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NUMERICAL ANALYSIS OF STATIC STRESSES IN PARTIAL HIP IMPLANT
NUMERIČKA ANALIZA STATIČKIH NAPONA U PARCIJALNOM IMPLANTU KUKA

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Keywords
- partial hip implant
- finite element method
- Ti-6Al-4V alloy
- 3D scanning

Abstract

Research presented here involves numerical analysis of stresses in partial hip implant subjected to static loads, for two cases of patient weight. The numerical analysis requires the development of 3D models that would accurately represent real partial hip implant geometry, hence a reverse engineering approach via 3D scanning is also included. This combined approach provides reliable insight into the behaviour of partial hip implants under static load, while also exposing certain issues related to the application of this specific implant geometry at higher weight levels.

Ključne reči
- Parcijalna proteza kuka
- Metoda konačnih elemenata
- Ti-6Al-4V legura
- 3D skeniranje

Izvod

Istraživanja u ovom radu obuhvataju numeričku analizu napona u parcijalnoj protezi kuka izloženoj statičkom opterećenju, za dva različita slučaja težine pacijenta. Numerička analiza zahteva razvoj 3D modela koji bi tačno predstavljali stvarnu geometriju parcijalne proteze kuka, stoga je takođe primenjen pristup reverznog inženjeringa putem 3D skeniranja. Ovaj kombinovani pristup daje pouzdan uvid u ponašanje parcijalnih proteza kuka pod statičkim opterećenjem, pri čemu otkriva i određene probleme u vezi sa primenom ove specifične geometrije veštačkih kukova za veće težine.

INTRODUCTION

One of the earliest prostheses was developed specifically to replace degenerated joint surfaces in osteoarthritic hips. These prostheses were made of various materials, starting from MP35N and stainless steel, including Ti6Al4V alloy more recently, /1-9/. Joint replacement has revolutionized the treatment of diseased or damaged joints, allowing relief from pain and restoration of function. Models designed with short stems were subject to high shear stress, which in some patients resulted in premature loosening of the bone-prosthesis connection and failure. Implants with short stems were gradually replaced by implants with long stems, which allowed less stress concentration. Long-stem prostheses enabled more of the load-bearing force to be transferred to the femur through the intramedullary stem.

Figure 1. Example of partial arthroplasty Moore prosthesis, /10/.

Currently, the hip implant femoral stem is made of titanium- or cobalt-chromium based alloy and cemented with polymethyl methacrylate, PMMA, /11, 12/. Implant fixation with PMMA provides immediate stability, which allows the patient to become active relatively fast. To do this, the femur is machined so that a 1-5 mm thick cement layer can be placed. Since the implant is placed on liquid cement, the cement moves and penetrates the hollow bone structure. In the optimal case, this enables the formation of an uninterrupted cement layer that is well fixed to the bone and tightly adheres to the implant. The cement hardens in a few minutes thanks to the exothermic reaction. However, by applying the cement fixation method, loosening may occur at the joint, that is, at the point of contact between bone and cement and cement with implant, which might cause premature failure, /12-19/. For cement prostheses, a rounded model is preferred, without sharp edges and protruding parts, to achieve a uniform thickness of the cement shell, and to prevent the occurrence of stress concentration in a weak cement shell. Material properties, shape, and implant fixation determine the load transfer characteristics in every individual case.

Therefore, during the optimisation process of implant material and geometry, pre-clinical tests must be performed to verify whether the new models can guarantee mechanical endurance to physiological loading. In this sense, a combined experimental and numerical approach is applied, when implants of Ti-6Al-4V alloy were scanned to obtain the most accurate numerical models, which were analysed for further tests. In this paper, static load simulations are presented as an example of a successfully developed and optimised model, obtained by 3D scanning, /18-22/.

NUMERICAL MODELS OF PARTIAL HIP IMPLANT

In this research an Atos Core 200 (GOM, Braunschweig, Germany) non-contact optical 3D scanner was used, Fig. 2, /23, 24/. 3D scanner properties are listed in Table 1. This 3D scanner uses UV (blue) light projection and structured white light technology to capture accurate and detailed 3D data. Before scanning, the model was sprayed with white powder to achieve adequate surface detection. The scanning was performed in two phases, for top and bottom surfaces.

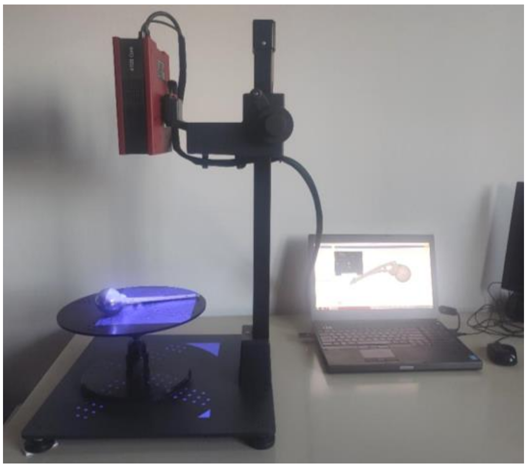

Figure 2. Atos Core 200 3D scanner during the scanning process.

Table 1. Properties of the Atos Core 200 3D scanner, /23, 24/.

No. of cameras	Measure area [mm]	Work distance [mm]	Resolution [mm]	Sensor geometry [mm]	Operational temperature range
2	200×150	250	0.13	206×205×64	5-40 °C

In this research, the optimal Atos Core 200 ‘standard’ option was used. The file is saved in STL (Standard Tessellation Language) file format, Fig. 3a. In the next step, the file was imported to SolidWorks® (Dassault Systèmes, Vélizy-Villacoublay, France) for 3D model creation. The *Geomagic* for SolidWorks® extension helped here to manage CAD modelling from the 3D-scanned mesh. Certain irregularities from the mesh, such as holes and spikes, had to be repaired and removed via this extension. After hours of manual modelling, the CAD model was completed, Fig. 3b. The created SolidWorks® file was then saved as a STEP file, usable in ANSYS® software, see Fig. 3c.

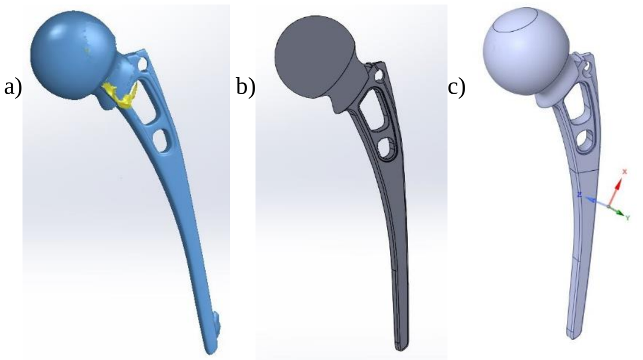

Figure 3. a) Scanned model; b) created CAD model; c) numerical model for FEM analysis.

RESULTS AND ANALYSIS

Once an accurate and usable 3D model was obtained, numerical analysis was performed by applying the finite element method (FEM), using ANSYS® R2.2022 software. The FEM is commonly used as a tool for such analyses, as it provides quick and reliable means for determining the stress states in various models, enabling detection of critical locations which could initiate a crack under various loading conditions /1-6, 25/. For this analysis, a simple case is selected - static loads that occur in hip implants during walking at 5 km/h. Two different options were observed, one with a person weighing 70 kg (considered as normal loading conditions), and a more extreme case with a weight of 130 kg. Actual loads in the model were defined as forces acting on the hip implant head, and their magnitudes were calculated by converting weight into Newtons and then multiplying it with coefficients that correspond to a walking scenario /10, 25/. According to the above, the load for the 70 kg weight is 2944.8 N, and the load corresponding to 130 kg is around 5460 N. The model, including finite element mesh and force location, is shown in Fig. 4. Boundary conditions are defined as fixed on the bottom half of the model, corresponding to how real hip implants are fixed within the bone.

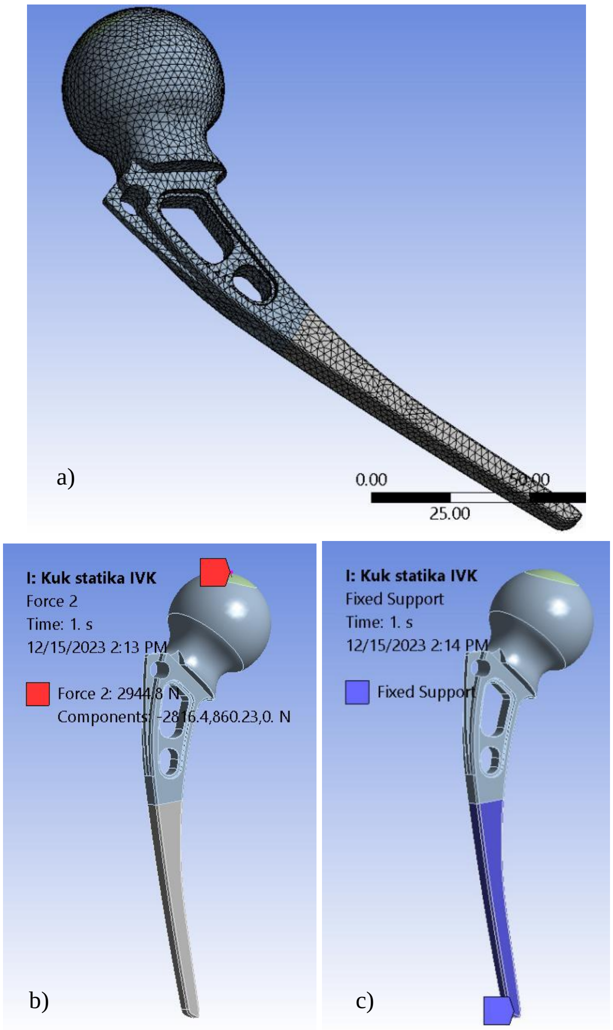

Figure 4. ANSYS® model geometry: mesh (a); loads (b); and boundary conditions (c), based on the scanned hip implant.

Results of the numerical analysis are shown in Fig. 5 (force 2944.8 N, weight 70 kg) and Fig. 6 (force 5460 N, weight 130 kg), indicating maximal values in the region of relevance. It should be noted that maximal values of stress occur close to fixed points due to the boundary condition, whereas the maximal strain value occurs in the area of the applied force. Furthermore, there were stresses higher than those shown in the figure at other locations, but as compressive stresses, and as such were dismissed from further analysis.

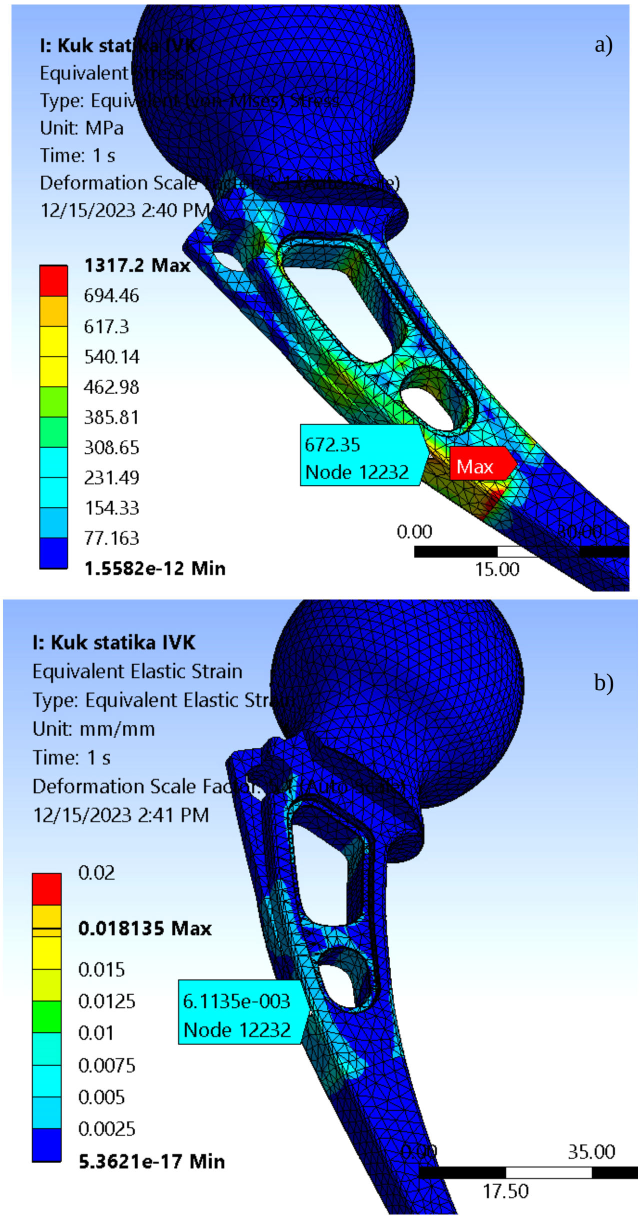

Figure 5. Elasticity: a) strains; b) stresses.

As one can see from Fig. 5, maximal strains in the relevant region are still elastic, but close to plasticity, which would occur at approx. 7.27e-003, i.e., with a force 19 % higher, cca. 3500 N instead. Therefore, significant plasticity was to be expected for the force 5460 N corresponding to weight 130 kg. Indeed, results in Fig. 6 show strains and stresses in the plastic domain, with the maximal stress value 906.53 MPa, and maximal plastic strain 7e-003, i.e., total maximal strain 1.427e-002.

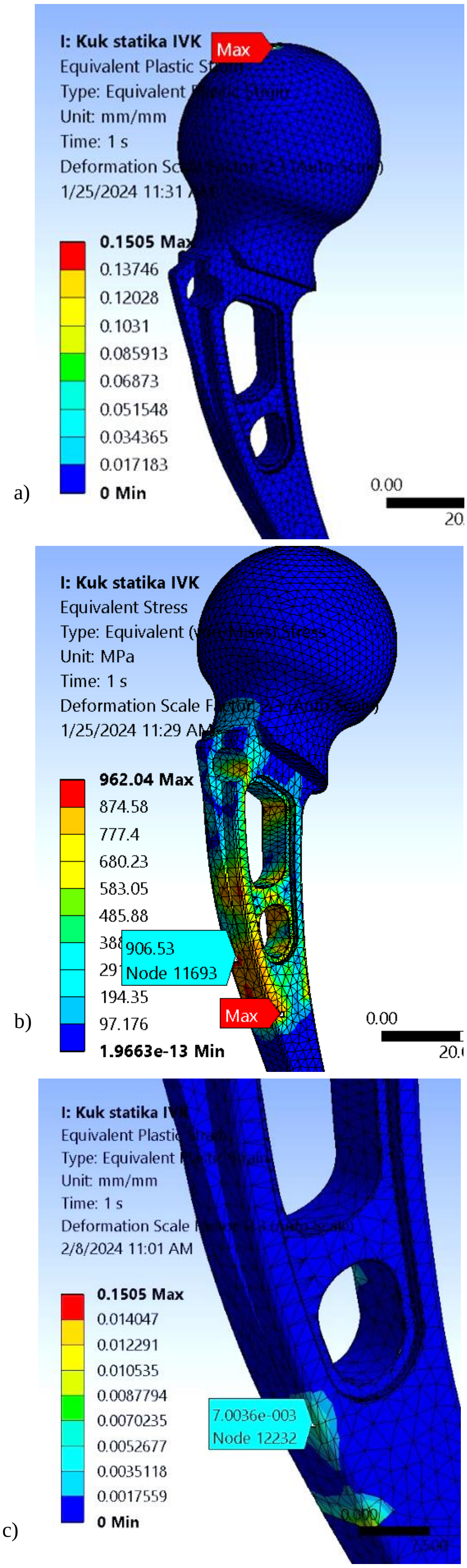

Figure 6. a) Strain distribution; b) stress distribution; c) equivalent plastic strain (enlarged).

Obviously such unfavourable stress-strain state makes the Moore partial implant not very reliable, even for normal static load corresponding to weight 70 kg.

CONCLUSION

Based on the results and analysis presented in this paper, one can conclude the following:

- Design aimed to reduce the mass of hip implant is not an optimal one, since maximal stress at critical cross-section is close to the yield stress even at static loading for normal walking of a person of 70 kg.
- Maximal stresses are obtained for fixed points, but this is not realistic, since dome movement of implant is possible due to flexibility of cement used for fixing. This issue should be further investigated with more realistic boundary conditions.
- Furthermore, defining of the load as a concentrated force causes significant plastic strain in non-realistic locations - namely the implant head and future models should consider the possibility of defining a load distributed form over a small part of the implant head surface.

REFERENCES

1. Milovanović, A., Sedmak, A., Grbović, A., et al. (2020), *Design aspects of hip implant made of Ti-6Al-4V extra low interstitials alloy*, Procedia Struct. Integ. 26: 299-305. doi: 10.1016/j.prostr.2020.06.038
2. Smoljanić, T., Sedmak, S., Sedmak, A., et al. (2022), *Experimental and numerical investigation of Ti-6Al-4V alloy behaviour under different exploitation conditions*, Struct. Integr. Life, 22 (3): 353-357.
3. Mijatović, T., Milovanović, A., Sedmak, A., et al. (2019), *Integrity assessment of reverse engineered Ti-6Al-4V ELI total hip replacement implant*, Struct. Integr. Life 19(3): 237-242.
4. Sedmak, A., Čolić, K., Grbović, A., et al. (2019), *Numerical analysis of fatigue crack growth of hip implant*, Eng. Fract. Mech. 216: 106492. doi: 10.1016/j.engfracmech.2019.106492
5. Sedmak, A., Čolić, K., Burzić, Z., Tadić, S. (2010), *Structural integrity assessment of hip implant made of cobalt-chromium multiphase alloy*, Struct. Integr. and Life, 10(2):161-164.
6. Čolić, K., Sedmak, A., Grbović, A., et al. (2016), *Finite element modeling of hip implant static loading*, Procedia Engng. 149: 257-262. doi: 10.1016/j.proeng.2016.06.664
7. Dharme, M.R. (2013), *Comparison of fatigue analysis of hip joint implant for stainless steel, cobalt chrome alloys and titanium alloys*, Trends Biomater. Artif. Organs, 27(2): 58-61.
8. Guo, L., Naghavi, S.A., Wang, Z., et al. (2022), *On the design evolution of hip implants: A review*, Mater. Des. 216: 110552. doi: 10.1016/j.matdes.2022.110552
9. Merola, M., Affatato, S. (2019), *Materials for hip prostheses: A review of wear and loading considerations*, Materials, 12(3): 495. doi: 10.3390/ma12030495
10. Čolić, K., *Analiza otpornosti na lom biomaterijala za veštački kuk* (Fracture resistance analysis of artificial hip biomaterial) (in Serbian), doctoral thesis, University of Belgrade, Faculty of Mechanical Engineering, 2013.
11. Robu, A., Ciociou, R., Antoniac, A., et al. (2022), *Bone cements used for hip prosthesis fixation: The influence of the handling procedures on functional properties observed during in vitro study*, Materials, 15(9): 2967. doi: 10.3390/ma15092967
12. Hloch, S., Foldyna, J., Hvizdoš, P., et al. (2016), *Experimental in-vitro bone cements disintegration with ultrasonic pulsating water jet for revision arthroplasty*, Tech. Gazette, 22(6): 1609-1615. doi: 10.17559/TV-20150822145550
13. Paliwal, M., Allan, D.G., Filip, P. (2010), *Failure analysis of three uncemented titanium-alloy modular total hip stems*, Eng. Fail. Anal. 17(5): 1230-1238. doi: 10.1016/j.engfailanal.2010.02.011
14. Jasty, M., Maloney, W.J., Bragdon, C.R., et al. (1991), *The initiation of failure in cemented femoral components of hip arthroplasties*, J Bone Joint Surg. Br. 73(4): 551-558. doi: 10.1302/0301-620X.73B4.2071634
15. Johnson, J.A., Provan, J.W., Krygier, J.J., et al. (1989), *Fatigue of acrylic bone cement--effect of frequency and environment*, J Biomed. Mater. Res. 23(8): 819-831. doi: 10.1002/jbm.820230802
16. Kadakia, N., Noble, P., Beardsley, C., et al. (2000), *Do cement voids cause premature failure of cement mantles in total hip arthroplasty*, In: 46th Annual Meeting, Orthopaedic Research Society, Orlando, Florida, 2000: 0221.
17. Kärrholm, J., Borssén, B., Löwenhielm, G., Snorrason, F. (1994), *Does early micromotion of femoral stem prostheses matter? 4-7 year stereoradiographic follow-up of 84 cemented prostheses*, J Bone Joint Surg. Br. 76(6): 912-917.
18. Babić, M., Verić, O., Božić, Ž., Sušić, A. (2018), *Reverse engineering based integrity assessment of a total hip prosthesis*, Procedia Struct. Integr. 13: 438-443. doi: 10.1016/j.prostr.2018.12.073
19. Babić, M., Verić, O., Božić, Ž., Sušić, A. (2019), *Fracture analysis of a total hip prosthesis based on reverse engineering*, Eng. Fract. Mech. 215: 261-271. doi: 10.1016/j.engfracmech.2019.05.003
20. Haleem, A., Javaid, M. (2019), *3D scanning applications in medical field: A literature-based review*, Clin. Epidem. Global Health, 7(2): 199-210. doi: 10.1016/ j.cegh.2018.05.006
21. Afteni, C., Paunoiu, V., Afteni, M., Teodor, V. (2022), *Using 3D scanning in assessing the dimensional accuracy of mechanically machined parts*, IOP Conf. Ser.: Mater. Sci. Eng., 1235: 012071. doi: 10.1088/1757-899X/1235/1/012071
22. Negru, N., Leba, M., Rosca, S., et al. (2019), *A new approach on 3D scanning-printing technologies with medical applications*, IOP Conf. Ser.: Mater. Sci. Eng. 572: 012049. doi: 10.1088/1757-899X/572/1/012049
23. Jevtić, I., Mladenović, G., Milošević, M., et al. (2022), *Dimensional accuracy of parts obtained by SLS technology*, Struct. Integr. Life, 22(3): 288-292.
24. Golubović, Z., Travica, M., Trajković, I., et al. (2023), *Investigation of thermal and dimensional behavior of 3-D printed materials using thermal imaging and 3-D scanning*, Therm. Sci. 27(1, Part A): 21-31. doi: 10.2298/TSCI2301021G
25. Milovanović, A., Sedmak, A., Čolić, K., et al. (2017), *Numerical analysis of stress distribution in total hip replacement implant*, Struct. Integr. Life, 17(2): 139-144.