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# An Exploration of Alternate Materials for the Design of Hip Implant

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***Abstract*-The commonly used hip implant consists of three parts namely, one piece femoral stem and head, a polyethylene cup and acetabular cup. The polyethylene cup and the acetabular cup were fixed to the pelvis to the bone using PMMA (acrylic) bone cement. The present work involves understanding of stress shielding phases in hip arthroplasty using alternate material in various Hip-Implant designs namely, metal on polyethylene and all polyethylene for best combination for durability. The geometric models of hip implant will be generated from CT-scan using MIMICS software. After receiving hip 3D-model from MIMICS, other significant hip implant parts were generated from 3D modeling software CatiaV5 and also integrated with hip. Then the preliminary calculation for predicting the joint force is done based on free body diagram. A finite element model of hip and all implants will then be developed in HYPERMESH. The loads and boundary condition to be specified in the finite element model are based on the gait cycle loads. An implicit finite element analysis is done in ANSYS 14.5 for static analysis solution. Based on the result obtained, the comparison of various designs is made for best durability.**

***Keywords* — Acetabular shell, Finite element analysis, Stress shielding, Implant components with alternate material combination, Implants mass, Total hip arthroplasty**

## 1. Introduction

The hip is a true ball and socket joint surrounded with powerful and well balanced muscles, which enables a wide range of the motion in several physical planes while also exhibiting remarkable stability. As there are structural link between the lower extremities and the axial skeleton, hip not only transfer forces from the ground up but it's also carry forces from the trunk, head, neck, and upper extremities. Consequently this joint is also crucial to athletic activities in which it is often exposed to many greater than the normal axial and twisting forces. The hip joint is unique (single) physiologically, anatomically, and developmentally, and therefore the diagnosis of the pathologic condition is more difficult than for most joints in the human body. Because of these diagnostic challenges, the hip has received considerably less attention than the other joints in the past-particularly in the reference to sports medicine and the surgery literature. In the clinical setting of a plain x-ray of a pelvis exhibiting non-arthritic joints was the difficult situation; patients were potentially diagnosed erroneously with the 'groin strain 'or otherwise. With the advent of better MRI (magnetic resonance imaging) enhanced by arthrography, we now have a better comprehension of a pathological processes within the hip joint. This Accompanying increased in understanding the evolving potential to treat these problems. For single, hip arthroscopy is undergoing continued development and some excellent results have been reported treating varieties of intra-articular conditions. So now we can assess and treat patients with newer diagnoses, we should also ensure that our knowledge of hip anatomy and biomechanics also evolves in it. Only with this all fundamental understanding can the clinician or engineer can provide adequate treatment for the patient suffering from hip problem (disease or accidental case) or malfunction.


Fig 1.1: Unassembled & Assembled Total Hip
Fig 1.2: Hip & Leg Implant Components

THR (Total hip replacement) surgery is most commonly used nowadays to treat joint failure caused by osteoarthritis or in accidental fracture case. As shown in fig 1.1 & fig 1.2, the most commonly used hip implant consists of three parts named; femoral stem and head made of metal (stainless steel), a plastic hemispherical component made of HDPE/UHMWPE and acetabular component made of steel. The polyethylene cup (ball-top/head-top) and acetabular cup were fixed to the pelvis to the bone using Poly-methyl Meth-acrylate (PMMA) bone cement shown in fig 1.3.

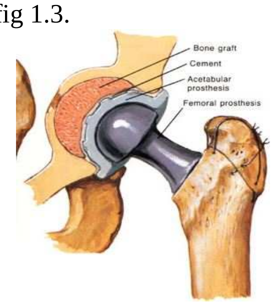


Fig 1.3: Schematic Diagram of Total Hip Replacement with Exploded View Illustrating Porous Nature of PMMA (Acrylic) Bone Cement

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The commonly used hip implant consists of three parts namely as shown in fig 1.1 & fig 1.2, one piece femoral stem and head made of Metals(stainless steel), a plastic cup component made of UHMWPE (Ultra High Molecular Weight Polyethylene) & PEEK (Polyether ether ketone) and acetabular cup component made of HDPE(High Density Polyethylene) or UHMPE. The polyethylene cup and the acetabular cup were fixed to the pelvis to the bone using PMMA (acrylic) bone cement.

## 2. HIP MECHANISM

During walking and running a person momentarily put all of his body weight (newton) on single leg (as right leg shown in fig 2.1). The forces which entirely acting on the leg carrying the total body weight are shown in fig 2.2 during such a single-leg stance. $F_M$ is the amount of the resultant force applied by the hip abductor muscles, $F_J$ is the amount of the joint reaction force applied by the pelvis on the femur head, W1 is the leg weight, W is the total weight of the body applied force as a normal by the ground on the leg (all are shown in fig 2.1) [16]. The angle between the line of action of the resulting muscle force and the horizontal is denoted as $\theta$.

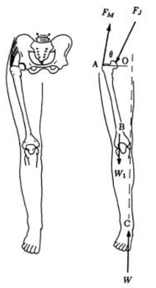

Fig 2.1: Forces acting on the right

Fig 2.2: Single-leg stance leg carrying the entire weight of the body

The mechanical model of the leg with the rectangular component of the forces acting on hip and the important parameters to explain the geometry of the FBD (shown in fig 2.3). O is a point along the instantaneous axis of spinning of the hip joint, A is where the hip abductor muscles are attached to the femur, B is a center of gravity of the leg, and C is where the ground response (reaction) force is applied on the foot. The distance between A and O, B and C are all named by a, b, and c, respectively. α is the angle of inclination of the femoral neck to its horizontal, and β is the angle of the long axis of the femoral shaft makes with horizontal. So, (α + β) is almost equal to the total neck to shaft angle of the femur [16].

Determination for the force exerted by hip abductor muscles and joint reaction force at the hip to support the leg and the hip in the position as shown in fig 2.1 & 2.2

### 2.1 Free Body Diagram (FBD) of the Leg.

For the solutions of the hip problems, we might utilize the free body diagram of the right leg (Note: approximately we can get same for left leg, like mirror image) supporting the entire weight of a person. As shown in fig 2.3a, the muscles and joint reaction forces are shown in terms of their component in the x & y directions. The resultant muscles force has a line of action that makes an angle $\theta$ with the horizontal [16]. Therefore:

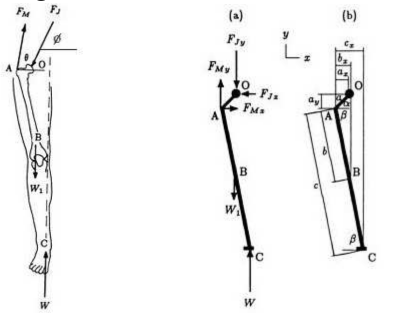

Fig 2.3: (a) free body diagram of right leg& (b) geometric parameters

Muscles force [16]:

$$F_M = \frac{(cW - bW_1)\cos\beta - a(W - W_1)\cos\alpha}{a(\cos\alpha\sin\theta - \sin\alpha\cos\theta)} \qquad (a)$$

Joint force [16]:

$$F_J = \sqrt{(F_{Jx})^2 + (F_{Jy})^2} \qquad (b)$$

Geometric parameters are (where h is height):

$$a = 0.05h, b = 0.20h, c = 0.52h,$$
$$\alpha = 45^\circ, \beta = 80^\circ, \theta = 70^\circ.$$

And also leg weight '$W_1$'with respect to total weight 'W' is

$$W_1 = 0.17W.$$

As shown in fig 2.3, the joint reaction force making an angle

$$\emptyset = \tan^{-1}(F_{Jy}/F_{Jx}) = 74.8^\circ.$$

### 2.2 Gait Cycle

Bipedal walking is a significant characteristic of the human beings. This present data about the different phases of the gait cycle and significant functions of the foot while walking.

Gait speed concludes the involvement of each body parts. Walking at normal speed mainly includes the lower extremities, with trunk and the arms providing steadiness and balance. Faster the speed more of the body depends on the upper extremities and trunk for thrust as well as balance and steadiness. The legs remain to do most of the work as the joints produce bigger ranges of motion trough larger muscle responses. In bipedal system the three major joints of the lower body and pelvis work with each other as muscles and momentum move the body onward. Degree to which the body's center of gravity moves throughout forward translation describes efficiency. The body's center moves equally both side to side and up and down throughout gait.

#### 2.2.1 Sequences for Walking and Phases Gait Cycle

We have some sequences for normal walking that occurs is summarized as follows:

a) Registering and beginning of the gait command within the central nervous system

b) Transmission of gait systems to the exterior (peripheral) nervous system

c) Generation of numerous forces

d) Contraction (Shrinkage) of muscles

e) Regulation of joint forces and moments across skeletal segments and synovial joints

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f) Generation of floor (ground) reaction forces

Sorting of the gait cycle includes two main phases: stance phase and swing phase. The stance phase lives in 60% of the gait cycle however the swing phase lives in only 40% of gait cycle. Gait cycle contains a combination of open- and close-chain actions.

Detailed sorting of the gait cycle (100%) distinguishes six phases shown in fig 2.4 as B:

There is some alternative sorting of gait contains the following eight phases shown in fig 2.4 as A:

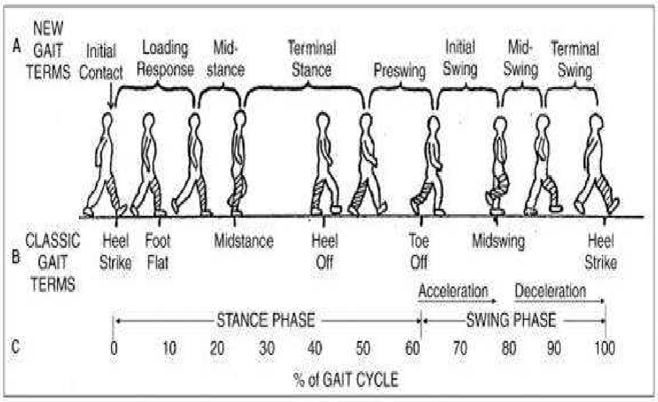


Fig 2.4: Stance Phase and Swing Phase (Single Gait Cycle)

Table 2.1 Analytic estimates of peak hip forces [5]

| Activity | Magnitude/Total weight ‘W’ |
|---|---|
| Walking slowly with/without a cane | 2.2/3.4 |
| chair raising | 3.3 |
| Walking | 4.8–5.5 |
| stair ascending/climbing | 7.2–7.4 |
| stair descending | 7.1 |

## 3. MATERIAL SPECIFICATION FOR HIP IMPLANT

In this present work main component on which we are going to focus is UHMWPE as hemispherical cup component which has moving contact with stem head component. If u focus on the assembly u can notice the component other than hemispherical cup and stem head are just fixed to respective places. As per the function of the hip joint the moving contact zone will have wear and also peak stress will be induced on stem head as it is holding total load of upper body as a reaction force plus moment on leg will generate the wear phenomenon after some cycle of fatigue life.

As per the earlier research were done on hip implant combination based on hemispherical cup and stem head are like MoM (metal on metal), CoC (ceramic on ceramic), MoC (metal on ceramic) and some combination with polymers. Material selections in present work are shown in table 3.1. Wear volumes and particles size for various material combinations (determined by hip simulator testing with one million simulated gait cycles) can be seen in Total Hip Arthroplasty [21].

Table 3.1: Material selection for THA components

| Component | Material class | Most used material |
|---|---|---|
| Femoral Stem | Metal | Stainless Steel, CoCrCo-wrought, Ti-alloy (Ti-6Al-4V), Tantalum |
| Femoral Head | Metal | Stainless Steel, CoCrMo-cast |
| | Polymer | PEEK |
| | Ceramic | Alumina($Al_2O_3$), Zirconia |
| Acetabular Cup Liner (Head Top) | Polymer | UHMWPE &PEEK |
| | Metal | Stainless Steel, CoCrMo-cast, |
| | Ceramic | Alumina(Pure Or Zirconia-Toughened), Zirconia |
| Acetabular Cup Shell (Metallic Backup Cup) | Metal | Stainless Stell, Titanium -Foam, Tantalum-Foam |

### 3.1 Material property

In this present work test are done only on MoP (metal on polymer) as there are very less risk of any biological problem and also it has good hold on life of implant, as polymer gives which light weight combination due to polymer and give longest experience. Also it’s an economic device to be used in THA.

Polymer like UHMWPE and PEEK is used in present work as a combination with SS316L, Co-Cr-Mo, Titanium alloy and Tantalum to obtain the alternate combination with UHMWPE and PEEK. In present work taking total weight of implant and stress shielding on hip is focused to get better combination as per the static analysis. We obtain six better and good combinations for MoP combination.

Also we work in reducing total weight of implant by using alternate material for acetabular shell which is a metal backup which is fixed with hip. Alternate materials for cup were like SS316L, porous titanium (Ti-foam) and porous tantalum (Ta-foam). Then we obtained 18 combination of alternate material for THA. On all 18 combinations analyses were done to understand the stress phase and stress shielding on hip.

Table 3.3: Mechanical properties of biomaterials used in THA in comparison with cortical and cancellous bone of hip as a host

| Material/ Properties | Young’s modulus “E” (Mpa) | Density "ρ" (Kg/m3) | Poisson Ratio "υ" | Yielding stress (Mpa) | |
|---|---|---|---|---|---|
| Cortical bone | 16200 | 1990 | 0.36 | 120 | [6] |
| Cancellous bone | 382 | 500 | 0.3 | 3.89 | [6] |
| Stainless steel | 200000 | 8000 | 0.29 | 182 | [5] |
| Titanium foam | 5200 | 4540 | 0.32 | 82 | [21] |
| Tantalum foam | 1800 | 16654 | 0.33 | 68 | [21] |
| UHMWPE | 550 | 933 | 0.4 | 21 | Test |
| PEEK | 3600 | 1320 | 0.4 | 80 | [21] |
| Ceramic ($Al_2O_3$) | 380000 | 3900 | 0.22 | 350 | [5] |
| Co-Cr-Mo (ASTM F-75) | 220000 | 8200 | 0.3 | 450 | [5] |
| Titanium alloy (Ti-6Al-4V) | 110000 | 4700 | 0.33 | 850 | [5] |
| Tantalum | 186000 | 16690 | 0.35 | 1060 | [21] |

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Also for test on UHMWPE we followed Reliance Technical Data for Relene Ultra 2504 (UHMWPE) and followed the test result as mechanical data for UHMWPE young's modulus as 550MPa, density 0.933 g/cc and Poisson ratio 0.4. Also PEEK mechanical data were used from the test and analysis.

Once a prefect assembly is obtained then material properties is assigned to the entire component respectively. Using alternate component for different component 18 combination was obtained. Each analysis will be done with alternate material assigning to each component.

Like this after analysis of all 18 combinations is done then study of stress shielding on hip and stress distribution will be compared with all combination to get the best and better combination for the hip-implant application.

## 4 FINITE ELEMENT MODEL

Meshing is the procedure of converting a part or a model into small pieces or elements called discretization. HYPERMESH tool is used to achieve fine meshing. This meshed model will be filled with elements and nodes. The field can be meshed by using numerous type of elements, here in the present work only TETRA mesh with tri elements are used, since the TETRA is the best suitable element for the 3D meshing. In present work we have 5 components which all are 3D meshed model. Full hip implant is using only TETRA mesh model for discretization. Using element type for the component is SOLID45.Finite element meshing is carried out for all the components of the hip with implants. Fine meshing is done at all the critical sections where the stresses are expected to be more, probable at the thin layer of hip and corner of all elements, since it creates the discontinuity.

Extracting geometry is the first phase (step) involved in the stress analysis process. In the next sections the details of the finite element mesh created on each part of the hip and implants using HYPERMESH are described. Fig 4.1 shows the global finite elements mesh of hip with implants. Fig 4.2 shows separately meshed model of Hip bone and implant component.

FE model of the hip and implants, meshing is completed by using only TETRA elements. Fine-meshing is at the thin layer of hip and corner of all elements, since all are the stress concentrated location; granular meshing is done at rest of the locations. Precaution has been taken during meshing the node of the adjacent part. Global analysis consist of Tetra type element, no. of elements used 1460011 and Nodes 310960

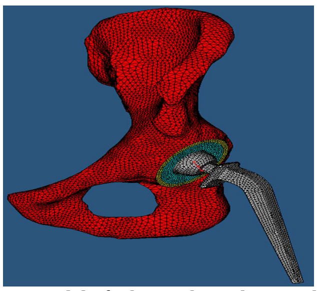

Fig 4.1: Global FEA model of a hip with Implant meshed with Solid 45 element

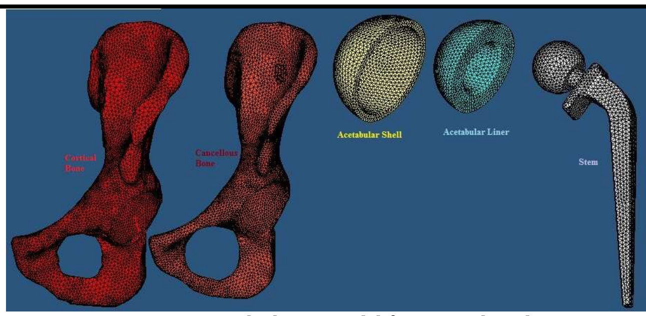


Fig 4.2: Distinguished FEA model for Hip and Implants

### 4.2 Loads and boundary conditions for static analysis

Once after completion of meshing of the wing box, loads & Boundary conditions are defined. As in the practical case wings are subjected to bending load like a cantilever beam i.e. one end is fixed & other side transverse load is applied.

#### 4.2.1 Load Calculation for the Joint Force Acting on the Stem Head [16]

As per the section 2.2 free body diagram and fig 2.3 we can calculate the joint force and the angle of joint force.

Also, we have simplified formula to find hip joint force and muscles force with respect total body weight (W).

$$F_J = 3.4W \quad \text{and} \quad F_M = 2.6W$$

Considering a person with mass (m) = 75 Kg

Total body weight

$$W = 75 \times 9.81 = \mathbf{735.75\ Newton}$$

Using simplified formula to find joint force, we get

$$F_J = 3.4 \times 735.75 = 2501.55 \cong \mathbf{2502\ Newton}$$

$$\therefore F_M = 2.6 \times 735.75 = 1912.95 \cong \mathbf{1913\ Newton}$$

As shown in fig 2.3, the joint reaction force making an angle $\emptyset$, We also know

$$\sum F_x = 0: \qquad F_{Jx} = F_{Mx} = F_M \cos\theta$$

Where, resultant muscles forces angle is $\theta = 70°$

$$F_{Jx} = 1913 \times \cos 70° = 654.267 \cong \mathbf{655\ Newton}$$

Also we have

$$\sum F_y = 0: F_{Jy} = F_{My} + W - W_1$$

$$F_{Jy} = F_M \sin\theta + W - W_1$$

$$F_{Jy} = 1913 \times \sin 70° + 735.75 - 125$$

$$= 2408.335 \cong \mathbf{2409\ Newton}$$

As we know all the resultant forces in x and y direction, now we can find the angle of joint force using above formula.

$$\emptyset = \tan^{-1}(2409/655) = 74.789 \cong \mathbf{74.8°}$$

Therefore, as per the load calculation the load is acting on the joint with an angle of 74.8$^o$ with loadof 2502 N. as shown in fig 4.3.Therefore the UDL acting on the neck of stem head with 33 nodes, so each node is carrying load of,

$$\therefore F_{UDL} = \frac{2502}{33}$$ Therefore, $F_{UDL} = \mathbf{75.81\ N}$

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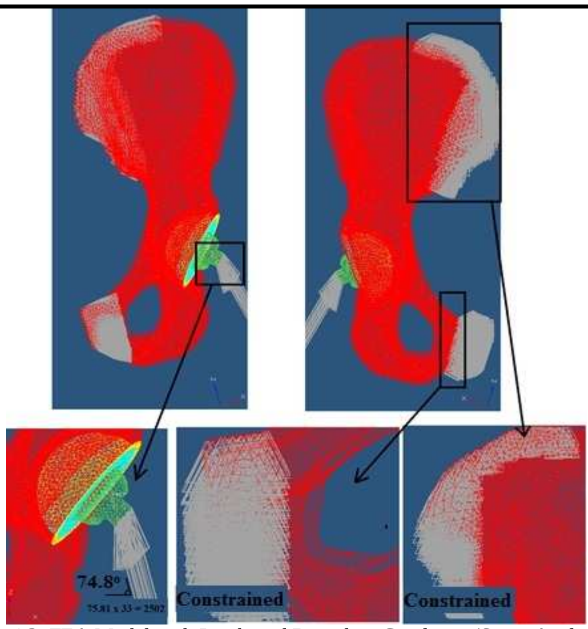


Fig 4.3: FEA Model with Loads and Boundary Condition (Static Analysis)

## 5 RESULTS AND DISCUSSION

### 5.1 Static Results

The understanding of the result for the separate group component is possible at ANSYS software since it is a post processor. The exact stress distribution can be observed after once solution is done. The stress like principal stress, normal stress, coordinate stress and von-mises stress can be seen in post processor of ANSYS software. Also stress can be seen in each component by hiding other components. And fig 5.1 shows the stress distribution in the hip with implants. The stress values are verified for the group of each combination to check the maximum stress concentration part of the implants. The maximum principal stress theory (von Mises stress theory) result mode was selected to review the analysis results.

The stress distribution for the given loads has been observed and that exposes, the stress is distributed uniformly to the stem head and head top (hemispherical cup/Acetabular liner). Also we can see the stress shielding phenomenon on hip which is also necessary for bone to be strong and tough as shown in in fig 5.1.

The main objective of this work is to use alternate material for combination of hip with implants. Main reason for using alternate material is to obtained better implant combination with less mass (gram), also implant should have better stress shielding on hip so that hip does not become weaker. Static analysis was done on all the combination with alternate material. Alternate combination was made by changing acetabular shell to achieve better stress shielding, changing of stem with head to achieve low mass combination with best life span (durability).

Whereas acetabular liner is kept constant for first three combinations as UHMWPE, other three combinations were using PEEK. As in this present work we are just focusing on metal on polyethylene (MoP), wear rate is to be control by using alternate material with less deformation wear. Also if wear is obtain it will be of polyethylene which does not have any biological reaction inside the human body.

In this present work totally 18 combinations were made for hip-implant, on which the analysis was done to find the better and good combination which have all the good and suitable result which fulfill the objective of this present work. After all the analysis we are having all combination masses in table 5.1 and all peak stress for the differenent materials and stress shielding value which is shown in table 5.1 and also in fig 5.7.

One thing was common in all the combination that maximum stress induced only on stem head and neck and also it was ranging 75MPa to 79MPa. Therefore as per the durability point of view all the combination were good and also can be used for THR.

When we observe all 18 combination in terms of mass (weight) then one can notice that where there is tantalum metal used in implant has high mass then other combination as shown in table 5.1. Therefore when there is a need of less mass implant, implant with tantalum will be rejected. Also one can notice that implant combination with Ti- alloy and Ti-foam has significantly very less mass which is very good so that it can be used for more life span also due to less weight it can be preferred first for THR. Otherall combination has average mass of 250-300 grams.

Finally we also know stress shielding on hip is also very necessary so that hip can't go weak due to less or no stress shielding occurring because of some tough and elastic material implant. But in present work we had focused on stress shielding to so as one can observe the stress distribution on hip with alternate combination as shown in table 5.1. One can notice that implant with Ti-foam and Ta-foam has very good stress shielding effect on hip stress value ranges from 21Mpa to 26MPa and it's a very needful for hip bone. Therefore in stress shielding cases 2nd& 3rd combination are best suited. Other all combination has average stress shielding with average stress value ranging 15Mpa to 18MPa.

The maximum deflection or displacement is carried on stem with head as it is moving joint. In present work the maximum deflection 1.536 mm is observed at the lower end of stem which is just due to moving contact part. As stem head is moving in result to gait cycle for normal walk. This deflection indicated just displacement for moving stem head.

Analysis is carried out by using joint force with joint force with joint force angle acting on hip joint. Static analyses were done for all the combination and above following results were found.

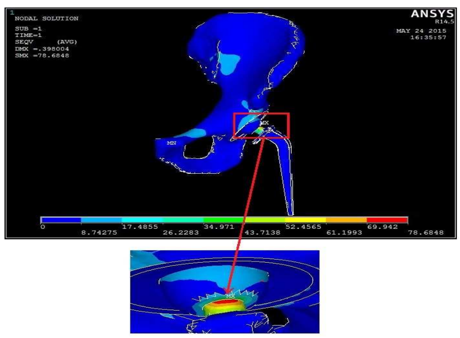


Fig 5.1: Stress contour on the hip with implants with critical stress location

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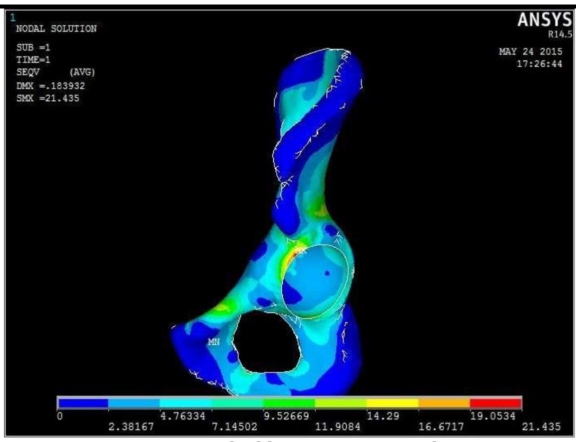

Fig 5.2: Stress Shielding on Hip Cortical Bone

Once global analysis is done, then maximum stress location and deformation in each component of assembly model is examine. One by one single component are seen from the global analysis and check out stress distribution on each parts of implants and stress shielding on hip. All components are separately shown from fig 5.2 to 5.6.

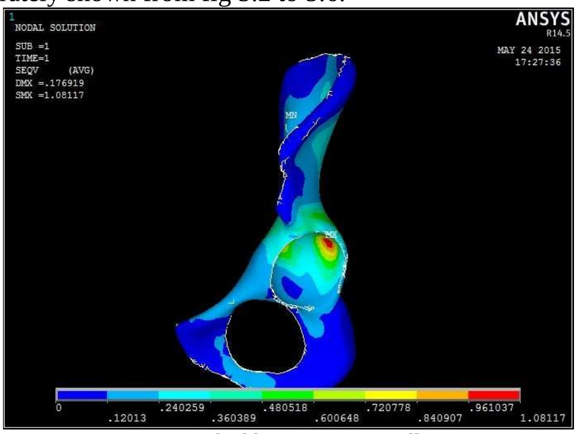

Fig 5.3: Stress Shielding on Hip Cancellous Bone

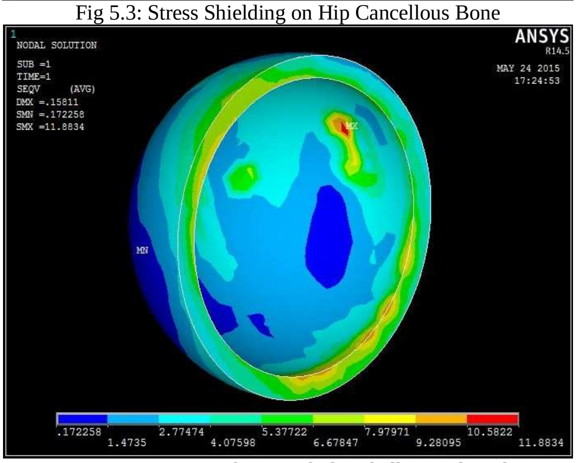

Fig 5.4: Stress Contour on the Acetabular Shell (Metal Backup cup)

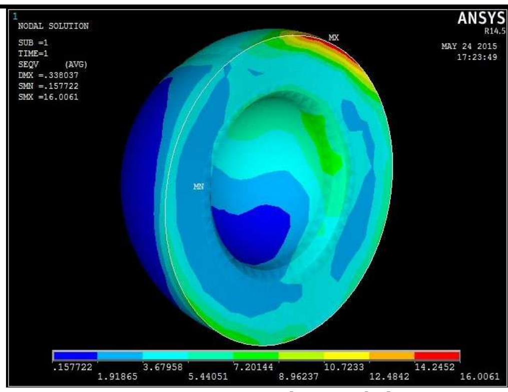

Fig 5.5: Stress Contour on the Acetabular Liner (Hemispherical Cup)

This work has exploded much material and many combinations with good results in any one objective and average in other, some combination gave best result in the entire objective which shows it was a great approach toward the biomechanical part which together has a very vital role in the future.

Fig 5.6: Stress Contour on the Stem with Head (Femoral component)

### 5.2 Stress Shielding

Stress shielding is one of the important aspects to be studied for better understanding of bone needs. As we know bone is solid element in human body which actsas connecting bones to bone with much different type of joints like hip joint, knew joint, shoulder joint, elbow and many more. Stress shielding is a phenomenon which means how much stress is applied to the bone so that bone accept it in good form which helps bone to become strong and strong. If there are no stresses acting on the bone, the bone will become weak and it will lead to many bone problem and become reason for many type of pain. Fig 5.7 shows the stress shielding value in all 18 combination which helps to decide which combination will give better stress shielding so that bone does not become weaker.

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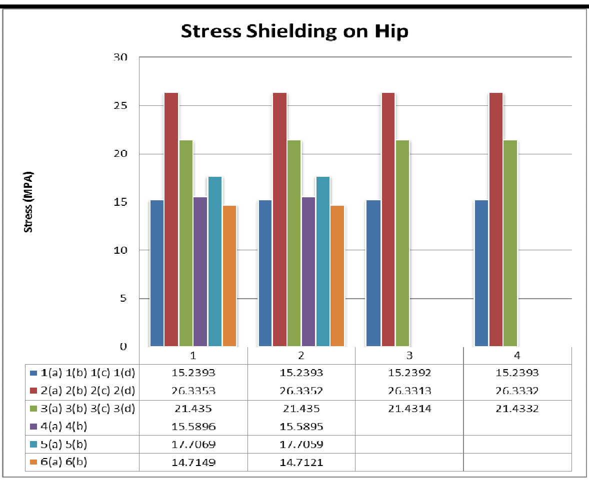


| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1(a) 1(b) 1(c) 1(d) | 15.2393 | 15.2393 | 15.2392 | 15.2393 |
| 2(a) 2(b) 2(c) 2(d) | 26.3353 | 26.3352 | 26.3313 | 26.3332 |
| 3(a) 3(b) 3(c) 3(d) | 21.435 | 21.435 | 21.4314 | 21.4332 |
| 4(a) 4(b) | 15.5896 | 15.5895 | | |
| 5(a) 5(b) | 17.7069 | 17.7059 | | |
| 6(a) 6(b) | 14.7149 | 14.7121 | | |

Fig 5.7: stress shielding stress acting on hip in alternate material combination

## 6. RESULTS & CONCLUSION

For this present work model created by modeling software and then the stress analysis for hip-implant was carried out by doing static analysis. The result from FEA was the only support for the development of an integrated procedure based on analytical methods.

Present work was done on many important objectives like stress shielding on hip, reducing implant mass and mainly using UHMWPE and PEEK as the combination with metals for metal on polyethylene (MoP) combination. And we got 18 good combination models. From which some are best in stress shielding on hip, some are very light weight and some are with low stress compare to other combination. but we have only few model which are best in all the objective such as 3rd combination which is having good stress shielding as well as less stress and also very less implant weight compare to all combination, after that combination 2nd combination is very good in stress shielding but comparatively high weight, and 1st, 4th, 5th& 6th combination is average.

If we arrange combination in stress shielding case combination will be in shown as,

$$2^{nd} > 3^{rd} > 5^{th} > 4^{th} > 1^{st} > 6^{th}$$

Same as, if we arrange combination in implant mass case combination will be shown as

$$3^{rd} < 6^{th} < 1^{st} < 4^{th} < 2^{nd} < 5th$$

These present works illustrate how stress analysis and alternate material design combination can be used for the hip implant application. This work has exploded much material and many combinations with good results in any one objective and average in other, some combination gave best result in the entire objective which shows it was a great approach toward the biomechanical part which together has a very vital role in the future.

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Table 5.1: Static Analysis Results Showing Peak Stresses, Deformation (DMX) and Total Implant Mass

| Combination No | Components Materials Used | | | Peak Stresses Induced (Mpa) | | | | | DMX | Implant grams |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Hip Bone | | Hip Implants | | | | |
| | Metal Backup (Cup) | Hemispherical Cup (Ball Top) | Stem with Head | Cortical | Cancellous | Cup | Ball Top | Stem | mm | |
| 1st combination | | | | | | | | | | |
| 1(a) | SS316L | UHMWPE | SS316L | 15.2393 | 0.684 | 47.1559 | 13.519 | 78.7152 | 0.370475 | 0.29246 |
| 1(b) | SS316L | UHMWPE | CoCrMo | 15.2393 | 0.68404 | 47.1559 | 13.5184 | 78.2813 | 0.370052 | 0.29636 |
| 1(c) | SS316L | UHMWPE | Ti alloy | 15.2392 | 0.684045 | 47.1519 | 13.5295 | 76.8699 | 0.374296 | 0.22664 |
| 1(d) | SS316L | UHMWPE | Tantalum | 15.2393 | 0.684044 | 47.1538 | 13.522 | 75.8108 | 0.370822 | 0.46566 |
| 2nd combination | | | | | | | | | | |
| 2(a) | Ta-foam | UHMWPE | SS316L | 26.3353 | 1.27898 | 10.4285 | 17.0213 | 78.6763 | 0.41476 | 0.41356 |
| 2(b) | Ta-foam | UHMWPE | CoCrMo | 26.3352 | 1.27894 | 10.428 | 17.0209 | 78.2426 | 0.414334 | 0.41746 |
| 2(c) | Ta-foam | UHMWPE | Ti alloy | 26.3313 | 1.27937 | 10.4343 | 17.0293 | 76.8322 | 0.418598 | 0.34774 |
| 2(d) | Ta-foam | UHMWPE | Tantalum | 26.3332 | 1.27903 | 10.4296 | 17.0239 | 75.7735 | 0.415102 | 0.58676 |
| 3rd combination | | | | | | | | | | |
| 3(a) | Ti-foam | UHMWPE | SS316L | 21.435 | 1.08117 | 11.8834 | 16.0061 | 78.6848 | 0.59086 | 0.24401 |
| 3(b) | Ti-foam | UHMWPE | CoCrMo | 21.435 | 1.08114 | 11.8828 | 16.0057 | 78.251 | 0.397579 | 0.24791 |
| 3(c) | Ti-foam | UHMWPE | Ti alloy | 21.4314 | 1.08137 | 11.8906 | 16.0149 | 76.8405 | 0.401835 | 0.17819 |
| 3(d) | Ti-foam | UHMWPE | Tantalum | 21.4332 | 1.08119 | 11.1725 | 16.0089 | 75.7817 | 0.398347 | 0.41721 |
| 4th combination | | | | | | | | | | |
| 4(a) | SS316L | PEEK | SS316L | 15.5896 | 0.687029 | 40.4085 | 16.6793 | 78.6916 | 0.174764 | 0.30116 |
| 4(b) | SS316L | PEEK | CoCrMo | 15.5895 | 0.68703 | 40.4061 | 16.6772 | 78.2581 | 0.174764 | 0.30506 |
| 5th combination | | | | | | | | | | |
| 5(a) | Ta-foam | PEEK | SS316L | 17.7069 | 1.07844 | 9.8905 | 27.1517 | 78.7227 | 0.199987 | 0.42226 |
| 5(b) | Ta-foam | PEEK | CoCrMo | 17.7059 | 1.07835 | 9.89117 | 27.1522 | 78.2899 | 0.199623 | 0.42616 |
| 6th combination | | | | | | | | | | |
| 6(a) | Ti-foam | PEEK | SS316L | 14.7149 | 0.953737 | 10.714 | 25.1057 | 78.7106 | 0.188588 | 0.25271 |
| 6(b) | Ti-foam | PEEK | CoCrMo | 14.7121 | 0.953644 | 10.7125 | 25.1058 | 78.2777 | 0.18823 | 0.25661 |

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