EFFECTS OF PROSTHESIS STEM LENGTHS AND TAPERS ON STRESS DISTRIBUTION IN CEMENTED HIP ARTHROPLASTY

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To my beloved family

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ABSTRACT

Stress shielding and bone remodeling effects are critical issues in considering the biomechanics of femur that has undergone total hip replacement (THR). Stress shielding occurs when local stress distribution in the presence of the prosthesis is lower than that observed with intact femur. In this study, the stress distributions in intact and THR femur are established using finite element method. The THR femur model consists of a cemented hip Ti-6Al-4V prosthesis implanted inside the femoral canal. Major muscle loads and contact forces are simulated for walking (toe-off phase) and stair-climbing conditions that represents 800N of bodyweight. The effects of Charnley's prosthesis stem lengths and tapers on the resulting stress and strain distributions are investigated. For the stem length cases, results show that tensile stress dominates in the lateral plane while compressive stress in the medial plane of the femur. In the iso-strain condition, greater part of the load to the THR femur is shifted to the stiffer Ti-6Al-4V alloy prosthesis. The stresses in the surface of the cortical bone are relatively low in the central region of the THR femur. The largest magnitude of maximum principal stresses are 24 and 34 MPa for walking and stair-climbing load cases, respectively, for THR femur while the corresponding stress levels for intact femur are 22 and 29 MPa, respectively. For the stem taper cases, the magnitude of Tresca stress for the THR femur in stair-climbing load case remains higher in the region of 85 MPa while the walking load case induces around 40 MPa. The stress range in the straight and single taper stem prosthesis is lower than 260 MPa, while localized Tresca stress is in the order of the yield strength of Ti-6Al-4V alloy for double and triple taper stem design.

ABSTRAK

Halangan tegasan dan pembentukan semula tulang merupakan isu kritikal yang berlaku selepas seseorang itu menjalani penggantian tulang pinggul atau lebih dikenali sebagai Total Hip Replacement (THR). Halangan tegasan akan berlaku apabila taburan tegasan pada tulang femur berimplan lebih rendah berbanding tegasan pada tulang femur normal. Dalam kajian ini, taburan tegasan pada tulang femur normal dan tulang femur THR dibuktikan melalui kaedah unsur terhingga. Model femur THR merangkumi implan pinggul dari bahan Ti-6Al-4V dan jenis bersimen yang ditanam di dalam rongga tulang femur. Bebanan otot-otot utama dan daya yang bertindak disimulasikn dalam keadaan berjalan dan menaiki tangga yang mewakili berat badan sebanyak 800N. Kajian dilakukan terhadap kesan pemanjangan dan ketirusan batang implan Charnley kepada taburan tegasan dan terikan. Bagi kes pemanjangan implan, keputusan menunjukkan bahawa tegasan regangan mendominasi di satah belakang (lateral) manakala tegasan mampatan di satah hadapan (medial) tulang femur. Pada keadaan iso-terikan, sebahagian besar bebanan kepada tulang femur THR berpindah kepada implan Ti-6Al-4V yang lebih keras. Tegasan di permukaan tulang luar (cortical) adalah rendah pada bahagian tengah tulang femur THR. Nilai terbesar tegasan prinsipal maksimum di tulang femur THR adalah 24 MPa pada keadaan berjalan dan 34 MPa pada keadaan menaiki tangga. Nilai tegasan di tulang femur normal adalah 22 dan 29 MPa bagi keadaan-keadaan tersebut. Bagi kes ketirusan batang implan, nilai tegasan Tresca bagi tulang femur THR pada keadaan menaiki tangga masih tinggi iaitu 85 MPa manakala pada keadaan berjalan dilaporkan sekitar 40MPa. Julat tegasan pada batang implan jenis tegak dan satu tirus adalah lebih rendah dari 260 MPa manakala tegasan Tresca pada batang implan jenis dua tirus dan tiga tirus menghampiri kekuatan anjal aloi Ti-6Al-4V.

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CHAPTER 1

INTRODUCTION

Total hip replacement (THR) is a common procedure to reform the hip joint. In this procedure, hip joints are replaced by artificial materials to relieve the pain and restore the function of the joint (Lu, 2001). There are approximately 800,000 total hip replacements being performed around the world, annually (Cristofolini, 1997). Indeed, it is projected that the number of hip failures will increase to 6.3 million by the year 2050 (Cooper *et al*, 1992; Lau, 2001).

In a typical THR, the diseased femoral head of femur (the bone that extends from the hip to the knee) is excised and replaced by a femoral component which consists of a femoral head, while the diseased surface of acetabulum is reamed and inserted by the artificial cup. The acetabulum is a surface layer of the socket in the pelvis (the two large bones that rest on the lower limbs and support the spinal column).

There are many different shapes, sizes, and designs of artificial components for the hip joint. Efforts to improve designs were continually developed to improve the fit in the femur (Kassim, 1997). It is important for the hip prosthesis to be implanted securely in the femur so that it functions properly as in normal condition. Apart from different types of design and materials, there are two main methods currently being used to fix the hip prosthesis to the femur, namely cemented and cementless total hip replacement. In general, bone cement is packed between the femoral bone and stem for cemented method. For cementless method, a porous coating layer is attached to the surface of the stem or the outer surface of the metal back that supports the acetabular cup. After the components are inserted, bone typically grows into the porous layer to form a permanent bond which also known as bone remodeling (Lu, 2001).

1.1 Cemented Hip Arthroplasty

The most successful cemented total hip replacement (THR) was developed by John Charnley in 1972. He introduced polymethyl-methacrylate (PMMA) as the bone cement and ultra-high molecular weight (UHMW) polyethylene for the acetabular cup. The prosthesis, known as 'low-friction' arthroplasty, consists of an all-polyethylene acetabular component and a stainless steel polished femoral component. Since then, Charnley's prosthesis is commonly used and regarded as the reference or benchmark design (Masterson *et al.*, 1999). The long-term clinical follow-up studies have demonstrated outstanding performance of Charnley's prosthesis. A 25-year follow-up review for eight hospitals worldwide showed that 92% of THR cases using Charnley's prosthesis remain good and functional until death (Older, 2002). However, frequently reported problems on THR femur failure is related to aseptic loosening.

Aseptic loosening refers to the failure of the bond between an implant and bone in the absence of infection. Aseptic loosening of joint implants is a disabling condition that can affect patients 10 to 20 years after joint replacement surgery (Yousef *et al.*, 2007). The Norwegian Arthroplasty Register reported more than 70% of the revisions of the hip replacements were due to aseptic loosening (Furnes, 2002). This is also supported by researchers through clinical review for 15 to 25 years follow-up of primary Charnley low-friction arthroplasty (Ohannes *et al.*, 2005; David and Andrew, 2003). Aseptic loosening may occurred due to biomechanical factors such as osteolysis induced by wear debris of bone cement, cement mantle fracture, and poor bone remodeling triggered by stress shielding (Lu, 2001; Ramaniraka *et al.*, 2000; Masterson *et al.*, 1999).

1.2 Statement of the Research Problem

Both stress shielding and bone remodeling effects are critical issues in considering the biomechanics of THR femur. Stress shielding occurs when local stress distribution in the presence of the prosthesis is significantly lower in magnitude than that observed with intact femur. It happens when there is a mismatch in the stiffness or elastic moduli of the femoral prosthesis and the bone. In the iso-strain condition, the stiffer femoral shaft will sustain the greater part of the load, primarily due to the body weight. Consequently, significant stress gradient occurs across the prosthesis-bone interface particularly in the proximal region of the femur. Such stress alternation leads to extensive bone resorption in the region leading to loosening of the prosthesis stem. This study examines the effects of different prosthesis stem lengths and tapers on the stress and strain distribution in cemented hip arthroplasty under different loading conditions. Biomechanics of THR femur is analyzed using finite element method. Finite element modeling of THR femur calls for accurate representation of the femur and the complex loading due to active muscle forces during the various activities including walking and stair-climbing.

1.3 Research Questions

This study addresses the following questions regarding the stress distribution in intact and THR femur.

1. What constitute a suitable finite element model for THR femur in cemented hip arthroplasty?
2. What are the effects of different prosthesis stem lengths on the stress distributions along the femur?
3. What are the effects of tapered prosthesis stems on the stress distributions along the femur?
4. What are critical prosthesis design parameters and values for Asian population?

1.4 Objectives

The objectives of this study are to;

i. Develop finite element modeling procedure for cemented hip prosthesis and femur for total hip replacement (THR).

ii. Perform static analysis of two different loading activities to examine the stress distribution along the femur and hip prosthesis.

iii. Investigate effects of hip prosthesis geometry, namely stem lengths and tapers on the resulting stress distribution along the femur and prosthesis.

1.5 Scope of Study

The scope of this finite element simulation covers the followings;

i. Intact or healthy femur.

ii. Femur with total hip replacement, with cemented Ti-6Al-4V prosthesis.

iii. Parametric study on (a) different stem lengths and (b) different stem tapers.

iv. Two loading cases (a) walking(toe-off phase) and (b) stair-climbing.

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