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MODELLING AND ANALYSIS OF A FEMORAL NECK PROSTHESIS

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ABSTRACT
This paper investigates the stresses around the femoral neck of hip replacements when compared with a repair procedure of hips, which include either a complete hip replacement, or the installation of a Dynamic Hip Screw to hold the hip together. Models were developed and analyzed to determine the high stress regions inside the bone which may cause pain or failure. For the Dynamic Hip Screw (DHS) the highest amount of stress on the bone was found to be near the top screw, and the screw supporting the head/neck of the femur. However, for a total hip replacement, the point of highest stress is located on the prosthetic-bone interface on the opposite side of the bone from the ball of the hip. Caution is required when selecting an appropriate hip repair or replacement for different people.

Keywords: Dynamic Hip Screw, Total Hip replacement, femoral, repair.

1. INTRODUCTION
Elderly people are at the greatest risk of hipbone fracture, which is partly due to Osteoporosis and Osteoarthritis[1]. The lifetime risk for a wrist, hip or vertebral fracture has been estimated to be in the order of 30% to 40% in developed countries – in other words, very close to that for coronary heart disease.

Osteoporosis is not only a major cause of fractures, it also ranks high among diseases that cause people to become bedridden with serious complications. Because of the morbid consequences of osteoporosis, the prevention of this disease and its associated fractures is considered essential to the maintenance of health, quality of life, and independence in the elderly population[1-3].

Osteoarthritis is a degenerative joint disease where the cartilage and lubricant between joints is decreased[2]. Severe cases of Osteoarthritis require joint replacement, as cartilage cannot be regenerated with current technology. According to Medicare Australia, over 16,000 hip repair procedures were conducted in 2007 in Australia[4]. This number includes both screw type repairs as well as total hip replacements. Of this number, roughly 1,300 (8%) were revision surgeries to repair or replace an existing implant. Current methods of repair involve either a complete hip replacement, or the installation of a Dynamic Hip Screw. In elderly patients however, several complications may arise such as osteoporosis and other bone weakening conditions associated with age.

This research expanded upon previous research to examine the bone surrounding hip replacements[5]. The aim of the current investigation was to study the stress in bone matter surrounding artificial implants so that future patients can avoid repeat operations. It is important to study these stresses because they can be caused by of non uniform material in femur, weakened bone conditions from osteoporosis, and the resulting thinning of bone sections in some locations within the hip associated with possible high stress regions inside the bone, especially in the face of Dynamic Hip Screws.

The scope of this work resulted in a data analysis of failure of hip replacements with a view to targeting an at risk population, and so developing information suitable for simple hip repair utilizing finite element modelling (FEM) techniques[6-8]. A model of the load- bearing structure of the femoral head of the hip with associated reaction forces within the bone itself was analyzed[9, 10].

2. HIP FRACTURE AND JOINT REPAIR
In general, there are three types of fracture; at the femoral head; transcervical neck fracture which occurs in the region of the femoral neck; intertrochanteric fracture, which occurs at the base of the femoral neck; and subtrochanteric fracture which appears as a horizontal fracture below the femoral neck[2].

All three forms of failure require either total hip replacement (THR) or insertion of Dynamic Hip Screws (DHS) which is dependent on the severity of the fracture and the condition of the patient. Total hip replacement involves the removal of the femoral head and surrounding bone[11]. An artificial replacement is then installed in its place.

THRs are often used to treat joint failures due to Osteoarthritis. This type of surgery is generally known to be highly invasive as it involves not only the removal of the femoral head, but also the removal of cancellous bone. A long section is inserted into the cancellous section of bone in order to stabilize it. The cup of the hip is replaced with a plastic or Teflon ball surface for low friction and bonded to the bone using bone cement. However, the DHS (also known as intramedullary hip screw) is a less invasive procedure which involves inserting a screw across the fracture and into the ball of the hip. This sort of repair is designed for intertrochanteric and subtrochanteric fractures[2].

The number of screws can vary according to the procedure from one to three. This method of repair requires less time and complexity compared to the THR and does not require the removal of significant amounts of bone. Its primary function is to allow the bone to heal the fracture instead of replacing the entire hip.

3. HIP POPULATION

In total, there were 13035 hip replacement procedures using a variety of techniques, performed in Australia in the period of January to December 2007, and 2041 Intramedullary screws installed, as shown in Figure 1. The number of total hip replacements is roughly equal for both genders. This number is expected to increase as the median age of the nation increases from 35.7 to 36.6.

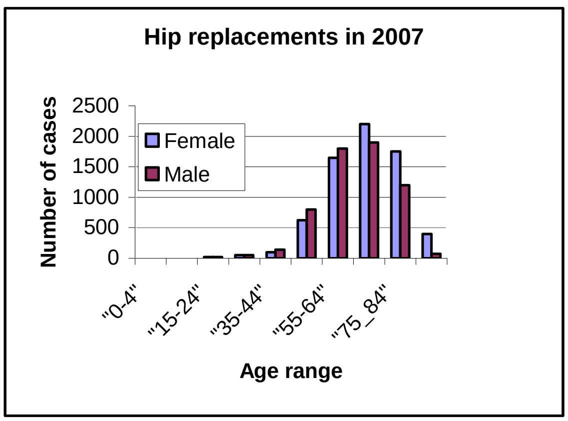

Fig 1. Number of cases versus age range in 2007

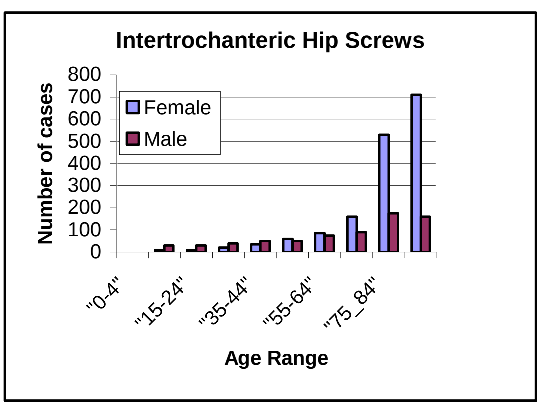

Fig 2. Number of cases versus age for interchrochanteric screws.

When analyzing specific data, as shown in Figure 2, a much larger proportion of females over the age of 65 undergo hip repair, compared to men and have an interochanteric hip screw inserted. The data indicates that a much larger proportion of females over the age of 65 undergo hip repair compared to men. This is in part due to the more profound effects of Osteoporosis This paper focused on female hip replacements for the over 75 year old persons.

4. PRELIMINARY MODEL

Anatomical and anthropological studies to-date have failed to establish a standard model for bone dimensions at the head of the femur. It is commonly accepted that bone dimensions are affected by diet, lifestyle, and heredity of a particular region of the world, were employed in this study, and are given in Table 1.

Table 1: Dimension of femoral head

Parameter of Femur	Dimension (mm)
Maximum length	422.5
Proximal breadth	90.2
Head vertical diameter	44.3
Head transverse diameter	44.5
Neck vertical diameter	30.6
Neck transverse diameter	25.9
Midshaft circumference	87.7
Midshaft antero-posterior diameter	26.9
Midshaft transverse diameter	26.6
Distal breadth	77.1
Collo-diaphyseal angle	119.6°

Although the data is mainly sourced from Anatolian individuals, the challenges of age, sex, and ethnicity should not affect the overall model. A further complication encountered while trying to model the femur is that the cross section of the femur itself also varies along its length. The cross-sectional geometry of the human femur is shown in Figure 3[10, 12]. The cortical wall thickness varied between 4.0mm to 7.6mm and was dependent on its position a along the femur.

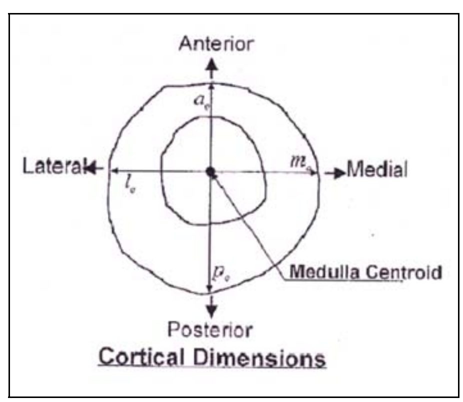

Fig 3. Geometry of the shaft of a real femur

The materials used in orthopaedic implants are typically stainless steels or Titanium alloys (used in the model). Two approaches were considered in modeling: a complete bone analysis without a screw and a model with a screw and the results were compared. Total hip replacements and Dynamic Hip Screws. The femoral head and part of the femur were modelled in Solidworks as two separate parts. These two parts were mated together with the Dynamic Hip Screw. This is the most realistic approach, as it simulates how a hip repair will be made during an actual surgery. The analysis will take the entire structure of the bone and implant into account. For the screw bone model because of complexities in the modeling and analysis process, only the proposed repair was modelled. Force restraints simulate the bone adhesion to the implant surface[7, 8, 13]. The resulting stresses on the implant can be safely assumed to have equal and opposite reaction forces from the bone. Again, in our case the analysis only considered the implant and not the surrounding bone.

The finite element(FE) solid model was constructed in Solidworks©, and was made up of three components: the hard Cortical bone shell; the soft Trabecular bone core; and the. Prosthetic device[6, 9]. The FE model of the human femur is shown on Figures 4a and 4b.

Fig. 4a. FE side view model of human femur.

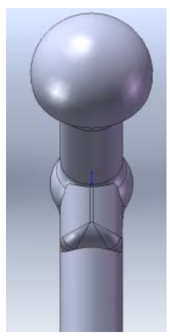

Fig. 4b. FE head on view of human femur.

The FE SOLID model of the dynamic hip screw and total hip replacement are shown on Figures 5a and 5b

Fig. 5a. FE side view model of commercial total hip. replacement

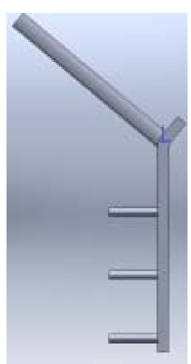

Fig. 5b. FE model of the Dynamic Hip Screw.

Fig. 6a. FE mesh of commercial hip replacement

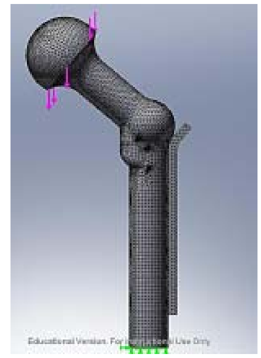

Fig. 6b. FE mesh of a complete bone and hip screw

5. RESULTS AND ANALYSIS

The highest stress for the complete bone study of the total hip replacement was found deep in the root of the bone. It was noted that there was a high fluctuation of stress in this region.

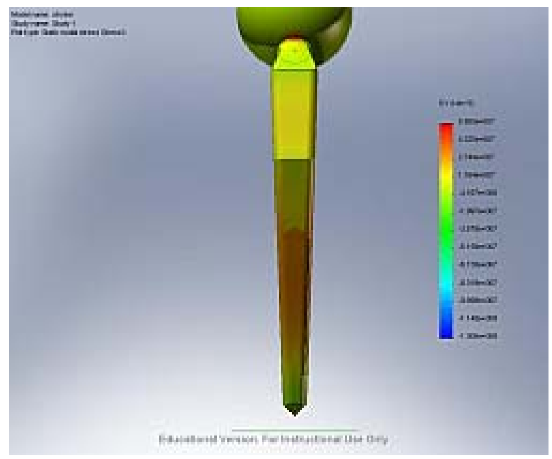

Fig 7. Location of highest stresses

This might be due to minor imperfections in the model where the prosthesis was in contact with the bone. The average stress on the face carrying most of the load was 8.5 MPa and the maximum stress was 33 MPa. However, the accuracy of this value is suspect due to the high amount of fluctuations. The highest stress for the reaction force study of the hip replacement was found at the sharp edge. This force is due to the boundary condition at that location and is pressing against the top surface of the bone. The average stress down the middle of the high stress area was 10 MPa. The highest stress was found to be 52 MPa

For the DHS, detail of stress on the top screw shows a high stress region at the root and at the tip of the screw. as shown in Figure 9. This area corresponds to the cortical bone part of the femur. The average stress recorded was 150 MPa while the maximum stress was 1 GPa (disregarding the outlying value of 3.5 Pa).

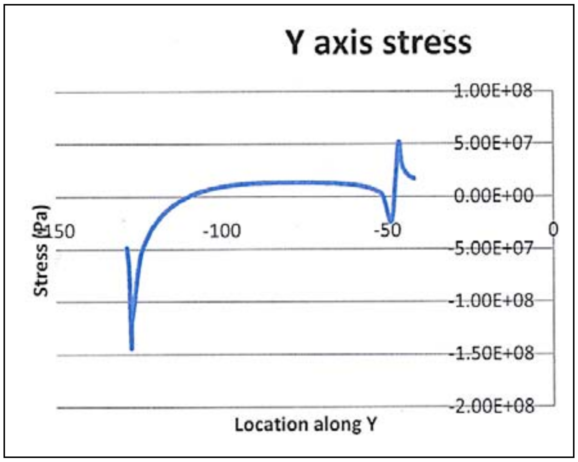

Fig. 8. Reaction force of the hip replacement

Detail of stress on the top screw shows a high stress region at the root and at the tip of the screw. This area corresponds to the cortical bone part of the femur. The average stress recorded was 150 MPa while the maximum stress was 1 GPa. When the stresses were plotted, it was found that each subsequent screw had progressively lower stress at the tips, as shown in Figure 9.

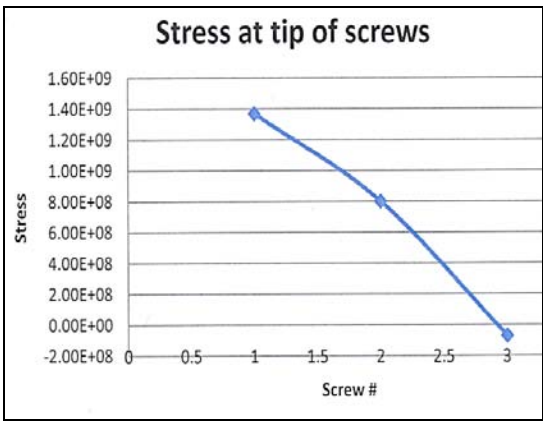

Fig 9. Stress at DHS Screw Tips

The stress for the reaction force case produced a more symmetrical stress distribution around the top screw. In this case, there was no sign of any stresses in the tip. The average stress was 63 MPa while the highest stress is 480 MPa. Unlike the complete bone model, there were some low stresses near the root of the subsequent screws.

For the case with no prosthesis, the highest stress is located on the outside of the femur away from the body. The average stress is 33 MPa as shown in Figure 10.

6. DISCUSSION

The average stress in the total hip replacement models showed a 1.5 MPa (15%) difference. This difference is largely due to sudden drops in stress on the surface of the Complete Bone study. Without these drops, the average stress would have been closer to that of the reaction force study.

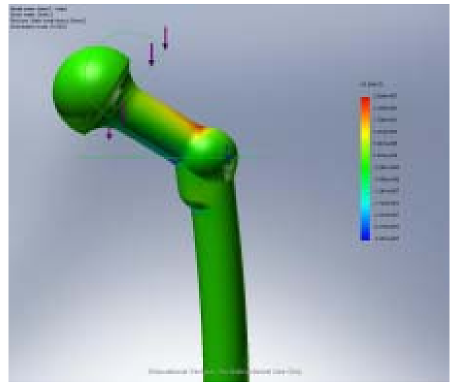

Fig 10. Stress distribution on the bone without a prosthetic.

In the case of the Dynamic Hip Screw, the difference in stress is much more dramatic with an error of 50%. This difference is probably due to the difference in mating conditions. The Complete Bone model had a mate through the cortical and Trabecular bone, which had different properties. For the Reaction Force case, all the screws were assumed to be fixed, treating the bone as a single, homogeneous material. The author feels that this also accounts for the lack of screw tip stress. A summary of the overall stress modeling results is given in Table 2.

Table 2 Modelling of Stress at various Locations

Model	Highest Stress Location	Average Stress (MPa)
Complete Bone –Total Hip replacement	Base of prosthetic embedded in the bone	8.5
Reaction Force –Total Hip replacement	Base of prosthetic embedded in the bone	10
Complete Bone –Dynamic Hip Screw	Root and tip of the first screw	150
Reaction Force –Dynamic Hip Screw	Root of the first screw	63
No Prosthetic	Outside of Femur	333

Hip Replacement surgery is a far more invasive approach compared to hip screws. In the case of the elderly, hip replacements has a longer recovery period and higher short term risk compared to hip screws. However, the long-term risk of failure is higher for a Dynamic Hip screw due to higher stress concentrations.

For hip replacement, the point of highest stress is located on the prosthetic-bone interface on the opposite side of the bone from the ball of the hip. This is consistent in both cases although the actual values are different. The implication of this is that the bone in this region has a higher concentration of stress, and thus a higher chance of failure at this location. This needs to be taken into account when performing a bone repair to minimize stress in the bone, and patients should pay attention to pain in that region as it may be a sign of impending failure.

When analyzing the Dynamic Hip Screw the highest points of stress for the Dynamic Hip Screw on the bone are located around the top screw, and the screw supporting the head/neck of the femur. Subsequent screws bear a comparatively low load. This is consistent in both cases, though the values show a large amount of error, and implies that subsequent screws mainly help to stabilize the head. Therefore, a larger diameter first screw should be considered in order to reduce the amount of stress concentration.

7. CONCLUSIONS AND RECOMMENDATIONS

The complete bone study of the Dynamic Hip Screw indicates that the amount of stress taken up by subsequent screws decreases in a linear fashion. In particular, the highest points of stress for the Dynamic Hip Screw on the bone are located around the top screw, and the screw supporting the head/neck of the femur. The investigation established the maximum stress in bone matter surrounding artificial implants (DHS prosthesis.) so that future patients can avoid repeat operations.

From these conclusions, there are two possible avenues for further study;
(a) the influence of a larger screw in the first position, and (b) how it would affect the stress on subsequent screws; and the influence of the number of screws, and the extent that a larger number would help to even out the load.

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9. NOMENCLATURE

Symbol	Meaning	Unit
DHS	Dynamic Hip Screw	N/A
FEM	Finite Element model	N/A
FE	Finite Element	N/A
THR	Total Hip Replacement	N/A
GPa	Stress	(Pa x 10^{9})
MPa	Stress	(Pa x 10^{6})

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