Material selection process for femoral component of hip prosthesis using finite element analysis and ranking method

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1. Introduction

Total hip replacement is considered as the most common orthopedic surgical treatment providing pain relief and an excellent alternative for patients. However, this technique is experiencing an increasing rate of failure and revision surgeries especially for young and active patient (Kandal and Connonck 2015). This has sparked the issue of improving the design and material selection of different components of a Total Hip Prosthesis (THP). Nowadays, the orthopedic market offers a wide range of materials which may be suitable for use in THP; on the other hand, the requirements of these materials are very complex and overlap, such as stress-shielding minimization, fatigue and wear resistance (Amit et al. 2015). This makes the material selection, a very difficult task for the designers (Farag 2014), hence the need to set up a process for the material selection of hip prosthesis components.

In this study, a combined process based on Finite Element Analysis (FEA) and Multi-Criteria Decision-Making method (MCDM) is proposed to select the optimal materials for the femoral components of THP in order to improve their design and longevity.

2. Methods

The ranking process was carried out with a 3-D model of femoral head connected to a stem by its neck (Figure 1). The 3-D geometry of the femur was reconstructed using quantitative computer tomography, while other components were created based on CAD data of a hip prosthesis.

The femoral stem was bonded to the bone by a 4 mm thick cement and the components were oriented in 10° adduction and 9° flexion. Using Abaqus/Standard, the complete model was constructed and the femoral components were meshed with tetrahedral elements (C3D10). A mesh convergence analysis showed that an element size below 1.5 mm did not further influence the results. Four materials were candidates for the femoral head and three for the femoral stem.

Therefore, twelve possible couples (4 x 3) were considered in the present study as shown in Table 1. Poly-methyl methacrylate (PMMA) as bone cement, cancellous bone and cortical bone were also considered. The materials were assumed to be homogeneous, isotropic and linear elastic solids. The established model offered a surface-to-surface contact at all interface regions. The loads applied to the head correspond to normal walking, calculated according to the experimental observations performed by Bergmann et al. (2001) on a patient who weighs 860 N, the proximal and distal of femur bone were totally fixed.

Eight decision criteria (Cj) representing the required behavior of the femoral component were considered. C1: bone stress must be minimal to avoid stress-shielding risk. C2 and C3 representing respectively displacements at cement/stem and stem/head interfaces. Maximum contact pressures C4 and C5 are required in these regions. The stem and head must have the highest factor of safety (FOS) which is given by the fatigue strength of the material normalized by the maximum stress (C6 and C7). Finally, C8 represents minimum displacement in the head which can lead to good biomechanical suitability.

The values of different decision criteria were predicted for the twelve material couples using the FE analysis (Table 1) and injected in an MCDM method, namely comprehensive VIKOR. This method has been used to rank material couples and determine the most suitable one according to the decision criteria values and their weights (w). The compromise rank is an optimal solution that is closest to the desirable target, and means an agreement established by mutual concessions, using a combination of objective (wObj) and subjective (wSub) weights according to the following formula (Gul and Celik 2016):

\[ w_j = \lambda w_{Obj}^j + (1 - \lambda)w_{Sub}^j \quad j = 1, 2, \ldots, 8 \]

\( \lambda \) represents a factor varying from 0 (\( w_j = w_{Obj}^j \)) to 1 (\( w_j = w_{Sub}^j \)), for sensitivity analysis of weights.
3. Results and discussion

In order to show the effect of the decision criteria on the ranking orders, the subjective weight has been calculated in a way to promote the criterion $C_1$ minimizing stress-shielding risk. The sensitivity of ranking orders of the best seven material couples obtained is graphically shown in Figure 2. Based on this graph, the stem in CoCrMo-wrought and the head in SS316L represent the optimal couple of materials satisfying and compromising the majority of design requirements. Moreover, Ti$_6$Al$_4$V/Al$_2$O$_3$ couple was ranked second.

The use of metallic materials such as CoCrMo, Ti$_6$Al$_4$V and SS316L may lead to the failure of THA, but the determination of optimal combination compromising their conflicting properties allows to reduce failure risks. CoCrMo-wrought is stiffer than Ti$_6$Al$_4$V and SS316L which undergo less bending displacements and a high contact pressure at the cement/stem region. The superior fatigue strength of CoCrMo-wrought provides a good factor of safety compared to SS316L. In general, stems in CoCrMo-wrought present the lowest stress at the bone which can lead to stress-shielding failures. For these reasons, for $\lambda = 0$, the couple Ti$_6$Al$_4$V/CoCrMo-cast was ranked the first thanks to the lowest stiffness of titanium alloy minimising stress-shielding risk. For $\lambda \geq 0.8$, the Al$_2$O$_3$ replaced SS316L in the head, because of its superior wear resistance and high stiffness. Ti$_6$Al$_4$V has a good factor of safety and minimum risk of stress-shielding, but its low Young’s Modulus leads to a larger displacement at the contact surfaces which causes wear debris, for this, a head in Al$_2$O$_3$ is the most suitable for titanium stems. This explains why the couple Ti$_6$Al$_4$V/Al$_2$O$_3$ was ranked second in the process.

4. Conclusions

In this study, a systematic process to select suitable materials for the femoral stem and head of a hip prosthesis was performed. Among the tested couples, CoCrMo-wrought/SS316L and Ti$_6$Al$_4$V/Al$_2$O$_3$ have given the optimal compromise of different requirements used in this study. This process can be used for competition of other biomaterials. However, such in vitro studies are limited as they cannot cover all in vivo requirements.

References

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