CAD-model-based Design and Stress Analysis of Resurfacing Hip Joint Prosthesis

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ABSTRACT

Artificial hip replacement arthroplasty has been developed and practiced in orthopedic surgery for many years. The conventional method is total hip replacement system consisting of a femoral stem and head and acetabular socket. However the high stress between the femoral head and the acetabular socket often causes stress shielding effect to occur and consequently results in the failure of the artificial hip replacement surgery. This study aims to provide an alternative solution to the aforementioned problem with hip resurfacing surgery. The CAD model concept for the design of resurfacing hip joint system is to eliminate stress shielding effect caused by conventional stemmed hip joint system. In this study, finite element analysis is employed to compare resurfacing hip joint system, stemmed hip joint system, and natural hip joint with regard to medial and lateral femur stress, and strain distribution on the femur in order to discuss the applicative characteristics of the two different surgical procedures of artificial hip joint replacement. The research finds that the metal femoral stem causes the stress distribution on the femur and the amount of force to the femur to differ significantly from that with natural hip joint and thus causes stress shielding effect to occur and subsequently post-operative complications such as osteoporosis and osteolysis. On the other hand, the stress to the femur in resurfacing hip joint system is homogeneously distributed to the femoral body and closer to that with natural hip joint. It significantly reduces the stress, via press-fit femoral neck resurfacing prosthesis, Minimized stress shield effect from happening, and lowers the possibility of femoral fracture. This study is therefore able to determine the advantages and disadvantages of resurfacing hip joint system in comparison to conventional stemmed hip replacement system.

Keywords: artificial hip joint prosthesis, acetabular socket, stress shielding effect.
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1 INTRODUCTION

1.1 Introduction

Aging, long term use, and injuries could cause human bones degradation and damage the joints, resulting in joint pain which could seriously affect the living quality of the patient. In the treatment of joint disease and degradation, hip replacement arthroplasty is the last and most effective way to relieve the symptoms and restore the functionality of the hip joint. Femur neck resurfacing hip joint

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system is specifically designed for younger patients whose femoral head and neck have not yet sustain severe damage. The technology for femur neck hip resurfacing replacement surgery has been developed and gradually become a mature procedure.

In total hip replacement arthroplasty, the portion of bone morrow in the cannel of femur stem,femoral head and neck have to be rasped and resected respectively and a reamer is used to enlarge and shape the medullary cannel to allow the femoral stem to be inserted. The massive bone removal causes subsequent revision surgery, if and when required, to be more difficult and the success rate much lower than the primary operation. If the femoral head and neck of the patient have not yet suffered complete damage and need not be removed, but total hip replacement arthroplasty is never the less opted for, it would not only prolong and complicate the operation but also impair the original anatomic structure and the physical stress distribution of the femur, resulting in non-ergonomic hip joint. After the implantation of the stemmed hip joint system, the body weight from above the hip joint will be mainly transferred down to the proximal end of the femur and the artificial hip joint. However, as the modulus of elasticity of the artificial hip joint is far larger than that of the femur, the load will be concentrated on the artificial hip joint and the proximal end of the femur therefore sustains far less stress than in the case of a healthy person. Furthermore, according to Wolffȯs law,the femur would strengthen with the increase of the sustained stress and weaken with the decrease. As a result, bone remodeling or necrosis occurs at the proximal end of the femur, while bone thickening occurs at the distal end of the femoral stem due to stress concentration. This is called bone remodeling caused by stress shielding effect. Hence, stress shielding effect is the biggest challenge in the design of stemmed hip joint system. In order to solve this problem, femur neck hip resurfacing hip surgery is researched and developed. Resurfacing hip joint could keep as much original bone stock as possible, offering a good bony condition for a necessary conventional revision hip replacement surgery while retaining the anatomic structure of original hip stem.

1.2 Research Motivation

Due to aging, long term use, and external injury, human joint would suffer from degradation and damage, losing its proper functionality and causing pain which would seriously affect the life of the patient. In the treatment of joint disease and degradation, hip replacement surgery is the last and most effective way to relieve the symptoms and restore the functionality of the hip joint. Conventional stemmed hip joint system has a different anatomical structure from that of the original hip joint, resulting in the different stress distribution. In the case of younger and more active patients, this appears to be one of the reasons that would cause the hip replacement surgery to end in failure. This study aims to examine how the newly developed and designed resurfacing hip joint system which has a similar anatomical structure to original hip joint affects the stress distribution on the femoral neck and stem. Finite element method is employed in the stress analysis to compare the strain distribution in each model to find out which is the most ergonomic artificial hip joint system. Nowadays several types of artificial hip joint that could solve previous problems have been developed among which femur neck resurfacing hip joint system is specifically designed for younger patients whose femoral head and neck have not suffered complete damage for diminishing trauma to the femur and maintaining homogeneous physical stress distribution along the surface of natural femur neck.

Human joint would suffer functionality degradation and joint damage due to aging and external injury, causing joint pain whose clinical treatment in the early stage involves resting, physical therapy and medications. However, if the condition becomes severe, arthroplasty, or joint replacement surgery, is the last treatment [2]. Ever since British surgeon, Dr. Sir John Charnley, designed the first generation artificial hip joint system in the 1960s [3], hip replacement surgery has been continually used in the clinical treatment avascular necrosis of the femoral head avascular necrosis and osteoarthritis. The clinical purpose of joint replacement surgery is permanent replacement of the original damaged joint. Never the less, if the contact force between the implanted femoral stem and the medullary cavity is distributed incorrectly, there will be too much contact force, resulting in bone destruction as well as the loosening of the artificial joint [4]. Hence, primary research of the designing of modular artificial hip joint is the prolonging of the service life of the artificial hip joint, the increasing of patient satisfaction, and the diminishing of stress shielding effect after the surgery which causes stress redistribution and results in bone remodeling and osteolysis [5]. Stolk et al. (2001)

discussed how muscle forces affect the stress/strain distributions in the femur and find that greatest difference occurs at the middle section of the femur and the middle and lower section of the implanted femoral stem [6]. Finite element method is first proposed by Brekelmans et al. in 1972 for the mechanical analysis of human bones, applying methods for engineering structure in the analysis of human skeletal parts [7]. Since then, many subsequent researches study the mechanical behavior of biological organisms using finite element method.

1.3 Literature Review

The research propose of this study is to compare and find out how different designs of artificial hip joint system affect the strain distribution in the femur. X-ray sliced data of the femur is obtained via CT scanner, and thereafter models of the femur and the femoral implants are reconstructed by using of 3D-Doctor medical DICOM image processing software. A finite element analysis is conducted by the ANSYS Workbench and implemented using the data of load and muscle forces provided by literature and the setting of material properties and meshing structure. The outcome of the analysis can subsequently be used to compare the effects of different femoral components on the femur which can later provide surgical options for the surgeons as well as academic reference for other researches.

Because of the advance in medical technology in recent years, total hip replacement surgery has become a relatively common procedure. There are several clinical explanations for the failure of hip replacement surgery, including infection, dislocation, femoral stem fracture, osteolysis, bone cement fracture, improper implanting location, and so on. The loosening between the implanted femoral stem and the femur is one of the most primary reasons for the failure of hip replacement surgery. It is mainly resulting from the stress shielding effect at the proximal end of the femur which causes bone remodeling and bone absorption at the proximal end, and consequently the implanted femoral stem could be loosening in the cannel of the femur. The elimination of stress shielding effect has become an important issue for the orthopaedists and designers of implant devices. This study analyses and compares existing artificial hip joints and newly designed femur neck resurfacing hip system hopefully would be of help for future artificial hip design reference and clinical evaluation.

1.4 Research Methodology and Propose

The research propose of this study is to compare and find out how different designs of artificial hip joint system affect the strain distribution in the femur. X-ray slice data of the femur is obtained via CT scan, and thereafter models of the femur and the femoral implants are constructed using CAD software. Finite element analysis is implemented using the data of load and muscle forces provided by literature and the setting of material properties and meshing. The outcome of the analysis can subsequently be used to compare the effects of different femoral implants on the femur which can later provide surgical options for the surgeons as well as academic reference for other researches.

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2 BASIC THEORY

2.1 Finite element method

For the past few decades, studies applying finite element method to orthopedic researches have been continually published. Viceconti et al., for example, employ finite element analysis to simulate hip replacement surgery and examine the strain distribution in the femur, and then utilizes a three-axial strain gauge to physically measure the strain, and find that the difference between the two methods is less than 10%, proving that finite element method is an applicable and reliable method for orthopedic research [8]. Finite element analysis is a computational analysis that utilizes numerical technique to address engineering problems and the stress distribution of irregularly shaped objects. Firstly it discretizes the object into a number of small geometric segmentations, such as a tetrahedron or a hexahedron, called elements that can be analyzed by the computer. There are nodes on these elements, and the nodes enable the elements to interconnect with each other. Sometimes two nodes can be merged into one to save computing time. The interconnection of elements is called mesh, and the interconnection of these meshes constructs a closed structure to form an integral object. An object therefore can be described as being composed of (m) elements. As the total number of the elements (m) is finite, this analysis is thus called finite element method. Its mathematical formation can be represented as:

$$\Sigma_e^m = 1^{\Omega^e} = \Omega$$

At current stage, finite element method can address the irregular shape, the inhomogeniety, the anisotropy and other material properties of the bones. Despite these particular characteristics, to address the complex geometries, material properties, and strain distribution of the bones, some reasonable hypotheses have to be postulated to simplify the complexity of the problems while retaining the desired accuracy at the same time. These simplified postulates must have been obtained and empirically tested by experiments or clinical data. In addition to those functions mentioned above, finite element method can also be applied to address the problems in a wide variety of engineering disciplines such as structural mechanics, fluid dynamics, heat transfer analysis, and electromagnetic field distribution, among others [9].

2.2 Femoral Neck Central Line Definition

In the superior-inferior view of the femur, pick two random points at the femoral neck, connect the two points to obtain a straight line L1 whose central point is A1. In the superior-inferior view of the femur, pick another two random points at the femoral neck to form another straight line L2 whose central point is A2. Connect A1 and A2 to form Plane 1 (Fig. 2-1). In the anterior-posterior view of the femur, pick two random points at the femoral neck, connect the two points to obtain a straight line L3 whose central point is A3. In the anterior-posterior view of the femur, pick another two random points at the femoral neck to form another straight line L4 whose central point is A4. Connect A3 and A4 to form Plane 2 (Fig. 2-2). Project Plane 1 and Plane 2 to form intersection. This intersection is the latest definition of femoral neck central line in this study.

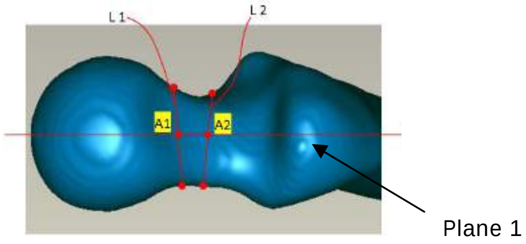

Fig. 2-1: Plane 1 on the femoral neck, superior-inferior view.

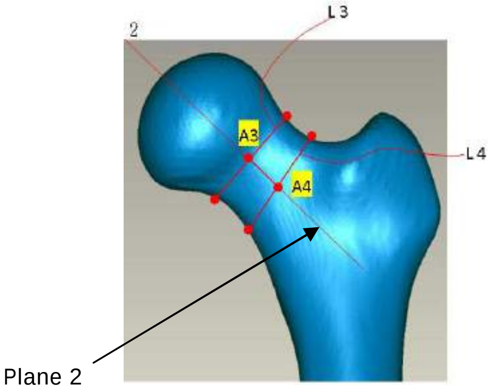

Fig. 2-2: Plane 2 on the femoral neck, anterior-posterior view.

3 RESEARCH PROCESS

3.1 Research Procedure

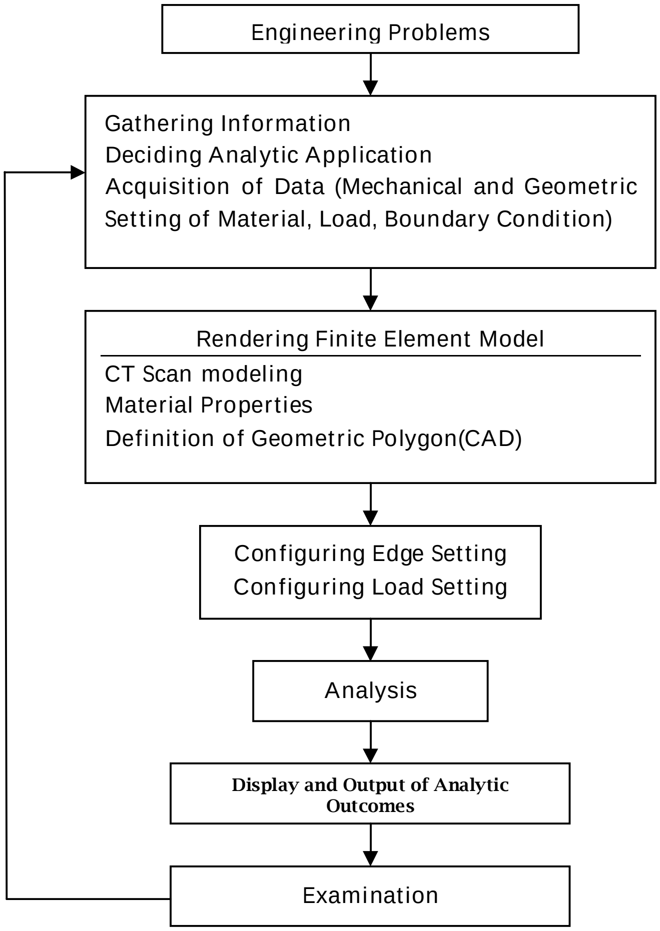

Fig. 3-1: Finite element analysis workflow diagram.

3.2 Research Methodology

This study is a research of natural hip joint and artificial hip joint systems. It explores the differences between different designs of artificial hip joint, using CAD and computer simulation analysis. The design of resurfacing hip joint in this study is based on the CT

(Computed Tomography) image files. CT sliced data in one millimeter increment are reconstructed via 3D-DOCTOR, a medical 3D imaging modeling and management software, to acquire image files of unknown format. 2D images are organized into a sequence of files for the rendering of 3D images and volume reconstruction. Physical polyhedral object is rapidly transformed into 3D digital model using rapid prototyping software Geomagic Studio. Using the proposed femoral neck central line, the central line is determined and located, and the femur neck resurfacing prosthesis body is designed to mount on the reformed femur neck with anatomical appearance. Computer image for the femur neck resurfacing prosthesis body is designed and rendered in Pro/Engineer(CAD) and entered into ANSYS(CAE) Workbench for the simulation analysis to be implemented, while analysis data are consequently obtained(fig. 3-2).

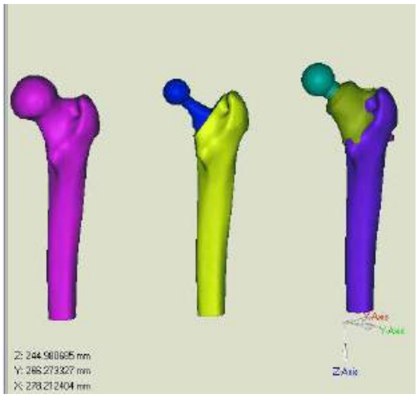

Fig. 3-2: Image file of femur analysis.

3.3 Material Properties

In this study, the material property for both the compact bone and spongy bone of the femur is set up as homogenous isotropic and linear elastic. The material for the femoral component in existing artificial hip joint never the less is mainly Co-Cr-Mo alloy. The material for the Durom implant from Zimmer is cobalt-chrome-molybdenum alloy. Following Radcliffe(2008), Youngõs Modulus is set at 200GPa and Possonõs Ratio is accordingly set at 0.3 [10]. The femur is postulated as being composed of homogenous, linear elastic, and isotropic material, however the material for the femoral component in existing artificial hip joint never the less is mainly Co-Cr-Mo alloy. The setting for Youngõs Modulus, Possonõs Ratio and Strength is demonstrated in Table 3-1. Due to the pressure on natural femur, compressive strength is opted for, whereas yield strength is adopted for Co-Cr-Mo alloy in contact with the bone, because if the stress on the material exceeds the yield strength, it would lose its functionality.

	Young's Modulus	Posson's Ratio	Strength
Hip joint bone	16.7GPa	0.3	157MPa
Co-Cr-Mo alloy	200GPa	0.3	630MPa

Tab. 3-1: Material properties.

3.4 Boundary Condition

The process of mesh generation includes five major steps: (1) solid surface conversion, (2) curved segmentation, (3) surface meshing, (4) crack detection, (5) solid model meshing. This study sets the edge size on the medial and Lateral side of the curve at 5e-3m for the use of next stage analysis (Fig. 3-3), while the meshing for the other regions is automatically generated to speed up the analysis.

When stationary, the force sustained by the hip joint is approximately the weight of the body, and it increases by 3 times (4 times) when walking and 4 times (8 times) when running. This study uses stationary condition as the boundary condition for the simulation, configuring the stress of the body weight as 1200N which is concentrated on the center of the femoral head, while the distal end of the femur is configured as fixed support, and all components in close contact (fig. 3-4). Cut distance refers to the length between the position and the bottom of the femur which is set as the reference plane. In this study, stress analysis is implemented at an interval of 15mm within the range between 15mm and 150mm (fig. 3-5). Load the image file into Pro/Engineer software(CAD), and draw a dividing line from the inner to the outer side of the natural femur. Draw a vertical line from the dividing line to the bottom base, and project it to both the inner and the outer surfaces of the femur (fig. 3-6).

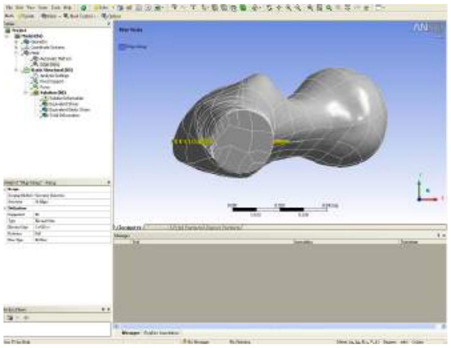

Fig. 3-3: Mesh setting.

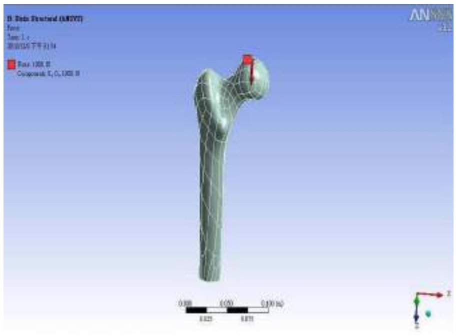

Fig. 3-4: Force setting.

Fig. 3-5: The bottom of the femur as the reference plane.

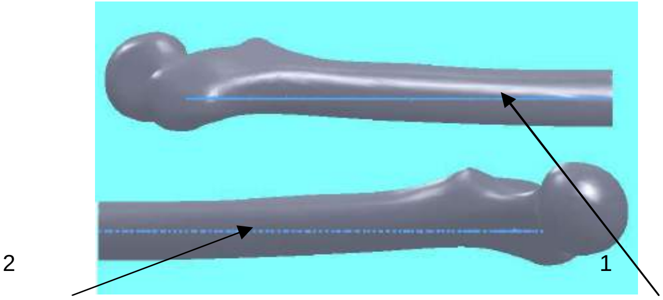

Fig. 3-6: Dividing line on the femoral body of natural hip joint.

3.5 Simulation Analysis by ANSYS Workbench

3.5.1 Simulation Analysis of Natural Hip Joint

Upon completion of the previous step, the file is loaded into ANSYS Workbench to implement the simulation analysis, and the analytic results are accordingly acquired (fFig. 3-7) 、(fig. 3-8)、 (fig. 3-9)、 (fig. 3-10).

Fig. 3-7: Image data of natural hip joint.

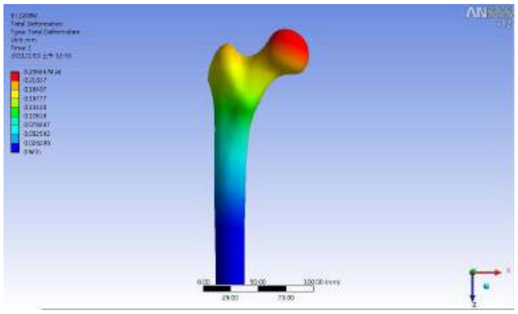

Fig. 3-8: Displacement analysis of natural hip joint.

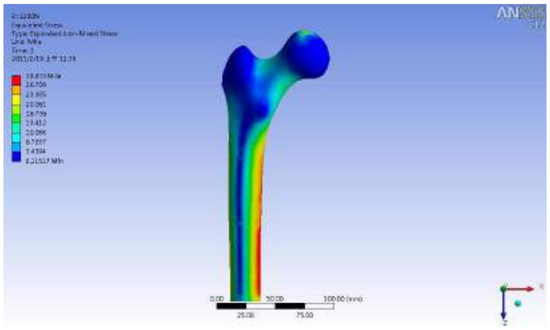

Fig. 3-9: Stress analysis of hip joint.

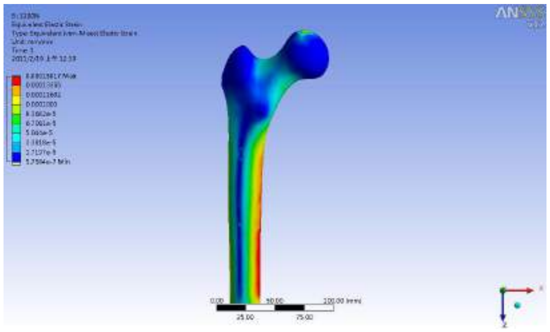

Fig. 3-10: Strain distribution analysis of hip joint.

3.5.2 Simulation Analysis of Stemmed Hip Joint

Upon completion of the previous step, the file is loaded into ANSYS Workbench to implement the simulation analysis, and the analytic results are accordingly acquired (fig. 3-11) 、(fig. 3-12)、 (fig. 3-13)、 (fig. 3-14).

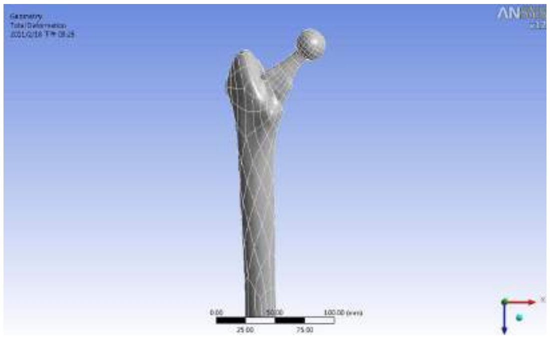

Fig. 3-11: Image data of stemmed hip joint system.

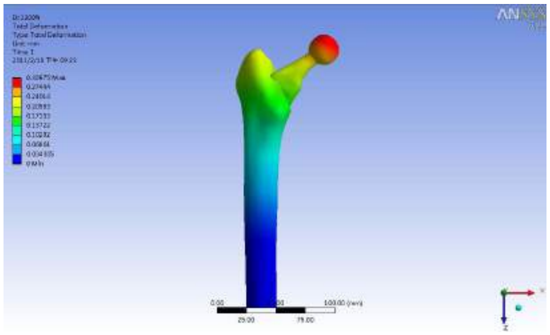

Fig. 3-12: Displacement analysis of stemmed hip joint.

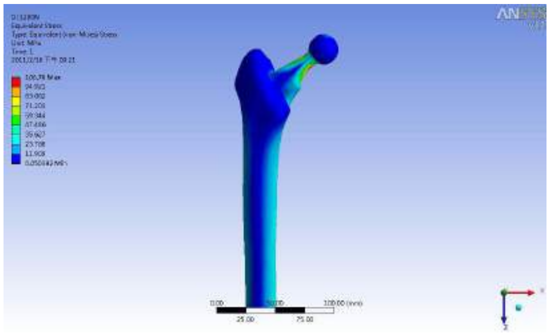

Fig. 3-13: Stress analysis of stemmed hip joint.

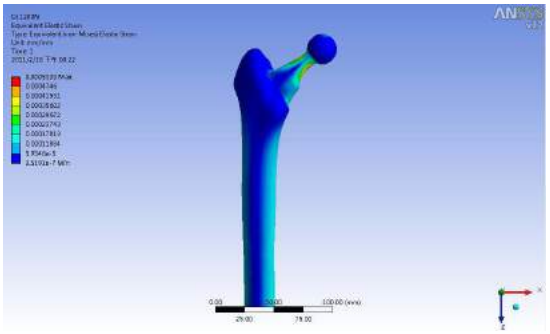

Fig. 3-14: Strain distribution analysis of stemmed hip joint.

3.5.3 Simulation Analysis of Resurfacing Hip Joint

Upon completion of the previous step, the file is loaded into ANSYS Workbench to implement the simulation analysis, and the analytic results are accordingly acquired (fig. 3-15) 、(fig. 3-16)、 (fig. 3-17)、 (fig. 3-18).

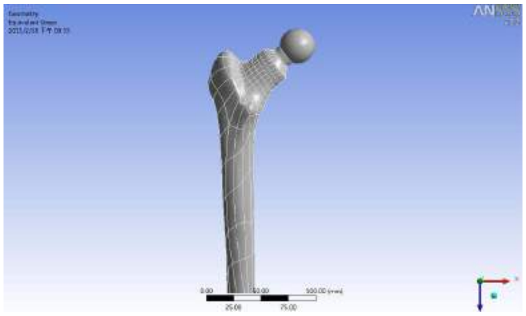

Fig. 3-15: Image data of resurfacing hip joint.

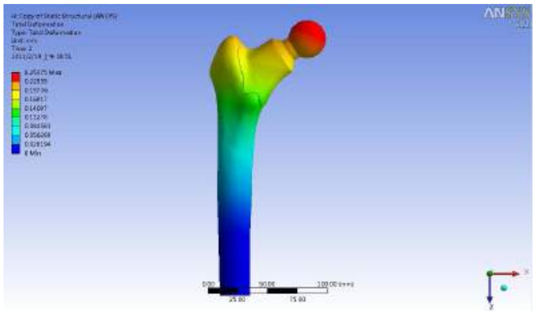

Fig. 3-16: Displacement analysis of resurfacing hip joint.

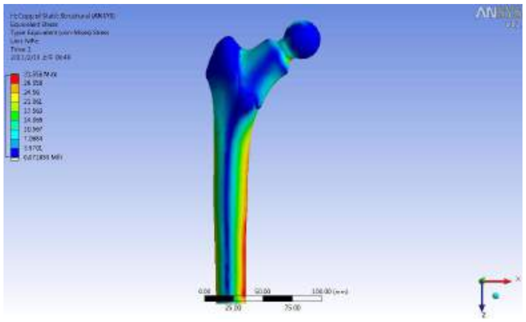

Fig. 3-17: Stress analysis of resurfacing hip joint.

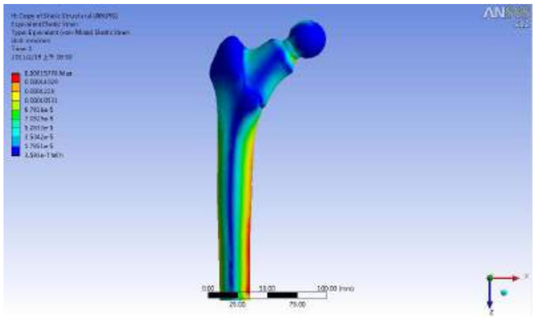

Fig. 3-18: Strain distribution analysis of resurfacing hip joint.

4 DATA STATISITICS

4-1 Analytic data are listed in the following Table 4-1, Table 4-2, and Table 4-3.Analytic data are listed in the following tables. Distance refers to the length between the position and the bottom of the femur therewith the stress analysis is implemented. This study sets the interval at 15mm within the range between 15mm and 150mm.

Distance (mm)	150	135	120	105	90	75	60	45	30	15
1 Medial Femoral Stress (MPa)	16.41	23.59	25.9	27.02	26.87	28.12	28.2	29.32	29.67	29.94
2 Lateral Femoral Stress (MPa)	12.46	17.11	20.32	20.7	21.04	21.63	22.14	22.77	21.72	21.28

Tab. 4-1: Stress data <1200N> of natural hip joint (T1).

Distance (mm)	150	135	120	105	90	75	60	45	30	15
1 Medial Femoral Stress (MPa)	19.21	25.65	27.93	28.48	28.93	29.61	29.76	31.59	32.59	31.62
2 Lateral Femoral Stress (MPa)	14.94	20	23.02	23.04	23.82	24.6	25.79	27.17	26.51	27.56

Tab. 4-2: Stress data <1200N> of stemmed hip joint (T2).

Distance (mm)	150	135	120	105	90	75	60	45	30	15

1 Medial Femoral Stress (MPa)	18.69	23.8	26.13	27.83	28.17	28.85	29.53	30.74	30.81	31.08
2 Lateral Femoral Stress (MPa)	14.01	17.41	19.97	20.91	21.34	22.68	23.71	24.53	24.84	25.67

Tab. 4-3: Stress data <1200N> of resurfacing hip joint (T3).

Statistics Charts

Upon completion of the previous step, the file is loaded into ANSYS Workbench to implement the simulation analysis, and the analytic results are accordingly acquired (fig. 4-1) 、(fig. 4-2)

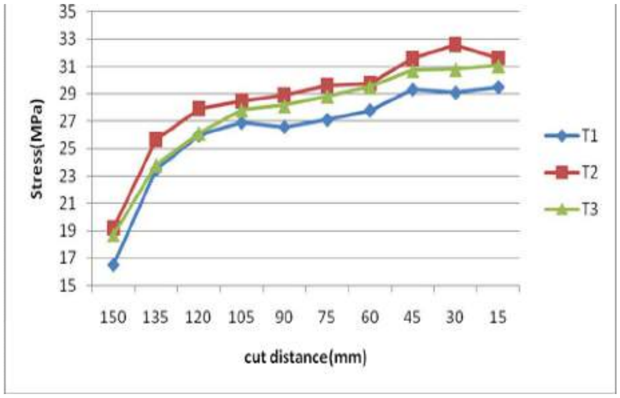

Fig. 4-1: Data statistics of medial femoral stress.

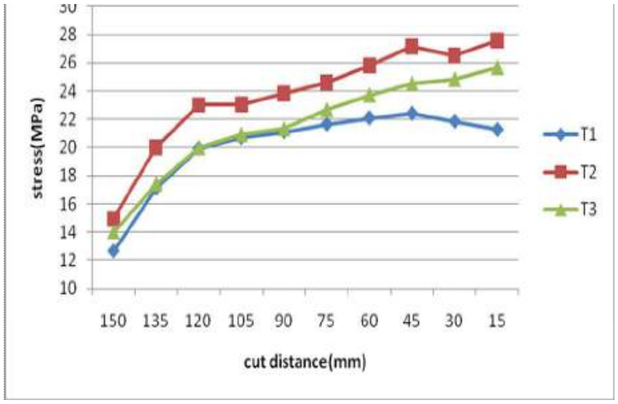

Fig. 4-2: Data statistics of lateral femoral stress.

5 CONCLUSION

The purpose of this study is determining which design of artificial hip joint system has stress distribution on the femoral neck that is closer to that on the femoral neck of a healthy hip joint, as well as providing data statistics for the designers. The definition of femoral neck axial line is proposed by this study and the 3D models of different femoral implants are rendered for finite element analysis to compare the stress distribution of each artificial hip joint system with reference to that of natural hip joint.

In this study, the simulated femur neck resurfacing hip anthroplasty preserves the stress distribution pattern much closer to the original femur especially in the inter-trochantor section. And the loading stress on the femur stem is obviously to be distributed homogeneously. It hence will avoid the osteolysis from stress shielding effect and improve the blood circulation in the proximal femur section. Further, the patient will also have the opportunity for another stemmed hip joint replacement surgery if and when revision surgery becomes necessary. As a result, femur neck resurfacing hip joint replacement surgery can benefit younger patients more than stemmed hip joint replacement surgery can. This study never the less has only conducted finite element simulation and analysis and lacks data of clinical trials and approval of empirical experiments. In order to increase the reliability of this study, it is suggested that clinical trial could be implemented so that a comparison with the findings of this study can be made.

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