Mechanical Evaluation of the PEEK Cranial Implants

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Abstract: Additive manufacturing and new polymeric progressive biocompatible materials enable the production of individual cranial implants. The advantage of this approach is a reduction in the number of complications during surgery due to inaccuracies in the design and manufacture of the implant. Critical areas of implants are their attachment to the skull and their mechanical properties. The paper deals with the finite element method analysis of force action on a cranial implant made of PEEK. The simulation was made for two methods of fixing the implant to the skull, where in case A, they were used to fix the screw, and in case B, it was only about placing the implant on the defect without fixing it to the bone.

Keywords: Cranial implant; PEEK; Finite Element Analysis

1 Introduction

In the field of medical surgery, skull defects are mostly often caused by congenital deformity, tumors, and traumatic injuries [1, 2]. Cranioplastic reconstruction is one of the more demanding surgeries due to that it involves the brain, nerves, and tissues of the human body [1]. Nowadays, the development of modern additive manufacturing technologies and biocompatible materials makes it possible to design and manufacture different personalized cranial implants. The implementation of implants produced by additive technologies such as material extrusion or selective laser sintering leads to higher production efficiency (lower material consumption), higher precision of implant production, and lower input material costs [3]. Due to suitable mechanical properties and minimal radiodiagnostic disadvantages, it is passing to polymer materials, e.g., polyetheretherketone (PEEK). PEEK is a high-temperature thermoplastic that has similar mechanical properties to cortical bone, so it is suitable for skull bone replacement. Its advantages include high chemical resistance, bioinertness, and translucency [4]. Due to the variety of defects (dimensions, shape, position), it is necessary to carry out a numerical simulation to verify the mechanical characteristics and guarantee the appropriate functionality of cranial implants made of this material [5-7].

2 Material and methods

To perform the simulation, a model of the implant and part of the skull was designed from DICOM data in the software package Mimics Innovation Suite (Materialise, Belgium). The overall methodology of the experiment is shown in Fig. 1.

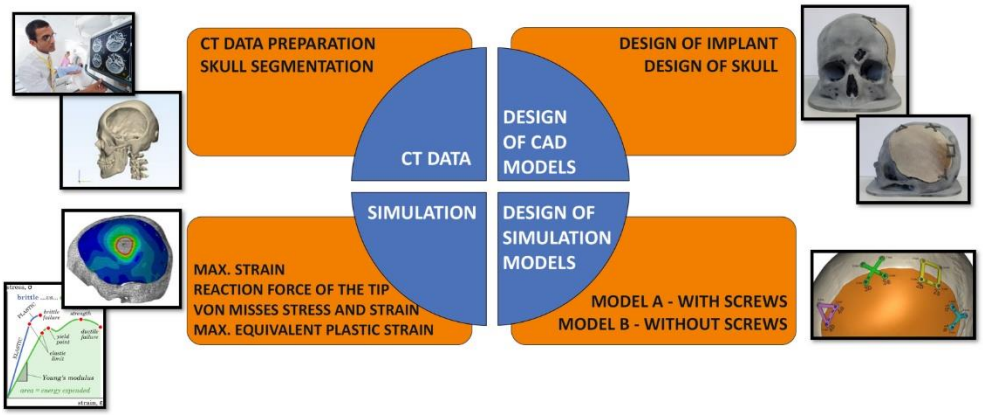


Fig. 1 Experiment plan.

The pressure tip model was designed in the software SolidWorks (Dassault Systèmes, Canada). Nonlinear static analysis of the implant was done in Abaqus (Dassault Systèmes, Canada) with the skull and tip set as perfectly rigid bodies and the implant model as a homogeneously deformable body. Tables 1 and 2 show the mechanical properties and material parameters of the implant used for the finite element method simulation. The analysis was performed for two types of implant fixation – fixed with screws and loose without fixation with screws. The test was completed when a displacement of 5 mm was reached.

Table 1. PEEK mechanical properties.

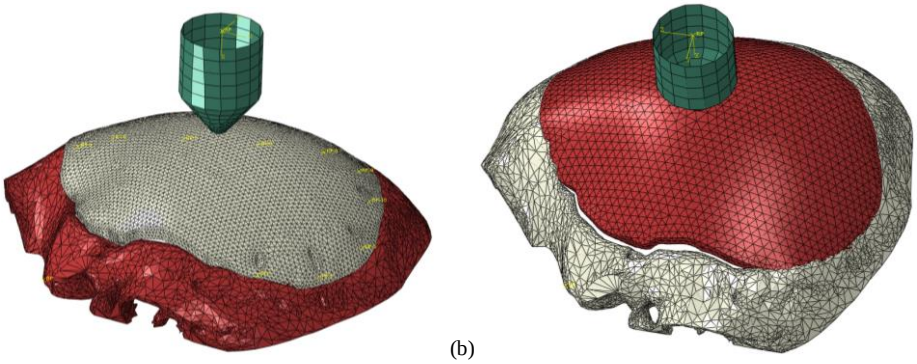
Elastic modulus PEEK [MPa]	3600
Poisson's ratio μ [-]	0.4
Yield strength [MPa]	132
Yield strength deformation	Approx. 0.06
Ultimate tensile strength deformation	Approx. 0.4

Table 2. Johnson and Cook model parameters.

Parameters	A [MPa]	B [MPa]	n	C	m
Values	132	10	1.2	0.034	0.7

2.1 Boundary conditions of the simulation

The skull was fixed firmly in both cases. The motion of the tip was controlled by a single reference point (RP), and displacement was allowed in the direction of the tip axis. A surface frictional contact between the tip and implant and the skull and implant was defined. The friction coefficient was 0.1. In the first case, the implant was attached to the skull using simplified screw connections that were represented by kinematic couplings and MPC beams (Fig. 2a). In the second case, the implant was positioned loosely on the skull (Fig. 2b), and thus deformation and displacement were limited by the contact regions.



(a) (b)

Fig. 2 FE model of the implant with screw holes (a) and without screw holes (b).

The implant mesh was formed by C3D10 quadratic solid elements with an average size of 4 mm. The tip and skull were meshed using Rigid Body elements. Due to the structural response of the implant, nonlinear static analysis was used for the simulation (Table 3).

Table 3. Settings and constrains for simulation elements.

CAD model	
Implant (PEEK)	homogeneous deformable body
Skull	rigid body
Tip	rigid body
Boundary conditions	
Implant	With/without fixation screws
Skull	motionless
Tip	1° degree of freedom
Loading	
Tip	Forced displacement of 5 mm
Surface contact	
Tip/implant	Surface contact, finite sliding, friction $f = 0.1$
Skull/implant	Surface contact, finite sliding, friction $f = 0.1$
Finite Element Mesh	
Implant	C3D10 quadratic solid elements with an average size of 4 mm
Tip/Skull	Discrete Rigid Element
Analysis	
Static	General

3 Results

Fig. 3 shows the course of the reaction force depending on the displacement of the tip for both models. The graph shows that the difference in the course of the force, as well as the maximum force achieved between the implant fixed with screws and without fixation, is negligible.

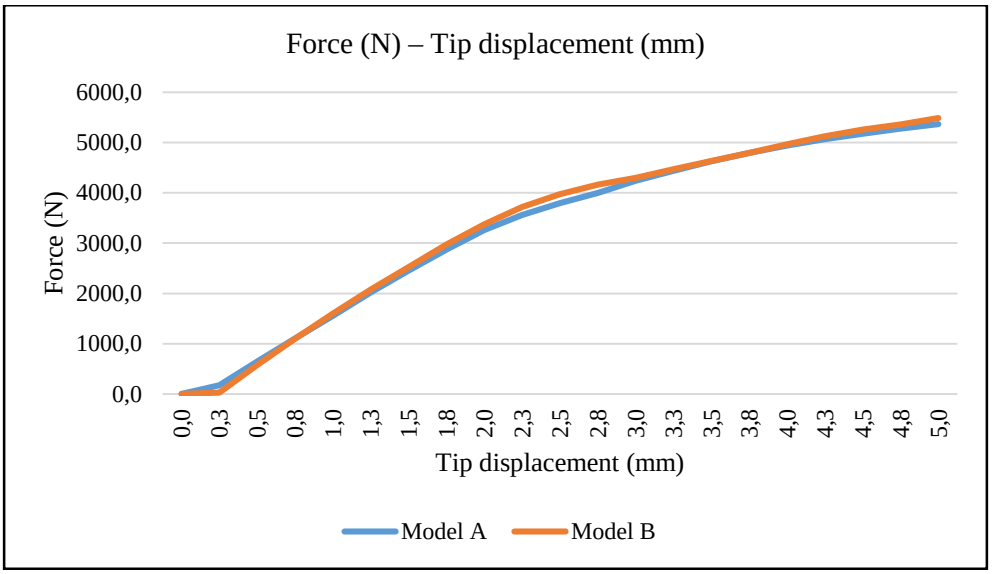


Fig. 3 Reaction force of the tip during loading.

Fig. 4 shows the total strain depending on the tip displacement. The courses of both models are the same at the beginning. For model A, the total strain then has a steeper course and is greater by approximately 0.07, which is probably caused by the screws attaching it to the skull.

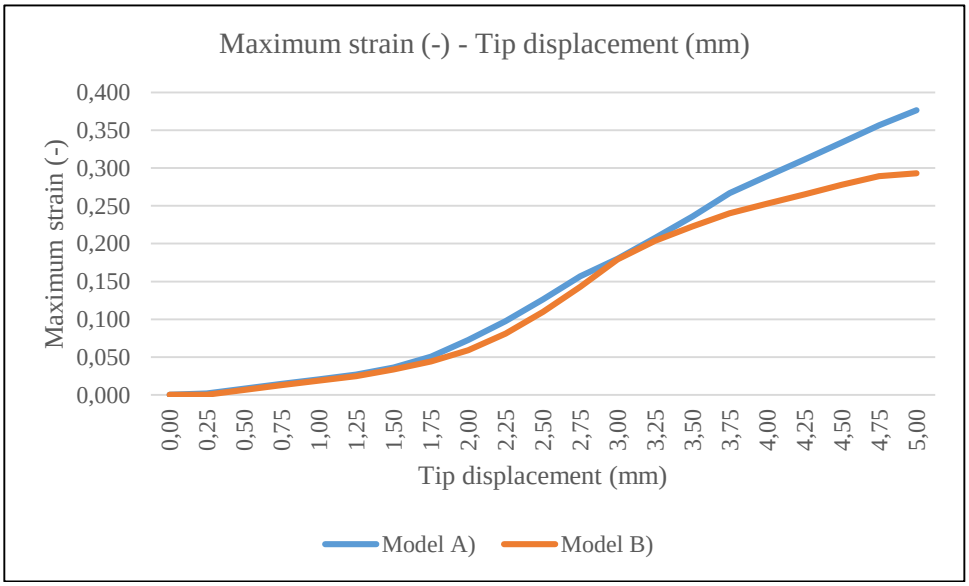


Fig. 4 Dependence of maximum strain on tip displacement.

Fig. 5 shows the maximum equivalent plastic strain at the point of contact depending on the tip displacement. The course of model A has a significantly steeper course, which may be caused by the attached screws and the non-ideal fitting of the contact surface of the implant on the skull.

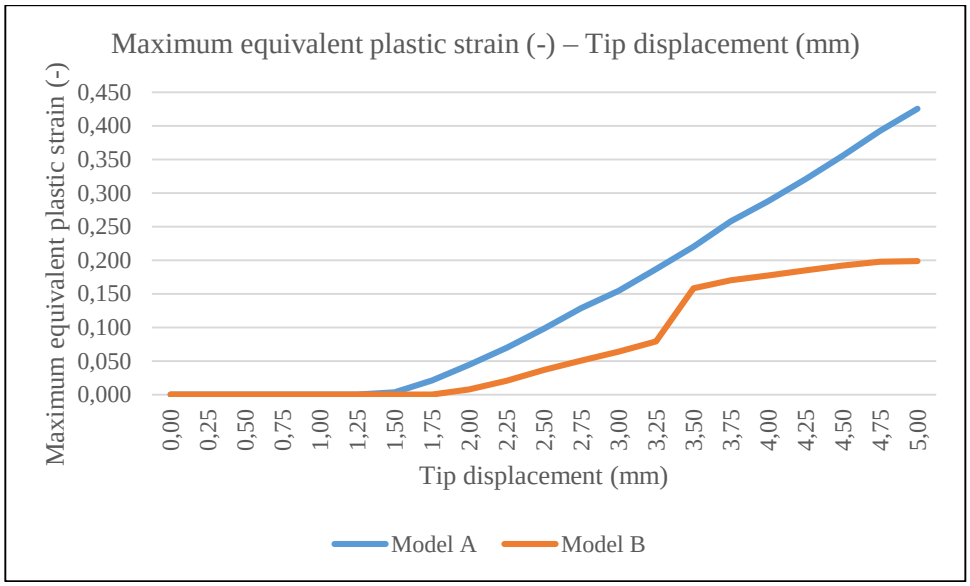


Fig. 5 Dependence of the maximum equivalent plastic strain on tip displacement.

Fig. 6 and Fig. 7 show the von Mises stress distribution and the proportional limit for both models. From the stress distribution, it follows that for model B (Fig. 7), the stress area above the yield strength is larger than for model A (Fig. 6).

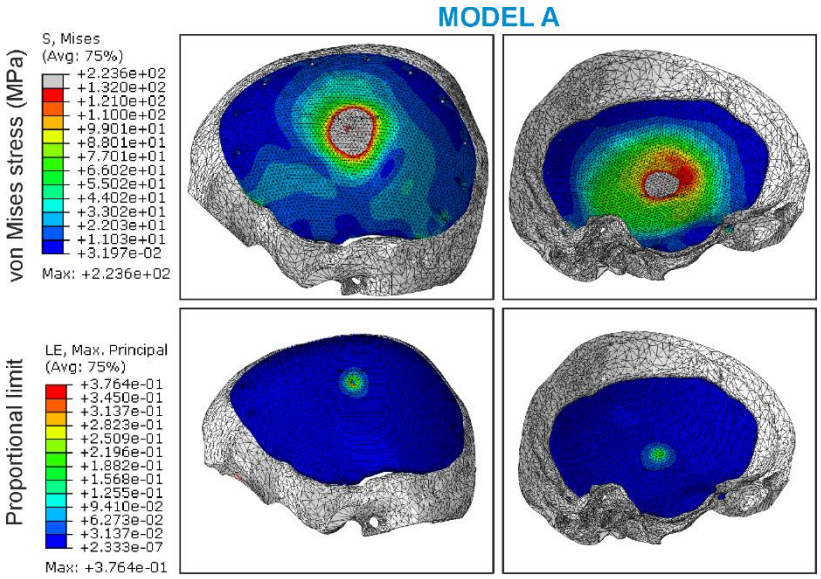


Fig. 6 von Mises stress and proportional limit distribution for Model A.

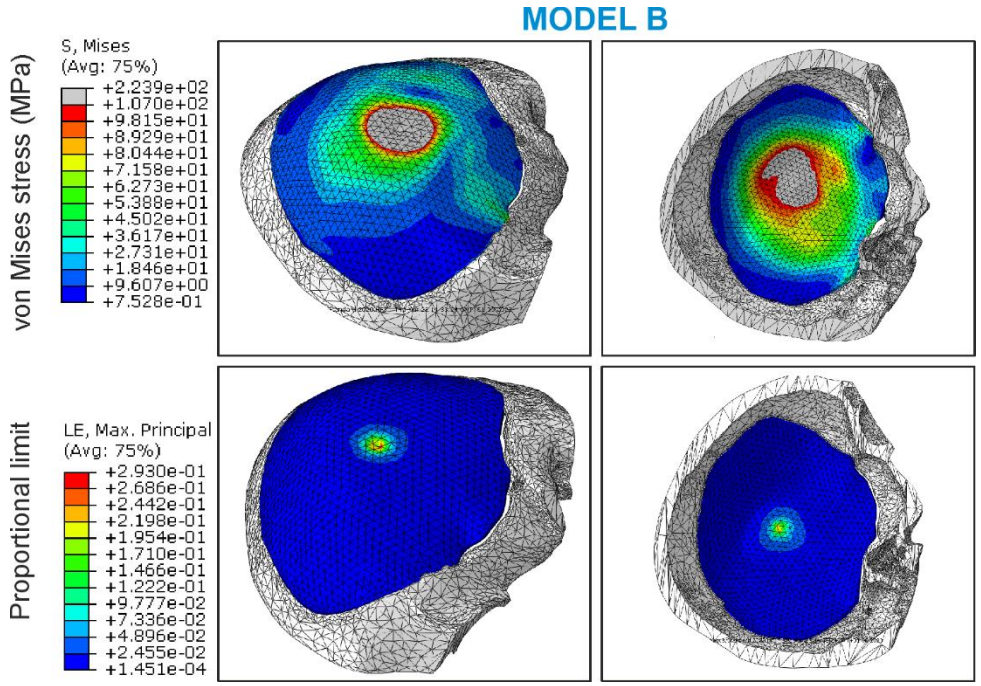


Fig. 7 von Mises stress and proportional limit distribution for Model B.

Conclusions

The results of the simulations show that the course of the force depending on the displacement of the tip differs only to a minimal extent for fixation of the implant with and without screws. The total proportional deformation at the point of action of the tip, depending on the displacement of the tip, is greater by 0.07 for the implant fixed with screws, and its plastic deformation of the implant has a steeper course. During the simulation, the influence of production technology (layering of material) and porosity impact during production were not considered.

Acknowledgements

This publication is the result of the project implementation CEMBAM - Center for Medical Bioadditive Research and Production, ITMS2014+: 313011V358 supported by the Operational Programme Integrated Infrastructure funded by the European Regional Development Fund, KEGA 021TUKE-4/2022 “Implementation of computed tomography in an interdisciplinary technical-natural area”, VEGA 1/0516/22 “Research on the impact of composite materials production technology on their mechanical and fatigue properties using numerical and experimental methods” and VEGA 1/0500/20 “Research of mechanical properties of materials with a complex internal structure by numerical and experimental methods of mechanics”.

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