4-9].

The metallic biomaterial for implants is determined on the basis of: constructional, shape of the implant, surgical technique, service life, biomechanical features of reconstructed tissue and also individual attributes of the patient are important. The most important is the ability of immunological reaction with metallic compounds, which are the parts of metallic biomaterials used to produce implants [10,11]. The mutual relation between these factors are very complex and make it difficult to select the metallic biomaterial type and to settle the physicochemical and mechanical properties.

These properties should be also adjusted to surgical technique connected with preoperative modeling of the implants [10].

The determined mechanical characteristics of the loaded internal fixation models of a bone fractures are a basic criterion of choosing metallic biomaterial and their mechanical properties. The internal fixation should provide the fracture stabilization and proper conditions for physiological stimulation of regeneration processes.

Therefore, the range of stresses and displacement in the fixation area should not exceed the boundary value, both according to tissues and metallic material. What is more, providing a desirable flexibility of loaded stabilization system should correspond to mechanical properties of passive layers which were created on the implants surface. The damage of the protective films could lead to corrosion initiation and evaluation processes. The surgical technique and the improvement of fracture place in biomechanical point of view contributes to diversification of corrosion process in particular implants areas. Moreover, identification of the corrosion processes is a base to modify the external metallic biomaterial layers and the constructional implants form modifications [12].

In presented work, the authors concentrate on the numerical analysis which consist of valuation of possibility of applying the alternative metallic biomaterials to produce a DCS stabilizer and subsequently to determine areas of maximum displacements and stresses in elaborated numerical models.

2. Methodology

In this work the dynamic system analysis of internal fixation of bone fractures around lower extremity of femur especially of simple and compound fractures was carried out. The displacement, strain and reduced stress distribution was shown for Dynamic Condylar Screw (DCS)-femur system with simulated simple epicondyle fracture type A1 according to AO classification [1]. DCS system was composed of: a plate adjusted to anatomical femur geometry, DCS screw, screws for cancellous bone, compressive screw which joins DCS plate with DCS screw and cortical bone screws which fix a plate in femur bone body.

The aim of carried out analysis was a biomechanical evaluation of DCS system after epicondyle fracture and a comparison of obtained results for two alternative biomaterials, from which it is possible to obtain stabilizer elements. Especially, the CrNiMo (AISI 316LVM) steel and Ti6Al4V alloy were used. The DCS is composed of: DCS screws thread with diameter G=12.5 mm (standard DCS screw used to cancellous bone), 5 standard cortical bone screws with diameter: BS=4.5 mm and 2 screws to cancellous bone CS=6.5 mm. Two models of femur-Dynamic Condylar Screw system were subjected to analysis:

- M-316LVM: Stabilizer made of CiNiMo steel-femur,
- M-Ti64: Stabilizers made of Ti6Al4V alloy-femur.

As reference the displacement, strain and von Misses stresses were determined in unbroken femur (M-HF).

2.1. Geometrical models

The geometrical model of DCS system applied in analysis was elaborated in BHH Mikromed. The Autodesk Inventor 2015 software was used to created models – Fig. 1.

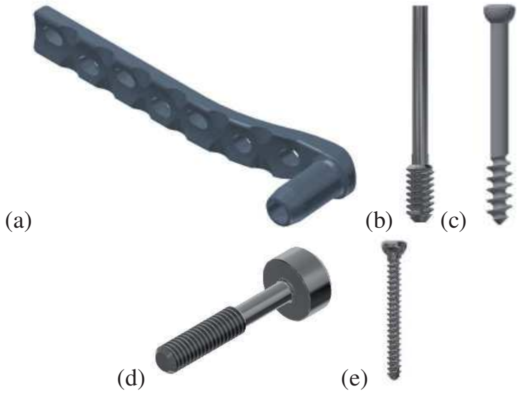


Fig. 1. Elements of dynamic condylar screw DCS: (a) DCS plate, (b) DCS screw, thread diameter: 12.5 mm, (c) Cancellous bone screw, thread diameter: 6.5 mm WG, (d) compression screw, (e) cortical bone screw, thread diameter: 4.5 mm WK

The geometrical model of femur was developed on the basis of data obtained from Computed Tomography. The geometric model of the femur was prepared in the Mimics Innovation Suite software based on CT images with the following parameters: the size of the pixel in the lateral plane: 0.684 mm, the imaging field width: 171.68 mm, distance between sections: 1.5 mm, the number of sections: 331.

In order to segment bones, thresholding operation was performed with the lower threshold value of 226 HU and upper threshold value of 1613 HU. The total volume of the model: 230 286 mm^3, while the total area of the model was: 67808 mm^2. It included both the cortical and the cancellous part of the femur.

For the numerical analysis, the assumed mechanical properties of used materials are shown in Table 1.

2.2. Numerical model

In order to carry out a numerical analysis with used of Finite Element Method the ANSYS Workbench 15 software was used.

On the basis of geometrical models, the numerical models were prepared. To limit the amount of finite elements, it was decided to simplify the geometry of cortical bone screws (BS) – Fig. 2, because of complex shapes of cortical screws and irregular bone geometry.

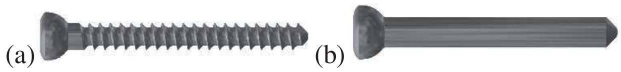


Fig. 2. Geometrical model of the cortical bone screw BS (a) and the corresponding simplified model (b)

The next step all elements according to surgical technique were assembling in Inventor software – Fig. 3. After that, the obtained geometry was exported to ANSYS Workbench software, where the boolean operations of cutting out the holes for: bones screws, DCS screws and DCS plate was performed. This step simulated the implantation surgery of the dynamic condylar screw supporting femur – Fig. 4.

Table 1.
Mechanical properties assumed in the numerical analysis of the femur-DHS system

Element of a computing system			Mechanical properties				
			Young's modulus, E, MPa	Poisson's ratio, υ	Ultimate compressive strength R_c, MPa	Yield strenght $R_{p0.2}$, MPa	Ultimate tensile strength R_m, MPa
Femur	Stem	[15]	17900	0.3	180	-	-
	Head	[13]	17000	0.3	-	-	-
	Trabecular bone	[15]	10500	0.3	-	-	-
	Early Stage of Fracture Healing	[13] [14]	3	0.4	-	-	-
Cr-Ni-Mo steel		[16]	200000	0.33	-	690	1300
Ti6Al4V alloy		[17]	110000	0.33	-	780	860

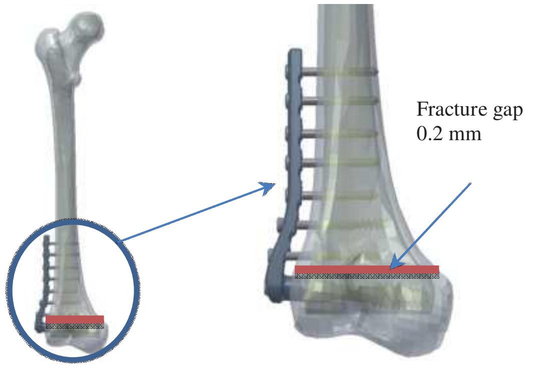


Fig. 3. Geometrical model of femur-Dynamic Condylar Screw DCS system

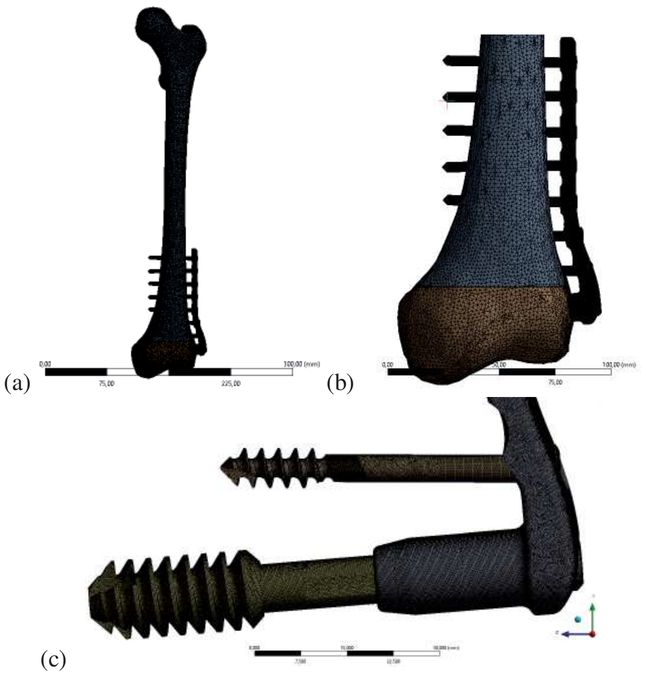


Fig. 4. Geometrical models with applied finite element mesh: (a) femur, (b) lower extremity of femur, (c) fragment of DCS stabilizer

On the basis of geometrical models, the finite element method mesh was generated – Fig. 4. The SOLID187 finite elements were used to model discretization (for spatial solids analysis). This type of element is defined by 10 nodes that three degrees of freedom in each node (displacements in x, y and z direction).

The mesh was constructed through convergence of analysis. Different element size were tested until the maximum stress value reached 5% in all components (elements sizes tested: 3, 2.75, 2.5, 2.25, 2, 1.75, 1.5, 1.25, 1 mm). As a finite element regular tetrahedron with side length of 1.75 mm was used.

Additionally, it was stated, that the generated finite element mesh was characterized by skewness parameters in range from 0 to 0.5, which indicate it's very good fitting to geometry of analysed system – Fig. 5 [18].

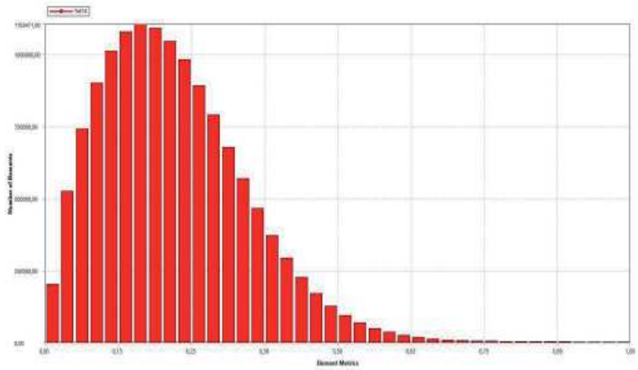


Fig. 5. Distribution of skewness parameter of generated finite element mesh

2.3. Boundary condition

In order to perform the solutions, it was necessary to identify and give initial and boundary conditions, which can simulate the occurring phenomena in a real system with sufficient accuracy.

For the analysis the following assumptions were made:

- lower extremity of femur was immobilized by taking away all the degrees of freedom from the reception nodes which were located in plane – area A (Fig. 6);
- the bone was loaded with use of Będziński model, which was also used in other works related to numerical analysis of the femur. Three groups of forces were used: the resultant force acting on the femur head – Force B, Muscle response force (gluteus medius) – Force D and iliotibial band syndrome Force-Force C – Table 2;
- in research, the assumed values of forces corresponded to reduced by half maximum values obtained during the phase in which loaded body carries 70 kg by one limb during walking – Fig. 6;
- in lower extremity of femur with epicondyle fractures with A1 type according to AO classification with crevice between bone fractures d = 0.2 mm and healing osseous tissue were simulated.

Table 2.
The values of forces adopted in the numerical calculations

Force B, N			Force C, N			Force D, N		
The direction of force action according to accepted co-ordinate system								
x	y	z	x	y	z	x	y	z
0	-912	-247	10.5	0	27	0	604	247

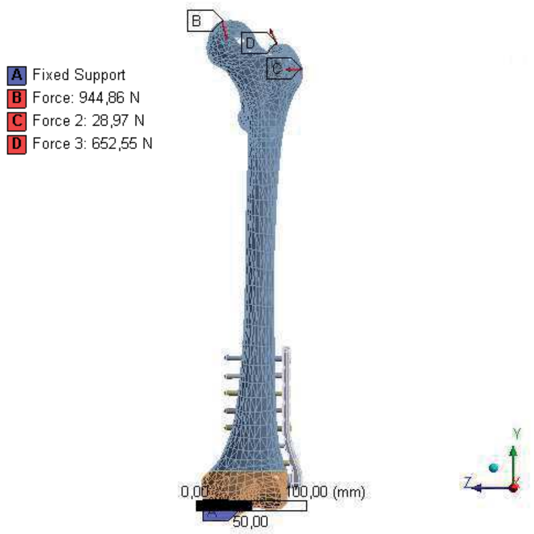


Fig. 6. The numerical model with assumed boundary conditions

The range of analysis included the determination of displacement, strain and stresses states for two system models: DCS-the femur (M-316LVM and M-Ti64) and unbroken femur M-HF.

Moreover, in all DCS system elements to femur contact areas, the standard contact "bounded" type contact was used.

The stresses and displacements obtained from the performed analysis are reduced values according to Huber-Misses-Hencky hypothesis.

3. Results and discussion

All results of displacement, reduced strains and stresses for all analysed models of femur-DCS system and unbroken bone are shown in Table 3.

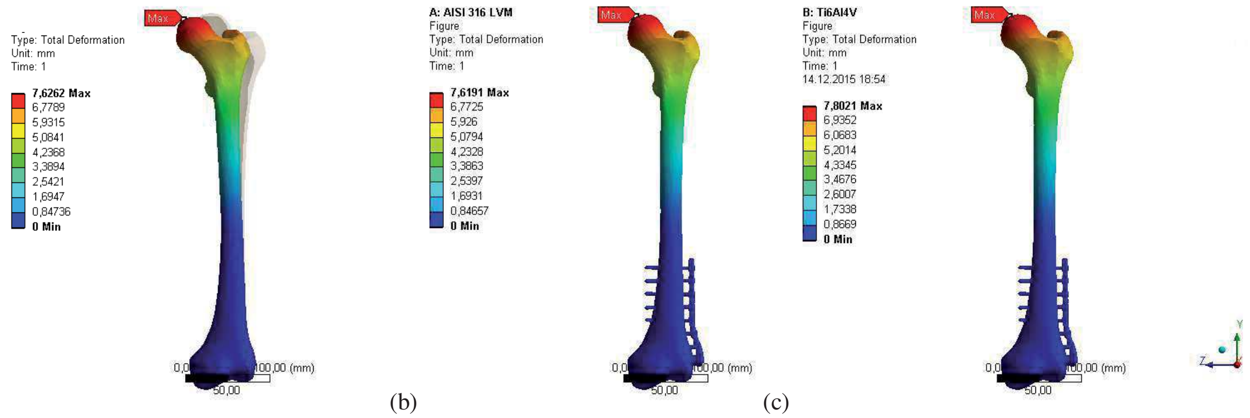
Exemplary graphical representation of obtained results for whole numerical models and DCS system are shown in Figs. 7-9. Due to the fact that the maximum values of displacements and von Misses stresses for the entire system, meaningfully differ from the average values of analysed models, displacements and stresses maps were presented in logarithmic scale.

Table 3.
Results of numerical analysis of femur-DCS stabilizer system and unbroken bone with different diameters and amount of used bone screws and diameters DCS screws

		Max value of von Misses stresses in particular system elements σ, MPa							
No.	Model	σ_{CortB}	σ_{CCortB}	σ_{CB}	σ_{DCS}	σ_{CompS}	σ_{DCSp}	σ_{BS}	σ_{CS}
1	M-316LVM	65	21	2	47	57	221	428	142
2	M-Ti64	67	21	2	24	40	161	293	115

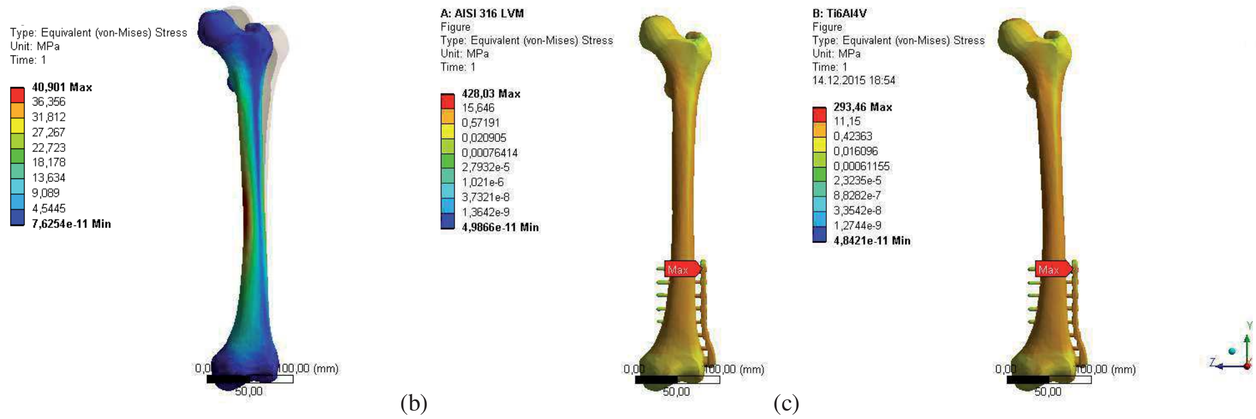
		Max value of displacements strains and stresses for all models		
No.	Model	L, mm	ε, mm/mm	σ, MPa
1	M-316LVM	7.62	0.71	428
2	M-Ti64	7.8	0.75	293
3	M-HF	7.6	0.0023	40

L – displacement, ε – von Misses strain, σ – von Misses stress, σ_{PCortB} – proximal cortical bone, σ_{CCortB} – condylar cortical bone, σ_{CB} – cancelous bone, σ_{DCS} – DCS screw, σ_{CompS} – compression screw, σ_{DCSp} – DCS plate, σ_{BS} – bone screws, σ_{CS} – cancelous screws



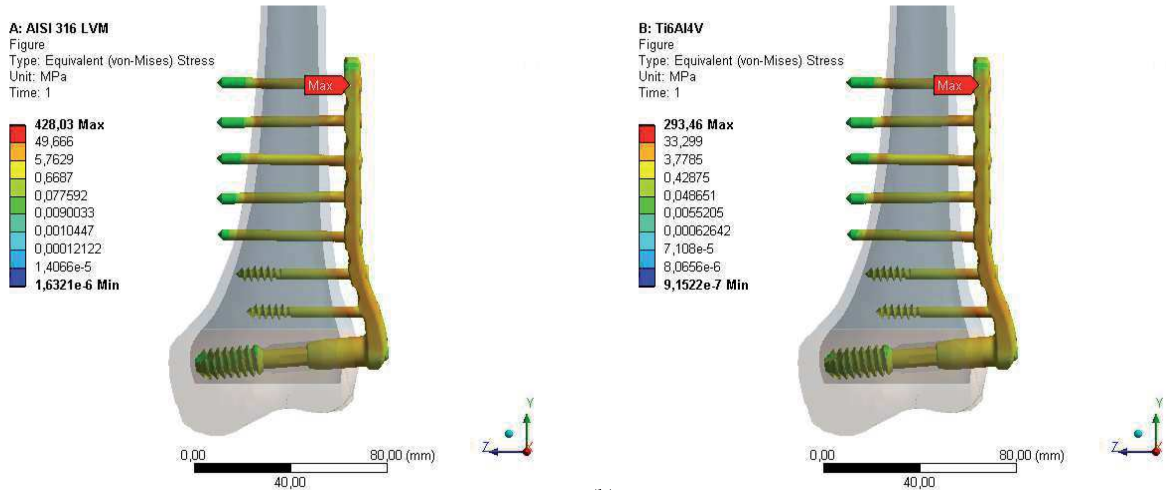
(a) (b) (c)

Fig. 7. Distribution of displacement for analysed numerical models: (a) unbroken bone, (b) DCS-femur system (CrNiMo), (c) DCS-femur system (Ti6Al4V)



(a) (b) (c)

Fig. 8. Example of distribution of reduced stresses σ for analysed models: (a) unbroken bone, (b) DCS-femur system (CrNiMo), (c) DCS-femur system (Ti6Al4V) – logarithmic scale



(a) (b)

Fig. 9. Distribution of reduced stresses for DCS system (logarithmic scale):(a) DCS (CrNiMo),(b) DCS (Ti6Al4V)

On the basis of obtained results, it was found that for unbroken femur model (M-HF), loading with force arrangement by Bedziński's model caused the displacement of upper extremity of femur equal to L=7.6 mm (Fig. 7a), which corresponded to strain and reduced stress equal to ε=0.0023 mm/mm and σ=40 MPa.

Moreover, it was found that the maximum strains and stresses values were located at half length of diaphysis shaft (Fig. 8a).

The obtained values of displacements for analysed femur-DCS stabilizer (Figs. 7b-c) system were similar to values obtained for unbroken femur and were respectively equal to L=7.62 mm for M-316LVM model and L=7.8mm for M-Ti64.

The maximum von Misses stresses in analysed models (Fig. 8) were concentrated in small, local areas of the fifth CS bone screw with DCS plate contact point (Fig. 8b-c) – Table 2.

What is more, for analysed models, there was no exceed in yield strength $R_{p0.2}$ of metallic biomaterials (Table 3) from which the analysed stabilizers were made. Besides, the maximum reduced stresses values in the cortical bone did not exceed the value of 66 MPa for all analysed models and they were located in the bone screw - bone contact place.

The obtained results are above three times smaller than boudary stresses values equal to 200 MPa causing the osseous tissue destruction. This is the reason why the dynamic condylar screw model of CrNiMo (AISI 316LVM) steel and Ti6A14V alloy is safe to use in case of epicondyle fracture treatment.

The maximum values of stresses in cancellous bone were equal to 2 MPa (Table 2) and in analysed models were located outside the area of DCS stabilizer placing.

Summarize, it was found that in case of fracture it is possible to apply implants made of both CrNiMo steel and Ti6A14V alloy. Moreover, for assumed loading model in none of the analysed option the boundary resistance values were not exceeded both in implant and bone (Table 2 and Figs. 9 a and b). Besides, it is possible to match the implant with individual patient's features. In particular, it is important to remember about individual inclination to allergies on chemical compounds which are ingredients of used metallic biomaterials. It is necessary to consider osseous tissue stiffness. Additionally, performed solutions enabled to indicate the areas of stabilizer that are affected by initiation and development of corrosion processes. The determined areas of maximum stresses are places, where the damage of passive layer caused by mechanical loads can occur. These places are subjected to crevice, pitting and fatigue corrosion expansion. In order to perform more detailed characteristics of DCS implant made of alternative metallic biomaterials in future works, it is expected to perform macro and microscopic analysis and to carry out electrochemical evaluation of the implants that were removed from the human body.

4. Conclusions

Summarize the numerical analysis, it was found that for all analysed models, for applied loading system, the assumed values of strength properties for cortical and cancellous bones were not exceeded.

Simultaneously, it is possible to use alternative metallic biomaterials such as CrNiMo steel or Ti6Al4V alloy to produce DCS stabilizer. The results of presented analysis and elaborated geometrical and numerical models can be applied in further numerical analysis of DCS system. In these analysis, the boundary conditions will be modified and can represent in more detailed way the cooperation between particular elements of the DCS system. What is more, the alternative material models for bone will be applied to represent it's real behavior (brittleness and fragility). The analysis allows the determination of potentially dangerous areas, exposed to damage due to overload. Furthermore, the analysis identifies the areas of initiation and development of crevice, pitting and fatigue corrosion.

Acknowledgements

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