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FINITE ELEMENT ANALYSIS OF CRANIAL IMPLANT

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Abstract: *Medical 3D-printing is a modern technology that offers the possibility to manufacture patient-specific implants offering shorter operating times and better clinical results at a lower cost. The patient-specific implants are nowadays on the rise in cranioplasty which uses e.g. polymetylmetacrylate (PMMA) implants to correct the damaged skull. The manufacturing accuracy of such constructs remain problematic and deserve a detailed investigation. The aim of this study was to assess the inaccuracy of the bone-implant interface when PMMA skull implant is employed. The assessment was performed using the computational simulation.*

1. Introduction

The most common surgery technique used for brain tumor removal is craniotomy. During this procedure, a portion of the skull is removed to allow access to the brain. Craniotomy is usually followed by cranioplasty which is a surgical procedure to correct the damaged skull. Such procedures are also performed to correct skull deformities. To date biocompatible materials such as PMMA, and titanium alloys are commonly used to manufacture implants that are subsequently used to treat such defects. Modern implants used for the treatment of the aforementioned skull defects are designed on computers and are manufactured using different rapid prototyping technologies (Narra et. al., 2014). The manufacturing accuracy of such constructs remains problematic. One approach to assess implant inaccuracy is by using computational simulations. Such techniques provide a good insight into potential problems. The purpose of this study was to assess the inaccuracy of the bone-implant contact (BIC) when PMMA implant is employed.

2. Methods

2.1 Patient-specific approach

Computer tomography (CT) is a standard diagnostic imaging tool that is commonly used prior to most skull surgeries. The acquired CT data sets can be converted into STL files and are then exported to CAD software packages to design patient specific skull implants (Huotilainen et. al, 2014). There are three basic ways how to plan the skull reconstruction and to design a skull implant:

- CT dataset of the patient's skull taken before the injury can be used to design the implant.
- The unaffected side of the skull can be mirrored it into the damaged part of the skull. However the skull is never 100 % symmetrical.
- Cranial defects can be reconstructed using spline algorithms.

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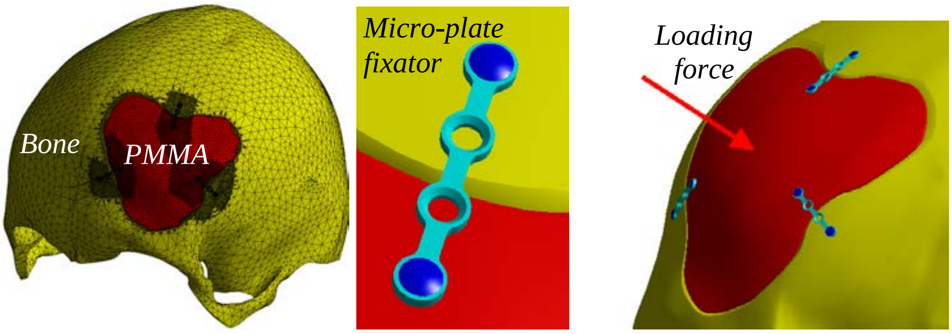
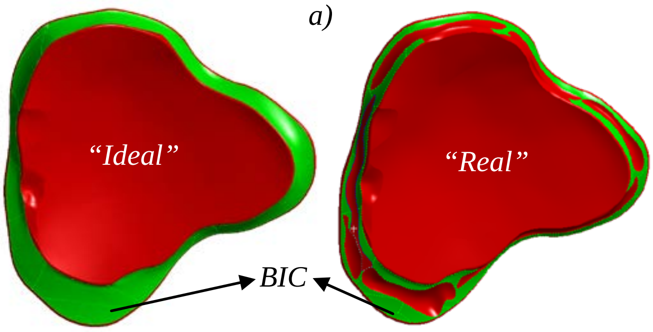
Despite the fact that patient-specific implants have advantages, design and manufacturing inaccuracies cannot be completely avoided. Moreover, the overall cost of patient-specific implants is still a limiting factor.

2.2 Computational modeling

CT images of 1 injured human skull (male, 45 yo) were used in this study. STL model of the skull was created using STL Model Creator (Marcián et. al., 2011) and SolidWorks software (Fig. 1a). The implant was designed following standard procedures described above. In order to test the influence of implant geometry inaccuracy, two versions of the implant model were created (Fig. 1b): 1. An ideal implant geometry that fitted exactly into the skull defect (labeled as “Ideal”); 2. An implant with randomly distributed inaccuracies in the BIC (labeled as “Real”). The real implant and corresponding defect were modeled using cut and Boolean operations. Both implants were assumed to be from PMMA as requested by the doctors. In the simulations, PMMA was modeled using a linear, homogeneous and isotropic material model (Young’s modulus (E) = 3000 MPa, Poisson’s ratio (μ) = 0.38; Preusser et. al., 2011, Gómez et. al., 2003). The implants were fixed to the skull using three micro-plates made of Ti6Al4V (KLS Martin). Micro-screws were modeled as threadless cylinders with an equivalent mean diameter. This simplification is acceptable as it does not significantly affect the results in the BIC. For the titanium alloy as well as for the bone itself, the same material model as for PMMA was used (titanium alloy: E = 110 000 MPa, μ = 0.3 (Niinomi (1998)); bone: E = 15 000 MPa, μ = 0.3 (Freedman et. al., 2013, Motherway et. al., 2009)). The computational model was finalized in ANSYS 16.2. All parts were discretized using quadratic element types SOLID186 and SOLID187. All contacting parts were connected using contact elements TARGE170 and CONTA174 (frictional contact). Number of elements and nodes were approximately 180 000 and 320 000, respectively. Friction coefficients for each contact pair (with an exception of micro-screws) were assumed to be as follows: 1. PMMA-Ti6Al4V = 0.3; 2. PMMA-Bone = 0; 3. Ti6Al4V-Bone = 0.3. The assumed coefficients were analyzed in preliminary test calculations and were conservatively set to maximize the final strains in the BIC and stresses in the fixators as presented in this paper. The screws were fixed to the implant and to the bone and no mutual movement was allowed. The models were loaded with a static force applied to the center of the implant. Specifically, the force was distributed to the nodes of the FE mesh in the small circular region (~1 cm^2) of the implant center. This loading case mimicked a relaxed person resting on a pillow as requested by the doctors. The force of 50 N corresponds to an approximate weight of the head (~5 kg (Ridwan-Pramana et. al., 2016)). In addition, the bone and implant were loaded with an intracranial pressure of 4 kPa (Czosnyka et. al., 2004). The models were fixed at the bottom side of the skull in the region where the spine is assumed.



a)



b)

Fig. 1: a) Geometry model of whole system b) two variants of PMMA implants.

3. Results

The BIC areas of the “Ideal” and “Real” models were 870 mm^2 and 490 mm^2. This difference significantly affected the implant displacements, contact pressures, von Mises stresses and von Mises strains. Maximum implant displacements in the loading direction were observed at the point of the force application (Figure 2). These displacements were 0.033 mm and 0.042 mm for the “Ideal” and “Real” cases, respectively.

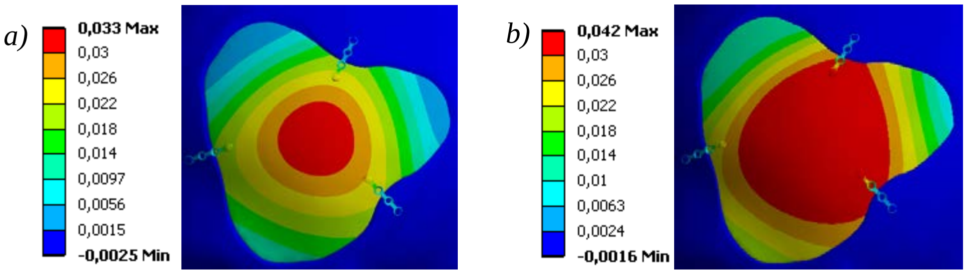


Fig. 2: Displacement [mm] a) “Ideal” b) “Real”.

Contact pressures in the BIC are shown in Figure 3. Maximum contact pressure for the “Ideal” and “Real” case is 0.067 MPa and 0.100 MPa, respectively.

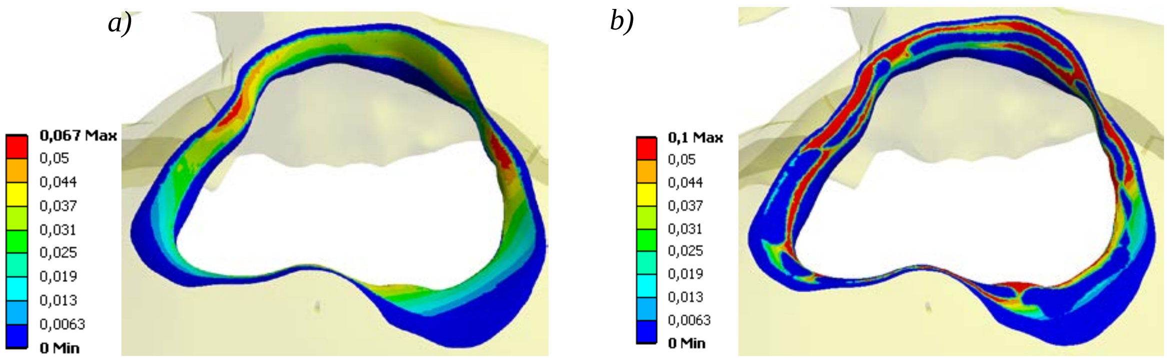


Fig. 3: Contact pressure [MPa] a) “Ideal” b) “Real”.

The bone in the BIC vicinity was evaluated for von Mises strains. Higher values of these strains were observed again in the “Real” case, especially under the fixators as shown in Figure 4.

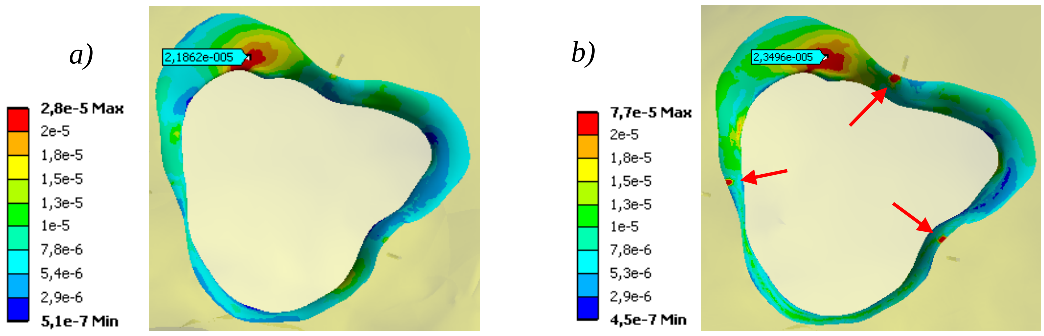


Fig. 4: von Mises strains [-] a) “Ideal” b) “Real”.

The fixators were evaluated for von Mises stresses (Figure 5). The maximum stresses were observed to be 30 MPa and 78 MPa in the “Ideal” and “Real” cases, respectively.

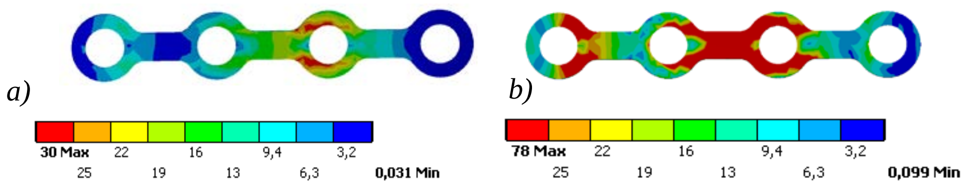


Fig. 5: von Mises stress [MPa] a) “Ideal” b) “Real”.

4. Discussion

The results of the study confirm that implant manufacturing inaccuracies significantly affect the biomechanical conditions in the BIC. In case of the "Real" model, all observed results showed to be more severe than in the "Ideal" case. Maximum normal displacement in the tested "Real" case was higher by 27% and the contact pressure was higher by 49%. In the "Ideal" case, the contact pressure exceeded 0.05 MPa only at two locations in the fixator vicinity; however, in the "Real" case, the pressure exceeded this value almost everywhere in the BIC. Similarly, maximum von Mises strain in the "Real" case was higher by 275% and, as a contrary to the "Ideal" case, extreme concentrations can be observed in a close vicinity of the fixators. The "Real" case implant is also much more stressed than the "Ideal" one; maximum von Mises stress is higher by 260%. The main reason for the significant differences in all monitored results is the fact that the "Real" case lacks the uniform bone support in the BIC and is, therefore, susceptible to stress/strain concentrators which might be a source of implant failure. In this study, only one randomly generated "Real" case was tested; however, it is evident that a considerable amount of attention should be payed to the implant accuracy as well as to accuracy of the craniotomy itself.

5. Conclusion

We are witnessing a boom in medical 3D-printing. This technology offers the possibility to manufacture patient-specific implants which offer shorter operating times and better clinical results at a lower cost. However, patient-specific implants are still somewhat idealized objects and their manufacturing accuracy should be considered carefully.

Acknowledgement

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