Analysis of an Improved Hybrid Stem Design for Total Hip Replacement (THR)

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ABSTRACT

This paper proposed an improvement in design and analysis of hybrid prosthesis in total hip replacement. A hip implant is a method for an artificial hip replacement which is made of a material that is different and is selected depending on the study in terms of strength. A hip implant is often focused on the damage to the hip joint. There are various factors which involve damage to the hip such as osteoarthritis, stress shielding, etc. Referring to the various types of total hip replacement products, several factors have been taken to differentiate between each type including the material, design and performance of the product. This project focuses on the stem of total hip replacement. By using computer aid design (CAD) software Solidworks 2013, the stem was redesigned with improvement and underwent the analysis using ANSYS 15.0 to analyses the behaviour which include the total deformation and equivalent (Von-Mises) stress.Higher stress shielding were found at the neck of the hip implant.The three major design types of the hip stems were compared in this study, and the design three (3) hip implant is the most stable among the others after being simulated using different activities.

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Introduction

Several diseases such as osteoarthritis, rheumatoid arthritis, post-traumatic arthritis, avascular necrosis and childhood hip have caused hip pain which leaves the patient to undergo total hip replacement surgery [9]. The lower limbs of the body are specialised for transmission of body weight and locomotive. The lower limb is divided into six parts of regions which are gluteal region, thigh or femoral region, knee region, leg region, ankle or taloctural region and foot region. The hip region overflies the hip joint and greater trochanter of the femur [2]. The head of the femur is spherical, smooth ancovered with articular cartilage [1].

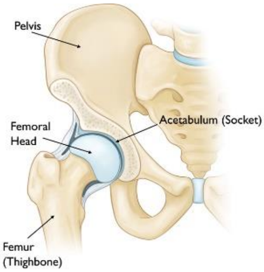

Fig. 1. Hip Anatomy [10]

The region that lies between gluteal, abdominal and perineal regions proximately and the knee region is called femoral region. The femur is the only bone in the thigh. The angle of convergence of the femora is a major factor in determining the femoral-tibial angle. In the general population of people without either genu valgum or genu varum, the femoral-tibial angle is about 175 degrees [2].

Total hip replacement has been termed as "Operation of Century" as it has revolutionised the treatment of a patient with advanced hip disorders. It is the removal of the hip joint part and replaces with artificial ball and socket [4]. Both cemented and uncemented hips can provide durable fixation. Better materials and design have allowed the use of large bearings, which provide an increased range of motion with enhanced stability and very low wear. Minimally invasive surgery limit soft tissue damage and facilitates accelerated discharge and rehabilitation. The surgeon will choose the type of THR design for the patient based on his or her age, body condition, activity level and budget. Artificial hip joint can easily last for 20-25 years. However, the hip implant may not last long for a patient that having more active lifestyle because it may end up with loosening or even failure that eventually requires revision surgery. The loosening or failure may relate to osteolysis or in some cases infection. Osteolysis is a biological reaction to the debris from the bearing surfaces of implant as they rub against each other during daily life activities. Infection of the prosthesis occurs in only a very small portion of patients [5-7], but this dreaded complication results in major immobility due to pain, immobility, failure and loss of prosthesis, reoperation, and in some cases loss of limb or life [8]. The osteolysis problems, on the other hand, may not cause loss of life but are still a major concern. It is notable that failure of prosthesis stems is a secondary event that follows stem loosening. Other factors that can promote stem loosening include bone resorption, degradation of bone cement, and unfavourable positioning of the prosthesis.

The total hip replacement comes in three types which are cemented, uncemented and hybrid. For cemented implant, a layer of cement is introduced between the stem and bone. This type of implant is usually used for elderly patients because the bone is less active to grow around the stem. So cement was used as an alternative solution to the problem. However, this type of implant have disadvantages where it will have loosening effect for long term use.

Uncemented implant or direct penetration use porous coating on the stem was introduced 20 years after that to avoid some drawback of cemented which are the possibility of loosening part and breaking off cemented particles. The bone will grow into the coating layer to create grip between the stem and bone or in another word it is called as osseointegration which has better outcomes for long-term fixation. Moreover, hybrid prosthesis act as uncemented but with more durability added to the features. This type of prosthesis consists of a cemented femoral component and an uncemented acetabular component.

Titanium was initially brought into surgeries in the 1950s in the wake of having been utilised as a part of dentistry for 10 years former. Titanium is viewed as the most biocompatible metal because of its imperviousness to corrosion from natural liquids, bio-idleness, limit for osseointegration, and high fatigue limit. These qualities are improved to make a perfect cell react. Titanium's capacity to withstand the real ruthless environment is a byproduct of the defensive oxide film that constructs naturally in the vicinity of oxygen. The oxide film is unequivocally followed, insoluble, and unnaturally impermeable, counteracting responses between the metal and the surrounding environment.

Mechanical scraped area of the titanium oxide film prompts an expanded rate of corrosion [11]. Titanium and its alloys are not insusceptible to corrosion when in the human body. Titanium alloys are defenceless to hydrogen assimilation which can impel precipitation of hydrides and cause embrittlement, prompting material failure [11]. Hydrogen embrittlement was seen as an in vivo system of corruption under fussing cleft corrosion conditions bringing about TiH arrangement, surface response and splitting inside Ti/Ti measured body tapers [11]. Contemplating and testing titanium conduct in the body permit us to maintain a strategic distance from acts of neglect that would bring about a deadly breakdown in the insert, similar to the utilisation of dental items with high fluoride focus or substances equipped for bringing down the pH of the media around the insert.

Methodology

In the first part of the study, the designing process was started by doing sketching on the stem to obtain the shape and dimension of the hip implant. From 2D drawing, 3D modelling was constructed in Solidworks Premium 2013. Modelling was started by drawing references axis of the stem. Ways of modelling take place using plane by plane sketching and transform into solid model by using lofted boss features. The stem of the prosthesis is designed to be a hybrid design. In this project, several features were combined to improve the characteristic of the stem. The first highlight is the stem has a collar. The collar acts to deliver stress on the bone and cement so that the stem does not penetrate trough the bone and cement. The second feature is the addition of sleeve on the stem. The sleeve or coating is useful for the cement to grip onto the stem. The neck part of the hip implant is improved as it is the main feature. The neck of this hybrid design has thicker in size which it will withstand more force or load exerted. Three designs were made at the beginning where the most efficient design was chosen to be the selected design. Each design were improvement from one another. The stem starts by the guardian line with 135 degrees to form the necking angle.

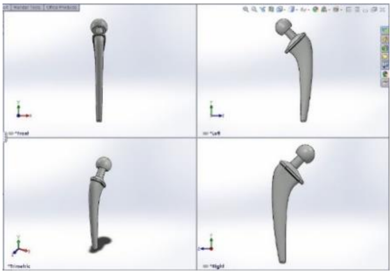

Fig. 2. Design 1 view

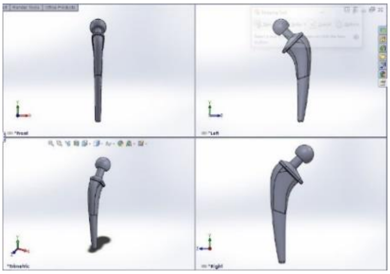

Fig. 3. Design 2 view

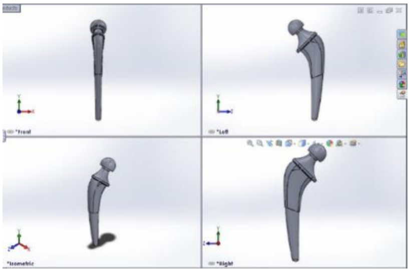

Fig. 4. Design 3 view

The first design of the hip implant is shown in Fig. 2. This design consists of collar feature. With 3 mm wider than the body and thickness of 3 mm, the collar feature lies between the body and the neck. The stem is also wider than the capital stem.

Next, the first design has been improved where the second design comes out with an additional feature at the stem. Fig. 3 shows a sleeve or coating layer existed halfway through the stem. The stem reinforced by adding coating layer on the body. This coating function is to grip the stem with the bone. Instead of normal stem design, with a coating layer, the durability of the total hip replacement can be longer. In this design, the coating covers almost 50% of the body from the centre up to the collar. The thickness of the coating is 1mm.

However, the major problem with this kind of application in total hip replacement is the neck. Therefore, the third design was made to improve on the necking part of the stem. The wider and stronger stem was considered in the third design. The neck is a dominant feature of the hip stem where the stress is distributed the most. In this hybrid design, the neck is improved by increasing the thickness. The radius of the neck is 10.31 mm and 15.01 mm in length as illustrated in Fig. 4. The curved part from the collar to the tip increases the strength at the section.

Table 1. Material properties

Material	Poisson's Ratio, v	Tensile Strength (MPa)	Compressive Strength (MPa)	Shear Strength (MPa)	Young's Modulus (MPa)
Titanium Ti-6A1-4V (Ti41)	0.3	830	830	830	100 000
PMMA (cement)	0.4	21-31	144	30-41	2240
Bone	0.36	167	121	68-84	16200

Table 1 indicates the material properties of the three main component in the hybrid prosthesis. The stem used is made of titanium Ti-6A1-4V (Ti41) while the cement will use PMMA type and lastly the properties for the human bone. A normal femur model was used for the analysis. The femur model was downloaded in the .stp file from the GrabCAD.com website where thousands of models to be shared with others. The femur bone is cut into half from the centre to the top of the femur head. Then the femur head has been chopped off by the angle of the stem collar position. After inserting the stem into the femur bone, the gap between both parts is filled with cement. The material properties are applied to the parts in ANSYS 15.0.

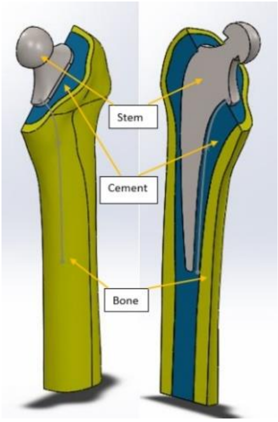

Fig. 5. Cross section of analysis

Fig. 6. Loading and boundary setup condition

Fig. 5 shows the condition of the stem that needs to be setup before running the analysis. The setup for the analysis is by inserting the stem into the bone and reinforce with the cement to get the actual results. The material properties are shown in Table 1.

By referring to Fig. 6, R_{fh} stands for femoral head resultant force where R_{gt} stands for greater trochanter resultant force. Both R_{fh} and R_{gt} are the forces that exerted on the stem and from the bone. In the analysis, the bottom part of the model is fixed. The force is in component F_y and F_z, while no force in F_x component. For example, as noticeable in Table 2, the resultant force at the femoral head from standing position is 1976 N downward and force from greater trochanter is 1240 N upwards.

Table 2: Load exerted on the model

Type of loading	**Femoral head (N)**		**Greater trochanter (N)**	
	Resultant	Component	Resultant	Component
Single leg stance	1392	Fx = -269.7 Fz = -270 Fy = -1338.1	1056	Fx = 56.8 Fz = 267.38 Fy = 1020.0
Standing	1976	Fx = 0 Fz = 927.6814 Fy = -1744.7	1240	Fx = 0 Fz = 797.4 Fy = 949.890
Walking	2093	Fx = 382.30 Fz = 339.47 Fy = -2029.58	972.89	Fx = 65.66 Fz = -551.62 Fy = 798.7
Stair climbing	2215.8	Fx = 639.548 Fz = 378.97 Fy = -2087.4	1115.3	Fx = 282.24 Fz = -686.98 Fy = 832.02
Abduction	1158	Fx = 0 Fz = -299.71 Fy = -1118.54	351	Fx = 0 Fz = 48.85 Fy = 347.54
Abduction 2	1548	Fx = 0 Fz = 1283.35 Fy = -865.631	468	Fx = 0 Fz = -268.43 Fy = 383.36

RESULTS AND DISCUSSION

The next part of this study was to benchmarking the model by comparing the result of analysis along the outer surface of the intact femur with the previous research [12]; hence, the boundary condition, geometry and loading used in the model were accepted when the result obtained were slightly same. Table 3 presents the results obtained from finite element analysis (FEA) for all three designs of the hip implant which have been compared with the Stryker hip implant result. The results are recorded in two parts, the first part is total displacement which is to observe how much displacement occurs on the stem and the second part is equivalent (Von-Mises) stress where the maximum stress can be detected.

Table 3. Results of total displacement and equivalent (Von-Mises) stresses on design 1, 2, 3 and Stryker (datum).

Model	Total Displacement (mm)	%	Equivalent (Von-Mises) Stress (MPa)	%
Design 1	0.6623	18.6	158.29	25.2
Design 2	0.5365	34.1	137.10	35.2
Design 3	0.4106	49.5	115.38	45.5
Stryker (datum)	0.8136	-	211.60	-

For total displacement, design 3 has the least amount of deformation compared to the other designs with 0.4106 mm of deformation. It is 49.5% reduction from the Stryker hip implant design (datum). For design 1, only 18.6% less from the datum at 0.6623 mm followed by design 2 with 0.5365 mm or 34.1%. Reduction in total deformation essential to avoid long term effect to the users.

From the information of equivalent Von-Mises stress, the point of stress concentration can be discovered and used to determine critical part of the design. From the results, the most critical area for all stems is at the neck area. Among all the three designs, design 3 has the least amount of stress exerted on the stem which is 115.38 MPa or 45.5% reduction from the datum which result in 211.6 MPa. For design 1 and 2, both are marked with 158.29 MPa and 137.1 MPa each with the percentage of 25.2% and 35.2% respectively.

Overall, these results indicate that design 3 is the best design to be chosen as the selected design as the percentage of the results is the most stable among all the designs as it has improvement and more efficient compared to the datum design. Thus, design three (3) will be used for further analysis with details condition to be tested.

Results on selected hybrid design through several conditions

The design three (3) hip stem has undergone a further analysis which involves human activities which included standing, walking, one leg standing, stair climbing, abduction 1 and abduction 2. The complete result is shown in Table 4.

Table 4. Complete comparison data of Stryker (datum) versus the hybrid design

Gait Condition	**Total Deformation, mm**			**Equivalent (Von-Mises) stress, MPa**		
	Datum	Hybrid	%	Datum	Hybrid	%
Standing	0.8136	0.4106	49.5	211.60	115.38	45.5
Single leg	3.7107	2.2521	39.3	258.99	98.34	62.0
Walking	2.5849	1.9155	25.9	274.59	113.86	58.5
Stair climbing	3.8109	3.0894	18.9	406.88	161.42	60.3
Abduction	1.6716	1.2698	24.0	218.39	70.013	67.9
Abduction 2	2.1439	2.0993	2.1	80.199	73.850	7.9

Standing condition was chosen as the main to be highlighted for the further analysis.

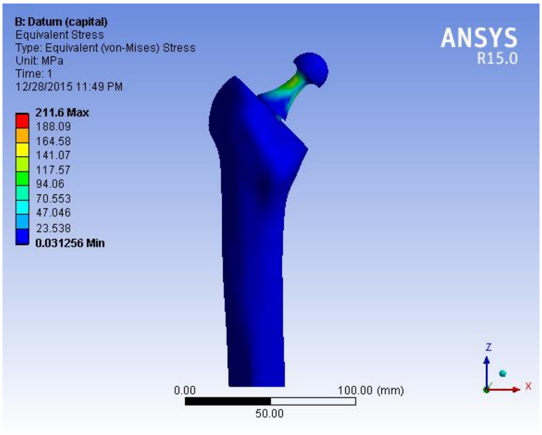

Fig. 7. Stryker (datum) equivalent (Von-Mises) stress

On the Stryker design, it has the most stress focused on the neck at 211.6 MPa as shown in the figure above. With the direction of force and the region of stress, the neck of the stem occurs tension for the datum as the region was on the top of the neck. Hence, it shows this is where the most point of failure may occur.

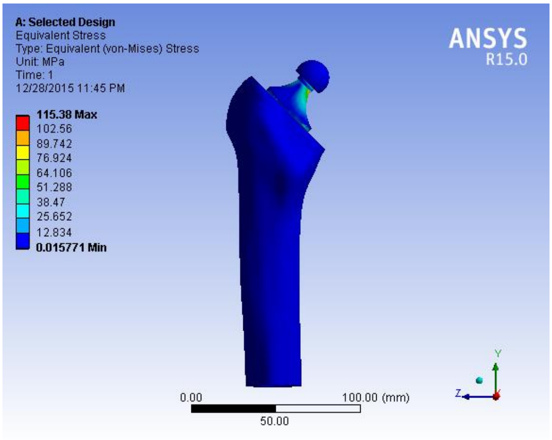

Fig. 7. Design 3 total equivalent (Von-Mises) stress

For the least amount of stress recorded in design 3 with 115.38 MPa. By observing on Fig. 7, the maximum stress also acting on the neck same as the Stryker design stem but this design is gradually better than the Stryker (datum) design. Also, both analysis shows that the stress shielding is more focus on the front part of the neck of the hip implant.

Conclusion

This project was undertaken to design a stem that can withstand the amount of load acting on several positions. Therefore, the stem must be able to provide better results from the chosen datum design. So an analysis on redesigned prosthesis for total hip replacement base on the strength and durability was done. The results of the analysis were compared between other types of the prosthesis of total hip replacement which in this study, the Stryker (datum) design was used. Mostly all the design have a critical point at the neck. To conclude the findings, the final designed stem, increase in strength about 50% from the datum design.

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