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Design optimization and material selection of acetabular component of hip prosthesis using computational concepts

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1. Introduction

The use of total hip prosthesis (THP) to replace a damaged bearing joint is considered as one of the major successes of orthopedic surgery. However, the longevity of a hip joint prosthesis *in vivo* is still limited (Hölzer and Schröder 2012); it is significantly reduced by osteolysis and implant loosening triggered by wear debris and stress-shielding (Heaton-Adegbile and Russerly 2006), which are complex phenomena governed by implant design parameters and material properties.

Several authors investigated the influence of geometrical parameters on the short-term and long-term behavior of the hip implant. Similarly, the consequences of using of materials for the acetabular cup have been treated and their advantages and drawbacks over different combinations have been reported. From the available literatures, the simultaneous impact of geometrical parameters and material combinations for the acetabular component is not consolidated and reported as one study. Therefore, the main objective of this study is to develop a methodology which brings together and elucidates the effects of design parameters and material selection of acetabular component. For this aim, a combination of numerical methods has been used such as : *i*) a parametric finite element study allowing the variation of the most potential geometrical and material parameters and their effects on the mechanical behavior, *ii*) a response surface method (RSM) to explore the relationships between several variables and to obtain an optimal response, *iii*) a multi-criteria decision-making method (MCDM) to evaluate multiple conflicting criteria and to select the most suitable material for the acetabular component of hip prosthesis.

2. Methods

The most potential geometrical parameters considered in this study being the femoral head radius, the clearance

and the cup liner thickness. In order to predict the influence of these parameters on displacement, stress distribution, contact pressure and sliding distance, a parametric three-dimensional (3D) FE model was developed using Abaqus. The model was constructed with three components: femoral head, acetabular cup liner and backing composed of compact bone. The material properties are assumed to be homogeneous, isotropic and linear elastic solids. The components are discretized using 8-noded hexahedral elements. The established model offered a surface-to-surface contact between the head and the cup by assuming a constant wear coefficient. The cup liner wear depth was computed using Archard's law; it was performed based on the methods presented in detail by Shankar and Gowthaman 2015. the model simulates a person who weighs 860 N in walking conditions and the direction of forces is acting on the center of the femoral head. the bone was fully constrained.

By relying on the Box–Behnken Design (BBD) which is a response surface methodology, a design of experiments was established by varying the head diameter from 22 mm to 42 mm, the clearance between the head and the cup from 0 mm to 0.5 mm and the cup thickness from 4 mm to 16 mm. A second-order model was used to find a suitable approximation for the functional relationship between design variables and the response surface. Finally, a multi-objective optimization procedure was aimed to determine the optimal design parameters leading to minimizing linear wear depth, contact pressure, cup liner stress and to maximize bone stress. The computational process was conducted for the six following bearing couples of the head on the cup: MoP: CoCrMo/UHMWPE, CoP: Al₂O₃/UHMWPE, – MoM: CoCrMo/CoCrMo, CoM: Al₂O₃/CoCrMo, MoC: CoCrMo/Al₂O₃, and CoC: Al₂O₃/Al₂O₃. The optimal geometry for each material coupling obtained was used to establish candidate for the final selection.

Table 1. Optimal geometrical parameters of cup liner.

(mm)	Diameter	Clearance	Thickness
MoP	35.16293	0.07703	7.82568
CoP	36.08550	0.01724	4.00003
MoM	28.08136	0.01226	5.81694
CoM	32.79895	0.01000	4.06707
MoC	31.99446	0.01003	4.20957
CoC	25.98317	0.01002	4.49296

The optimal geometry of the acetabular component for each material coupling obtained was used to establish candidates for the final selection, and then they were modeled and analyzed by FEA.

An MCDM method, namely comprehensive TOPSIS, was used to rank and determine the most suitable of the candidate material couples. It consists of selecting the best choice having the shortest Euclidean distance to find the highest relative closeness to the ideal solution (Mousavi-Nasab and Sotoudeh-Anvari 2017). TOPSIS is affected by eight decision criteria representing implant requirements considered in this study and evaluated using FEA. The cup liner contact pressure and the linear wear depth must be minimum (C1 and C2), the mean contact pressure values to the yield strength ratio (C3) must be minimum to move away from the elastic-plastic transition. The liner must have a minimum ratio given by the maximum stress normalized by the fatigue strength of the material (C4). To avoid stress-shielding, the bone stress must be maximum (C5). High contact pressures (C6) and low contact displacement (C7) are required in the cup/bone contact region. The bone compressive stress to its compressive strength ratio (C8) must also be minimum.

3. Results and discussion

The optimal geometrical design parameters obtained by the application of multi-objective optimization are shown in Table 1.

According to parameters interaction analysis, the large head diameters are preferred for couples having poor wear resistance properties (e.g. MoP and CoP), because they greatly minimize the wear depth, contact pressure and stress at the acetabular cup. Low values of clearance were found optimal for all bearing couples. This is due to the harmful effect of clearance on linear wear depth, whereas no significant effect of the liner thickness was found. The results obtained are in good agreement with the literature (Puccio and Mattei 2015 and Lin and Wu 2016). On the other hand, larger head sizes and thicker liners reduce the stress at the bone due to the high stiffness generated and causing a minimum load transfer. For this reason, low values of head diameter and liner thickness were

found optimal for stiffer materials because of their higher Young's Modulus, like metals and ceramics.

The results of FEA of optimal designs are the subject of the decision matrix used to select the material couple having the highest closeness to the ideal solution according to TOPSIS rules. The final ranking reveals that the metal-on-metal (MoM) couple is the closest one and it represents the best compromise of different requirements used in this study, although the ranking results are not so far apart from each other because of the use of optimal geometrical parameters. Liners in metal were best ranked, because of the moderate strength and wear resistance properties of CoCrMo; unlike Al_2O_3 which has the best wear resistance properties but a high Young's modulus and UHMWPE with poor wear resistance properties and a low Young's modulus.

The use of a combination of computational concepts has enabled to take into account different conflicting parameters of design and materials. Even for the case of metal-on-metal couples which clinically represents a source of problems, it was possible to find the geometrical dimensions that can reduce the factors leading to failure of the hip prosthesis.

4. Conclusions

Basing on computational concepts, optimal geometrical parameters and a suitable material couple have been selected for the design of the acetabular component of the human hip prosthesis, in order to improve their longevity and performance. Such results can be very useful to control and minimize *in vitro* tests which are very expensive and complex.

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