UNIVERSITI PUTRA MALAYSIA

STRESS ANALYSIS OF THE HUMAN TIBIA KNEE JOINT USING FINITE ELEMENT METHOD

NOR FADHILLAH MOHAMED AZMIN

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By

NOR FADHILLAH MOHAMED AZMIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

July 2007

This work is dedicated to

my family, teachers and friends
who gave me
their endless encouragement.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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Faculty: Engineering

Despite the several years of studies that have been contributed to the human knee joint in pursue of producing a failure free knee joint protheses, there are still a lot of rooms for improvement on the available prostheses. In this present study, a series of analyses on the human tibia has been carried out. The objectives of the present study were to study effects of stress distribution on human tibia in various degrees of flexion simulating walking and squatting. The Finite Element (FE) method was adopted for the analysis. Through the finite element analyses, data concerning the stress distribution and von Misses stress during gait cycle and squatting were obtained. The results obtained were compared with those of the experimental literature for validation. The results of this present study indicated that low stress value occurs during toe-off simulation while the high stress value occurs during deep flexion with the knee is flexed 90˚. The von Mises stress observed on the medial compartment during these

instants were 13.85MPa and 26.84MPa respectively. The obtained average stress distribution of a gait cycle and deep flexions were 15.29MPa and 25.09MPa respectively. it is worth to note that a high stress concentration occurs at the tibial plateau, distinctively at the medial compartment. This implies that under deep flexion a possible unstable fracture will be initiated since the maximum stress allowable on the tibia is 25MPa.

In conclusion, this kind of research gives a better understanding of the stress applied on the tibia by body weight that assist on designing Total Knee Replacement against failure. The result could support in the context of minimizing contact stress between the tibia bone and the tibial insert.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

ANALISIS KESAN TEGASAN TERHADAP TULANG TIBIA LUTUT MANUSIA MENGGUNAKAN KAEDAH UNSUR TERHINGGA

Oleh

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Pengerusi: Profesor Madya Megat Mohamad Hamdan Megat Ahmad, PhD

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Walaupun bertahun-tahun penyelidikan dan ujikaji telah dijalankan terhadap sendi lutut manusia dalam menghasilkan sendi lutut tiruan yang tidak bermasalah, masih banyak lagi ruang yang perlu diperbaiki dalam sendi lutut tiruan yang ada di pasaran. Di dalam kajian ini, analisis-analisis telah dijalankan terhadap tulang tibia manusia. Tujuan kajian ini dijalankan ialah untuk mengetahui kesan tegasan terhadap tulang tibia manusia di dalam beberapa darjah bengkokan yang mewakili keadaan berjalan dan bertinggung. Permodelan secara unsur terhingga telah digunakan untuk menganalisis kajian ini. Data-data mengenai sentuhan tegasan maksimum dan tegasan von Mises semasa pusingan berjalan dan bertinggung dihasilkan melalui analisis permodelan secara unsur terhingga. Keputusan- keputusan yang dihasilkan telah dibandingkan dengan maklumat dari ujikaji sebagai pengesahan. Keputusan yang

dihasilkan oleh kajian ini menunjukkan sentuhan tegasan yang rendah semasa simulasi ‘toe-off’. Manakala sentuhan tegasan yang tinggi terjadi semasa lutut dibengkokkan sebanyak 90˚. Tegasan purata von Mises di atas bahagian medial semasa kedua-dua keadaan tersebut masing-masing ialah 13.85MPa dan 26.84MPa. Purata tegasan untuk ‘gait cylce’ dan ‘deep flexions’ masing-masing ialah 15.29MPa dan 25.09MPa. Fokus tegasan yang tinggi terjadi di kawasan ‘tibial plateau’. Ini menyarankan bahawa semasa ‘deep flexion’, terdapat kemungkinan terjadinya rekahan yang tidak seimbang kerana tegasan maksima yang dibenarkan ke atas tibia ialah 25MPa.

Kesimpulannya, kajian ini memberikan pemahaman yang lebih baik tentang tegasan yang dikenakan ke atas tibia oleh berat badan yang mana membantu merekacipta ‘Total Knee Replacement’ yang mampu mengelakkan kegagalan. Hasilnya boleh menolong meminimakan tegasan sentuhan di antara tulang tibia dengan tibia gantian.

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To my family, friends and colleagues, who continuously give me their support in one way or another toward the completion of this study.

I certify that an Examination Committee has met on **date of viva** to conduct the final examination of Nor Fadhillah Mohamed Azmin on her Master of Science thesis entitled “Stress Analysis Of The Human Tibia Knee Joint By Using Finite Element Method” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Member of the Examination Committee are as follows:

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

NOR FADHILLAH MOHAMED AZMIN

Date: 19 October 2007

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3D	Three Dimensional
BW	Body Weight
CAD	Computer Aided Design
CPU	Computer Processor Unite
DF1	Deep Flexion 1
DF2	Deep Flexion 2
FEM	Finite Element Modeling
HS	Heel Strike
IGES	International Graphic Exchange System
ISB	International Society of Biomechanics
SLS	Single Lomb Stance
ST	Standardized Tibia
TKA	Total Knee Arthroplasty
TKR	Total Knee Replacement
TO	Toe Off

CHAPTER 1

INTRODUCTION

Total knee replacement (TKR), also referred to as total knee arthroplasty (TKA), is a surgical procedure where worn, diseased, or damaged surfaces of a knee joint are removed and replaced with artificial surfaces. The substitution of bone surfaces are crucial for arthritic knees where the articular cartilage is damaged. Normally, the cartilage acts like a cushion to reduce friction between joint surfaces. However, in damaged surfaces of a knee joint, the erosion causes aching and progressive degeneration of uncovered bone ends.

The knee is a hinge joint which provides motion at the point where the thigh meets the lower leg. The thigh bone (or distal femur) adjoins the large bone of the lower leg (proximal tibia) at the knee joint. During a total knee replacement, the distal femur and the proximal tibia are removed and replaced by metal shells. A polyethylene insert will be placed in between both of the metal shell.

The procedure has been proven to help individuals return back to moderately challenging activities such as golf, bicycling, and swimming.

The ultimate goals for total knee replacement are to relieve and restore normal knee kinematics while ensuring the biocompatibility of the prosthesis and its long-term fixation and durability.

1.1 Problem Statement

Undeniably, total knee replacement has been a great achievement in the medical history. The story is still unfolding as surgery and technology advance. To this day there are more than 100 different prosthesis designs available, and the choice is not only for size and geometry, but also involves more critical issues such as cruciate retaining/substituting, uni/tri-compartmental and mobile/fixed bearing (Zuffi et al. 1999).

The number of TKR has been increasing in the last years. In 1995, 216 000 TKR's were performed in the United States. However, this figure should have be seen together with the 18 000 revisions performed during the same period, which means an average failure rate of more than 8% (Zuffi et al. 1999). Problems faced by TKR are usually due to bone-implant bond loosening and other issues such as biocompatibility, instabilities, fatigue, wear, dislocation and inadequate bone in growth.

Annually, about 150,000 total knee replacement surgeries are performed in North America. Despite the huge number, the current designs of knee prostheses have mechanical problems that include a limited range of motion, abnormal gait patterns, patellofemoral joint dysfunction, implant loosening or subsidence, and excessive wear. These problems fall into three categories; failure to reproduce normal joint kinematics, which results in altered limb function; bone implant interface failure; and material failure (Hollerbach and Hollister, 1997).

Another hindrances in the TKA are the limited number of studies reporting biomechanics of deep flexion beyond 90˚ (Takeo Nagura et al. 2002 and Guoan Li et al. 2004); and the stress distribution within the bone implant construct where excessive stresses may lead to delamination of the polyethylene (Zuffi et al. 1999, Godest et al 2002, and Clarke et al.).

TKA and other current surgical treatments of the diseased knee have provided pain relief and excellent function in the range 0˚-120˚ of flexion. However, little data have been reported regarding knee kinematics beyond 120˚ of flexion. Knowledge of higher degrees of flexion is important to knee function for many drills such as in sports, hobbies like gardening and also religious worship. (Li et al. 2004).

As surgical technique and prosthesis design have developed, the range of motion (ROM) after TKA has improved enough to permit patients more than 100° of flexion, sometimes enough to perform squatting or kneeling. However, there are concerns regarding possible mechanical failure in the long term follow up, and also instability occurrences with both types of prostheses (i.e. posterior cruciate ligament(PCL) substituting and PCL retaining prostheses) (Takeo et al. 2002).

Part of the mechanical failure is due to effect of stress and strain on the prosthesis and also the bone itself. High contact stress causes early wear failure, and overconstraint causes early loosening failure (Buechel 1996). While according to Zuffi et al. 1999, implant failure is mainly due to wear of the polyethylene insert, associated with an excessive stress at the artificial joint interface, as consequence of an abnormal knee kinematics.

It is crucial to investigate ways that might help to reduce the failure rate of total knee replacement and the need of revision surgeries which are of great cost to both patient and health service. The problems in total knee replacement have motivated researchers to find a new novel means of enhancing the performance of the knee prosthesis. The challenge is to suggest new development in the designs with respect to new geometry.

1.2 Objectives

The main objective of this research is to investigate the stress distribution that arises in the weight-bearing FE tibia model in various degrees of flexion simulating walking and squatting. The objectives are to model the tibia bone and to determine the stress distribution on human tibia under different loading condition with respect to certain instant of gait cycle and squatting.

A numerical method Finite Element Modeling (FEM) is used to accomplish the set objectives. A FEM includes three phases, preprocessing, processing, and postprocessing. In case of complex structure such as bone, the most difficult phase of FEM laid in preprocessing.

1.3 Layout of Thesis

This thesis is divided into five chapters. Following this preliminary chapter, which is the introduction to this study; chapter two is the literature review where the biomechanics of the knee joint and the type of analyses which had been done on the tibia are discussed extensively. The history of the TKR and current design of the available knee prostheses are also discussed in details in the literature review. Subsequent to the literature review, the methodology of the study and specific details of the finite element modeling and simulation of the tibia model are described in chapter three. The results of the analyses and the discussion of the results are presented in chapter four. Finally, the conclusion and future recommendations are presented in chapter five.

CHAPTER 2

LITERATURE REVIEW

Total knee replacements (TKR) are now performed regularly all over the world. Most knee replacements are performed for relief from the symptoms of osteoarthritis. The aim of TKR is restoring movement whilst still relieving pain and maintaining stability. Looking at the prosthesis progress throughout several years and the way it is today, TKR experts (i.e. doctors and engineers) can have a better hope to understand future developments and evaluate future designs and modification. The anatomy of the knee joint is discussed in section 2.1. Section 2.2 focused on the biomechanics of the knee joint. The history of TKR and all known previous studies done on TKR are discussed in Section 2.3 and 2.4 respectively. Section 2.5 summarizes all discussion corresponding to TKR in the thesis.

2.1 Anatomy of the knee joint

The knee joint is the largest joint in the body. It is a synovial hinge type joint. It essentially consists of four bony structures; femur, tibia, fibula and patella. The femur, which is the large bone in the thigh, is attached to the tibia by ligaments and a capsule. The tibia or shinbone, is the large medial bone of the leg. The medial and lateral condyles of the distal end of the femur articulate with the medial and lateral tibial condyles at the proximal end of the tibia. The fibula is located parallel to the tibia. The patella (knee cap) slides up and down in a groove in the femur (the femoral groove) as the knee is bent and straightened.

The human knee is a two-joint structure composed of tibiofemoral joint and the patellofemoral joint. Figure 2.1 shows the lateral view of two-joint structure of the knee with patella attached. Figure 2.2 shows the anterior view of two-joint structure of the knee without patella. Figure 2.3 shows the proximal view of the tibia surface. The knee joint is the largest and perhaps the most complex joint in the human body compared to other joints. Its function is to transmit loads, participate in motion, aids in conservation of momentum, and provide a force couple for activities involving the leg. The knee is prone to injury due to the fact that it sustains high forces and is situated between the body's two longest lever arms.

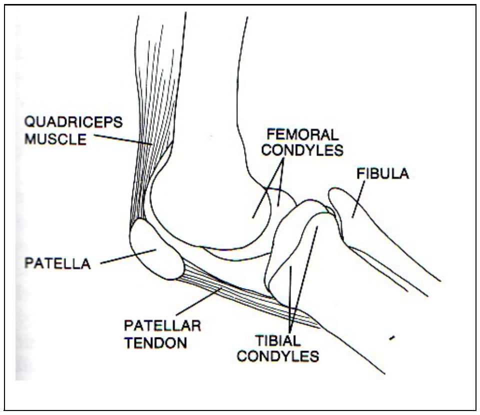

Figure 2.1: Lateral view of two-joint structure of the knee (adapted from Nordin and Frankel 1989).