UNIVERSITI PUTRA MALAYSIA

COMPUTER MODELING IN TAILORING OF FUNCTIONALLY GRADED MATERIAL AND DESIGN OPTIMIZATION OF FEMORAL COMPONENT IN TOTAL KNEE REPLACEMENT TO REDUCE ASEPTIC LOOSENING

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By

MARJAN BAHRAMINASAB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

"This thesis is dedicated to my ever-encouraging parents, my beloved husband and daughter for their love and support"

Abstract of thesis presented to the Senate of Universiti Putra Malaysia, in fulfillment of the requirements for the degree of Doctor of Philosophy

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Faculty: Engineering

Aseptic loosening is the main reason for failure/revision of Total Knee Replacements (TKR), which occurs for all TKR components including femoral, tibial and patellar components. It is particularly problematic for femoral component because its failure can be associated with different causes. The judicious considerations of femoral component materials and design may provide an immune response to aseptic loosening problem by minimizing the occurrence of leading causes. Literature review showed the need for more sophisticated multi-functional materials to be developed in order to match the biological and mechanical complexity of the prosthetic femur.

To reduce aseptic loosening problem a new multi-functional material, a functionally graded biomaterial (FGBM) composed of alumina and titanium, was introduced for femoral component. FGBM consists of two or more biocompatible constituents, whose mechanical properties vary with positions and can be designed for specific application. The potential advantages of applying FGBM were explained by reducing the leading causes of failure; wear, micro-motion and stress shielding effect. The primary proposed design of FGBM was analyzed using finite element to investigate the stress level in the distal femur and to find the influence of the suggested material on stress shielding effect. The results obtained were compared to using a standard femoral component material both with and without cement fixation, which showed the superiority of the proposed FGBM without cement fixation.

In order to have more precise material design leading to optimal function, a multi-objective design optimization for an FGBM femoral component was carried out using finite element analysis (FEA) and response surface methodology (RSM). Three performance outputs including stress shielding effect, micro-motion and wear index were optimized with respect to three FGBM design variables. Overall, the optimal FGBM showed better results; on average 3.8%, 13.6%, and 0.6% improvements were

found in the mean stress of the femur, mean micro-motion of the interface and wear index of insert, respectively compared with the use of standard Co-Cr alloy.

One of the geometrical features that play an important role in the effectiveness of primary and revision knee prostheses is the peg or stem. The design of the location pegs in the femoral component of the knee prosthesis is seen to have a critical effect on stress shielding. Therefore, different combinations of location peg geometries and material designs were assessed using FEA in conjunction with design of experiments. A multi-objective optimization was carried out to find the optimal geometries of peg for the femoral component and based on the results obtained a set of candidate designs was generated and a multi-criteria decision making approach used for final ranking. It was found that a FGBM femoral component with 60% porous Ti conical peg is the most suitable design. The selected design which was based on integration of material and geometry design, showed more than 10% improvement, on average, in stress shielding effect.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia untuk memenuhi keperluan untuk ijazah Doktor Falsafah

PEMODELAN KOMPUTER DALAM PENYESUAIAN BAHAN FUNGSIAN BERGRED DAN PENGOPTIMUMAN REKA BENTUK KOMPONEN FEMUR PADA PENGGANTIAN LUTUT KESELURUHAN UNTUK MENGURANGKAN KELONGGARAN ASEPTIK

Oleh

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Kelonggaran aseptik adalah punca utama bagi kegagalan/semakan bagi penggantian lutut keseluruhan (TKR). Ianya adalah sangat bermasalah kepada komponen femur (tulang peha) kerana kegagalannya disebabkan oleh sebab yang berbeza. Pertimbangan bijak bagi bahan komponen femur dan reka bentuk dapat memberikan respons yang berimun kepada masalah kelonggaran aseptik dengan mengurangkan punca utama. Sorotan kajian ilmiah menunjukkan yang keperluan untuk bahan yang lebih canggih dan pelbagai fungsi perlu dibangunkan dalam usaha menangani kerumitan biologi dan mekanikal femur prostetik.

Untuk mengurangkan masalah kelonggaran, satu bahan pelbagai fungsi, biobahan fungsi bergred (FGBM) terdiri daripada aluminum dan titanium dicadangkan bagi komponen femur. FGBM terdiri daripada dua atau lebih bahan asas yang serasi bio, di mana sifatnya berubah dengan kedudukan dan boleh direka bentuk untuk penggunaan khusus. Potensi kelebihan menggunakan FGBM telah diterangkan dengan mengurangkan punca kegagalan utama; haus, gerakan mikro dan kesan perlindungan tegasan. Cadangan reka bentuk utama bagi FGBM telah dianalisis menggunakan permodelan unsur terhingga bagi menyiasat tahap tegasan dalam distal femur dan mencari pengaruh bahan yang dicadangkan ke atas kesan perlindungan tegasan. Hasil dapatan telah dibandingkan dengan menggunakan bahan piawai komponen femur bagi kedua-dua kaedah, dengan dan tanpa simen yang telah menunjukkan kelebihan menggunakan bahan FGBM tanpa simen.

Untuk mendapatkan reka bentuk bahan yang tepat bagi fungsi yang optimum, pengoptimuman reka bentuk pelbagai objektif bagi komponen femur FGBM telah dijalankan menggunakan analisis unsur terhingga (FEA) dan kaedah sambutan permukaan (RSM). Tiga hasil termasuk kesan perlindungan tegasan, gerakan mikro dan indeks haus telah dioptimumkan dengan tiga pemboleh ubah reka bentuk FGBM. Secara

keseluruhannya, FGBM menunjukkan hasil yang lebih baik, dengan purata 3.8%, 13.6%, dan 0.6% penambahbaikan telah dijumpai dalam min tegasan bagi femur, min gerakan mikro antara muka dan indeks haus sisipan, masing-masing berbanding dengan penggunaan aloi piawai Co-Cr.

Salah satu ciri geometri yang telah memainkan peranan penting kepada keberkesanan lutut palsu utama dan semakan adalah batang dan pasak. Reka bentuk bagi lokasi pasak dalam komponen femur bagi lutut palsu boleh dilihat mempunyai kesan kritikal ke atas perlindungan tegasan. Oleh sebab itu, dalam bahagian terakhir bagi kajian ini, pelbagai kombinasi lokasi geometri pasak dan reka bentuk bahan telah dinilai menggunakan FEA berserta dengan reka bentuk ujikaji. Satu pengoptimuman pelbagai objektif telah dijalankan dalam mencari geometri pasak yang optimum kepada komponen femur dan berdasarkan kepada hasil yang diperolehi, satu set calon reka bentuk calon telah dihasilkan, dan percubaan membuat keputusan pelbagai ciri digunakan untuk reka bentuk terakhir terbaik. Didapati bahawa komponenfemur FGBM dengan pasak tirus Ti rongga 60% adalah yang paling sesuai. Reka bentuk ini terpilih berdasarkan kepada integrasi bahan dan rekaan geometri menunjukkan penambahbaikan 10%, secara puratanya kepada kesan perlindungan tekanan.

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I certify that an Examination Committee has met on 1 April 2014 to conduct the final examination of Marjan Bahraminasab on her thesis entitled " COMPUTER MODELING IN TAILORING OF FUNCTIONALLY GRADED MATERIAL AND DESIGN OPTIMIZATION OF FEMORAL COMPONENT IN TOTAL KNEE REPLACEMENT TO REDUCE ASEPTIC LOOSENING " in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the PhD.
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