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Improving of artificial hip joint design by studying multiple angles of articulation between femoral head and acetabular liner

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Abstract
Artificial Hip Joints is a complicated field as it is related to material wear rate, biocoMPatibility and stability. While these factors might seem enough, but more factors are affecting implant performance such as hip joint design. This theoretical work is performed by ANSYS 18.2 software to simulate a force of 3000 N load applied on a design for a different angle of movement (α) and angle between femoral head and acetabulum (β), α is taken as (-10°, 0° and +30°) and β is taken (35°, 45°, 55°, 65° and 75°). The results of Von-Mises stress, total deformation, pressure, gap and penetration was taken from simulation results for femoral head of Alumina and Cobalt-Chrome alloy with HDPE liner to represent the case of Metal on Plastic (MoP) and Ceramic on Plastic (CoP), the results of both cases for α and β angles is drawn and then coMPared to choose best β value. The selection of design is utilized by evaluating results and then rating it in a selection matrix, it was found that β at 65° shows highest rating.

Keywords: HDPE; Polyethylene; Alumina; Cobalt-Chrome alloy; Total hip arthroplasty; Ansys.

1. Introduction
Artificial Hip Joints consist of four parts (Stem, Femoral Head, Acetabular Liner and Acetabular Cup) shown in Figure 1. It is used to replace the joint due to disease, aging or accident. The origins of this operation are back to 1891 where ivory was used to replace femoral head [1], which is one part of the hip. The number of patients going through this operation is growing bigger, where old people suffer from joint disease or deformation which cause acute pain and uncomfortable life when doing activities. Another group is young people as some jobs requires hard activities that is performed incorrectly or accidents due to development of fast cars.
Since the beginning of this operations, researches were focused on materials, wear mechanism, biocompatibility, hip design, manufacturing methods and fixation techniques. The femoral head generally is taken between (26-32) mm, although some designs goes up to 60 mm, the femoral head can be metal or ceramic. Acetabular cup is made of plastic, metal or ceramic which is covered by metallic backing that is made of stainless steel usually. Stem is made of metals only. The acetabular cup plastic option is widely used, it was first introduced in 1962 by Sir John Charnley when he proposed polyethylene cup against stainless steel head, stainless steel is nowadays replaced by a better alloy of CoCr or CoCrMo. While polyethylene was developed into Ultra-High Molecular Weight Polyethylene (UHMWPE), High-Density

Polyethylene (HDPE), PEEK (Polyether ether ketone). Each type has its own characteristics, but UHMWPE is the most used option for plastic. Generally, MoP is the most used coupling as it showed very good results and statistics claimed that some patients had them for over 40 years [1], while ceramic is not a new options but during 90s when products were developed from pure alumina which had reports of sudden fracture due to low ductility was improved by adding zirconia to increase ductility and strontium oxide to increase fracture toughness.

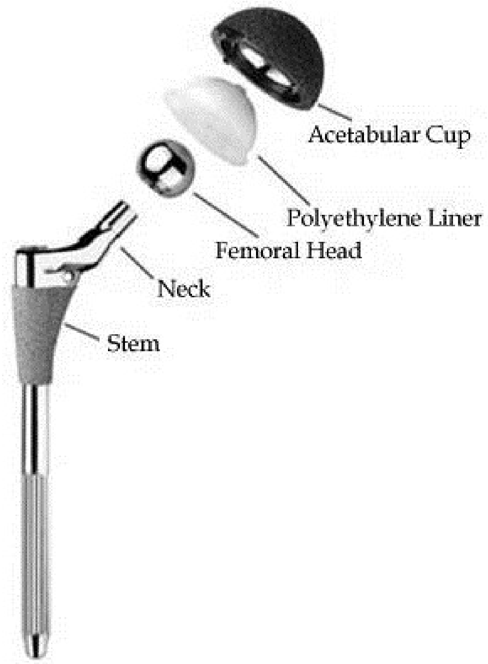

Figure 1. Components of an artificial hip joint.

Where, the materials used for hip joint are bio-materials with various properties, dependent on the requirement properties. There, in general the bio-materials can be evaluating from pure materials or composite materials, [2]. Thus, the composite materials using in rage bio-mechanical application, through the human body or through the external part for human, [3-8], as in Prosthetic Socket, [9-14]; Prosthetic Foot, [15-20]; Prosthetic Knee, [21, 22], with various materials used.

Uwe Holzwart, Giulio Cotogno [1], illustrated comprehensive total hip arthroplasty study on medical and mechanical side, characteristics and options of materials were discussed then summarized that femoral stem and acetabular shell can only be metallic, femoral head can be metallic or ceramic and acetabular liner can be a polymer or metallic or ceramic. Another study on behavior of femoral head and liner combination (MoP, MoM, CoP, CoM, and CoC) has shown that in MoP combination some cases had over 40 years of serviceability and it is the most economic with acceptable wear rate, still polyethylene wear and loosening a major issue. CoP showed lower wear rate than MoP but ceramic fracture and polyethylene wear and loosening are still a major issue. K. Saika [23], compared characteristics of materials against properties in order to select a material that offer best possible combination of properties (density, elastic modulus, wear resistance, strength/weight, corrosion, compression and biocompatibility). Materials are (Si_3N_4, Al_2O_3, Peek, UHMWPE, Steel, Ti-6A1-4V and CoCr). These properties and materials were put into a matrix and then evaluated with a rating from 1 to 5 and then performed Decision Matrix which showed that PEEK has the highest score at 32. The selection process is far more complex, although wear rate and mechanical properties are major parameters, but more factors should be taken into considerations like material combination, biocompatibility and hip design. Mainly femoral head articulation on acetabular cup is the main point of study while stem fixation is not considered at this point.

In general, before using the bio-materials with any human part, must be testing it materials with behaviors as, mechanical properties, [24, 25]; dynamic behavior, [26-28]; buckling behavior, [29-31], and other. There, the aim of this study is to effect of β angle of articulation between femoral head and acetabular liner on Von-Mises stress, total deformation, pressure, gap and penetration. Then the results are evaluated in a selection matrix to choose best β.

2. Finite element analysis

The finite element tool using to evaluating the mechanical behavior for structure under different load, static, [32]; dynamic, [33]; or impact load, [34]; thermal effect, [35] and other effect. Where, the results evaluated are accept approximate results comparison with other results were evaluated by other techniques, [36, 37].

For hip design shown in Figure 2, the main design has β angle of 45° between femoral head and acetabular cup with head radius of 19mm. β was studied for five angles (35°, 45°, 55°, 65° and 75°) each of three angles of motion (α) which is taken as (-10°, 0° and +30°), refer to Figure 3 [38].

The parameters taken from static simulation with 3000N forces are (Von-Mises stress, deformation, maximum pressure, gap and penetration), then these parameters are graphed for each value and then a selection matrix is utilized to decide the best β that compromise best results from previously mentioned parameters.

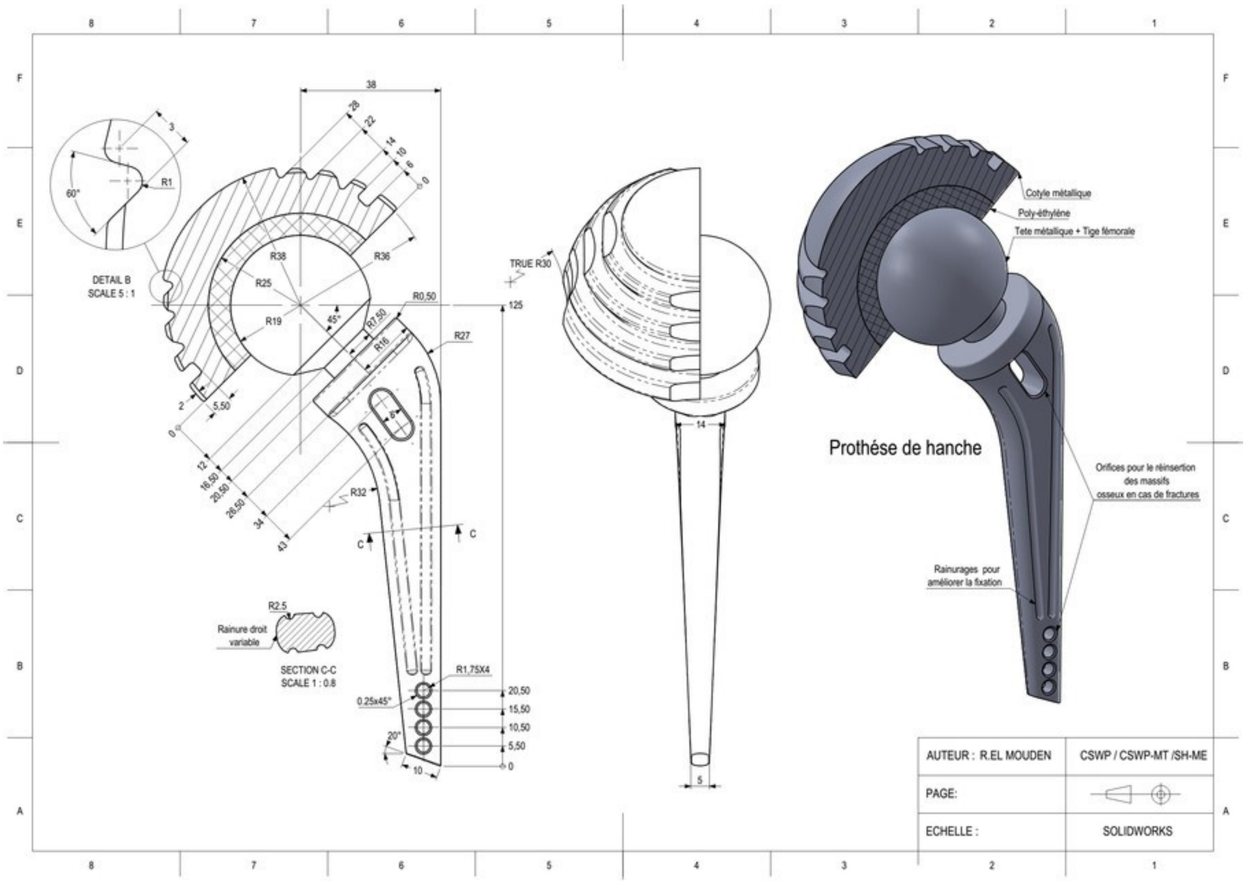

Figure 2. Proposed artificial hip joint design.

The design was drawn using SOLIDWORKS software for each α angle and then imported by ANSYS 18.2 software in order to simulate the motion and apply load. The simulation process can be summarized as follows: Load design through ANSYS software, define engineering data which is mentioned in Table 1, define connection between head and cup as frictionless and revolute solid to solid, define mesh size at 0.001m, set cup boundary condition to fixed as it is fixed in human body, apply force and set required parameters then start solution.

Von-Mises stress, deformation, maximum pressure, gap and penetration were investigated, the importance of stress and deformation is clear for any design while gap is related to implant loosening, pressure is related to the comfortableness of the patients and penetration affect implant wear as its ages.

The investigation started by gathering finite element results for each femoral head material (alumina or Chrome-Cobalt alloy), then the results are separated for each parameter, a graph is used to compare the behavior of parameter for each β and α angles.

After analysis, a selection matrix is utilized to choose the best results as used by K. Saika [23] but with other parameters as he focused on density, elasticity modulus, wear resistance, strength/weight, corrosion, compression and biocompatibility.
HDPE is the option used for acetabular liner and it was defined as fixed in boundary conditions since it is fixed in acetabular cup, it was simulated against alumina head and then cobalt-chrome alloy head, in order to find best angle of articulation between femoral head and acetabular liner for multiple angles of movement (α) in case of MoP and CoP coupling.

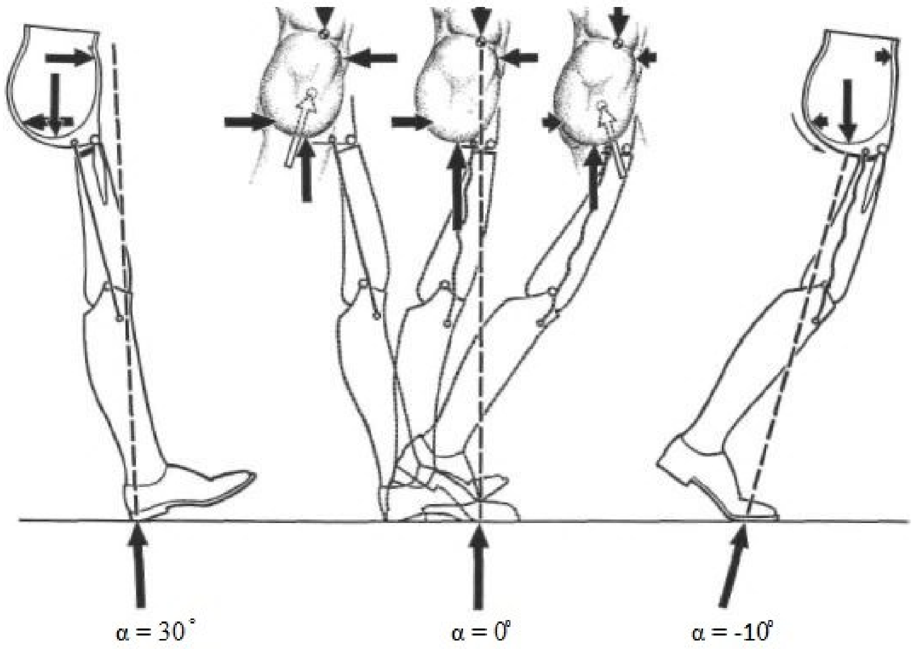

Figure 3. α angle for different hip movement.

Table 1. Material Properties (SolidWorks).

Material/Property	HDPE	Alumina (Al_2O_3)	Cobalt-Chrome (CoCr)
Elastic Modulus (MPa)	1070	370,000	210,000
Poison's Ratio	0.41	0.22	0.29

3. Results and discussion
The results are obtained for each β angle and then graphed for (Von-Mises stress, deformation, maximum pressure, gap and penetration). Table 2 shows results for alumina head and Table 3 shows results for Cobalt-Chrome head. The results obtained from ANSYS software are shown from Figure 4 to Figure 29. The results were further investigated later for each case to evaluate the results and then utilize a selection matrix. The matrix will summarize the best parameters obtained for a specific β, it is based on results obtained from numerical Analysis and was evaluated as follows: NA (Not Acceptable) =0, PA (Partially Acceptable) =0.5, FA (Fully Acceptable) =1.
Note that the results of von-mises stress, deformation for HDPE liner with both femoral heads are identical. Pressure, Gap, Penetration results are identical for both couplings which shows that theses parameters are dependent on force and β angle of design only.
Tables (2 and 3) summarize the results obtained from ANSYS software, then the results are graphed (Figure 30-38).

Table 2. Results for multiple angles of alumina femoral head.

β=35°	Von-Mises Stress (MPa)		Total Deformation (mm)		Maximum Pressure (MPa)	Max Gap (mm)	Max Penetration (mm)
α	HDPE	Al_2O_3	HDPE	Al_2O_3			
-10°	15.246	254.78	0.043381	0.30852	58.413	-0.03943	0.043786
0°	12.009	168.76	0.033945	0.26163	43.746	-0.03436	0.037816
+30°	7.3156	120.88	0.022045	0.14949	25.581	-0.01990	0.021209
β=45°	**Von-Mises Stress (MPa)**		**Total Deformation (mm)**		**Maximum Pressure (MPa)**	**Max Gap (mm)**	**Max Penetration (mm)**
α	HDPE	Al_2O_3	HDPE	Al_2O_3			
-10°	11.301	124.29	0.031045	0.26879	47.136	-0.03640	0.039195
0°	10.921	146.43	0.030504	0.26362	45.561	-0.03583	0.038529
+30°	5.5376	91.376	0.016431	0.11246	19.36	-0.01539	0.016051
β=55°	**Von-Mises Stress (MPa)**		**Total Deformation (mm)**		**Maximum Pressure (MPa)**	**Max Gap (mm)**	**Max Penetration (mm)**
α	HDPE	Al_2O_3	HDPE	Al_2O_3			
-10°	11.15	143.93	0.030446	0.295420	56.943	-0.04052	0.043210
0°	9.6273	128.34	0.026420	0.265260	46.569	-0.03691	0.039111
+30°	3.6495	50.64	0.010469	0.052027	8.3037	-0.00702	0.006885
β=65°	**Von-Mises Stress (MPa)**		**Total Deformation (mm)**		**Maximum Pressure (MPa)**	**Max Gap (mm)**	**Max Penetration (mm)**
α	HDPE	Al_2O_3	HDPE	Al_2O_3			
-10°	9.9222	126.37	0.026587	0.311150	60.081	-0.04358	0.044468
0°	8.1737	102.03	0.021845	0.265640	43.935	-0.03792	0.037986
+30°	1.8829	45.363	0.007020	0.025037	4.0628	-0.00302	0.003367
β=75°	**Von-Mises Stress (MPa)**		**Total Deformation (mm)**		**Maximum Pressure (MPa)**	**Max Gap (mm)**	**Max Penetration (mm)**
α	HDPE	Al_2O_3	HDPE	Al_2O_3			
-10°	8.4758	108.68	0.022062	0.32672	59.400	-0.04676	0.044212
0°	6.6325	81.54	0.017024	0.23901	36.277	-0.03484	0.031926
+30°	2.6805	68.881	0.01156	0.060769	10.056	-0.00711	0.008333

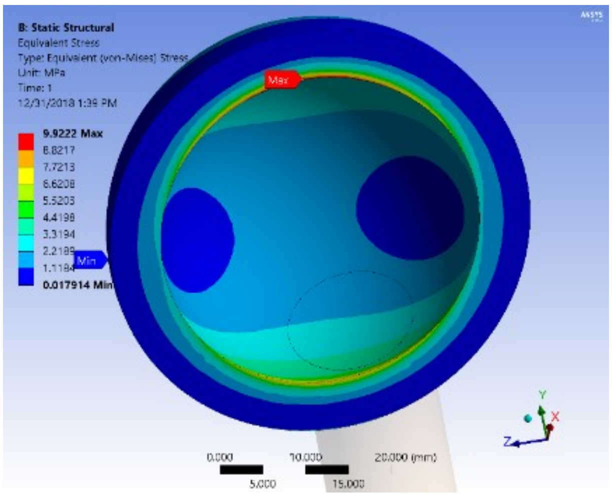

Figure 4. HDPE liner stress at α= -10°.

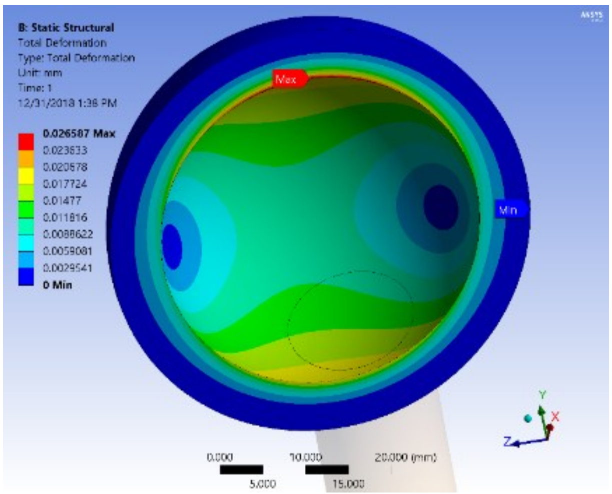

Figure 5. HDPE liner total deformation at α= -10°.

Table 3. Results for multiple angles of cobalt-chrome femoral head.

β=35°	Von-Mises Stress (MPa)		Total Deformation (mm)		Maximum Pressure (MPa)	Max Gap (mm)	Max Penetration (mm)
α	HDPE	CoCr	HDPE	CoCr			
-10°	15.246	249.6	0.043381	0.30946	58.413	-0.03943	0.043786
0°	12.009	165.05	0.033945	0.26231	43.746	-0.03436	0.037816
+30°	7.3156	118.84	0.022045	0.14953	25.581	-0.01990	0.021209
β=45°	**Von-Mises Stress (MPa)**		**Total Deformation (mm)**		**Maximum Pressure (MPa)**	**Max Gap (mm)**	**Max Penetration (mm)**
α	**HDPE**	**CoCr**	**HDPE**	**CoCr**			
-10°	11.301	120.97	0.031045	0.26938	47.136	-0.03640	0.039195
0°	10.921	143.73	0.030504	0.26423	45.561	-0.03583	0.038529
+30°	5.5376	89.871	0.016431	0.11246	19.36	-0.01539	0.016051
β=55°	**Von-Mises Stress (MPa)**		**Total Deformation (mm)**		**Maximum Pressure (MPa)**	**Max Gap (mm)**	**Max Penetration (mm)**
α	**HDPE**	**CoCr**	**HDPE**	**CoCr**			
-10°	11.15	139.99	0.030446	0.296030	56.943	-0.04052	0.043210
0°	9.6273	126.03	0.026420	0.265320	46.569	-0.03691	0.039111
+30°	3.6495	50.016	0.010469	0.052027	8.3037	-0.00702	0.006885
β=65°	**Von-Mises Stress (MPa)**		**Total Deformation (mm)**		**Maximum Pressure (MPa)**	**Max Gap (mm)**	**Max Penetration (mm)**
α	**HDPE**	**CoCr**	**HDPE**	**CoCr**			
-10°	9.9222	124.07	0.026587	0.31115	60.081	-0.04358	0.044468
0°	8.1737	99.771	0.021845	0.26564	43.935	-0.03792	0.037986
+30°	1.8829	44.353	0.00702	0.025037	4.0628	-0.00302	0.003367
β=75°	**Von-Mises Stress (MPa)**		**Total Deformation (mm)**		**Maximum Pressure (MPa)**	**Max Gap (mm)**	**Max Penetration (mm)**
α	**HDPE**	**CoCr**	**HDPE**	**CoCr**			
-10°	8.4758	105.74	0.022062	0.32672	59.400	-0.04676	0.044212
0°	6.6325	80.688	0.017024	0.23901	36.277	-0.03484	0.031926
+30°	2.6805	67.954	0.01156	0.060769	10.056	-0.00711	0.008333

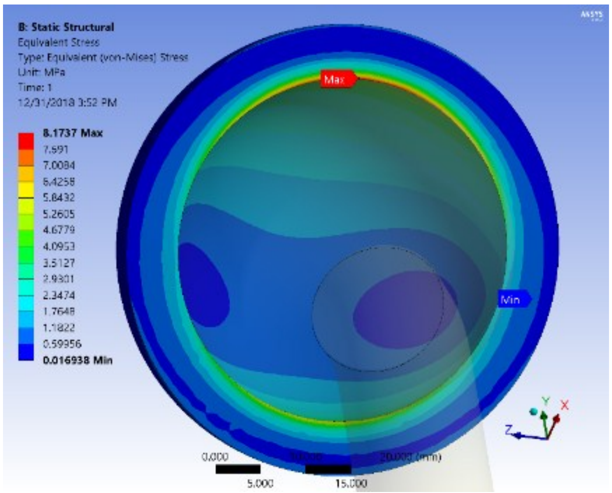

Figure 6. HDPE liner stress at α= 0°.

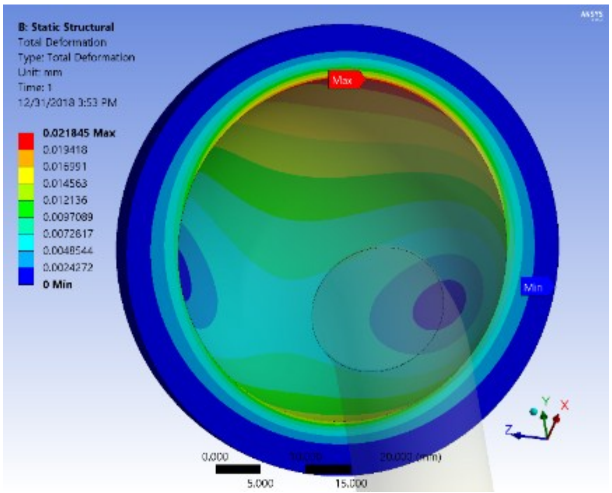

Figure 7. HDPE liner total deformation at α= 0°.

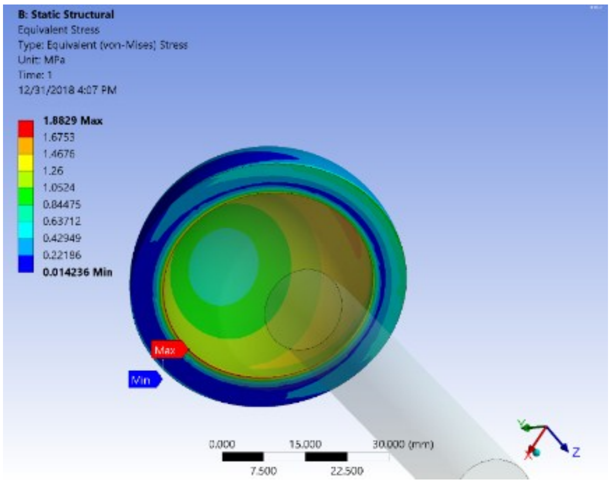

Figure 8. HDPE liner stress at α= +30°.

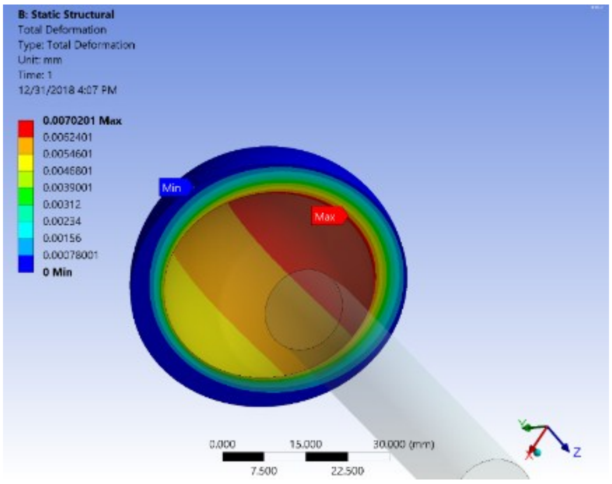

Figure 9. HDPE liner total deformation at α= +30°.

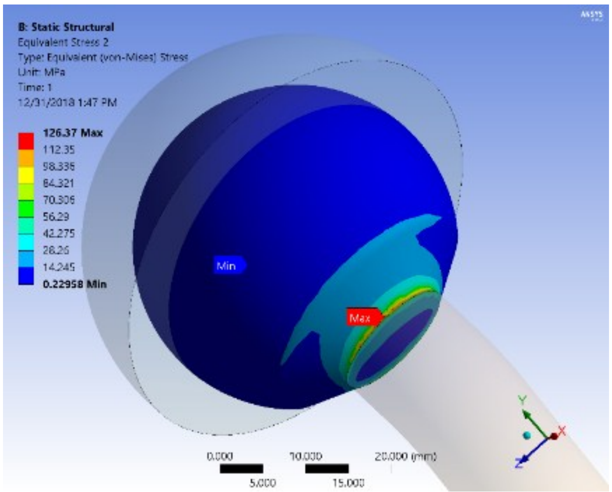

Figure 10. Alumina head Stress at α= -10°.

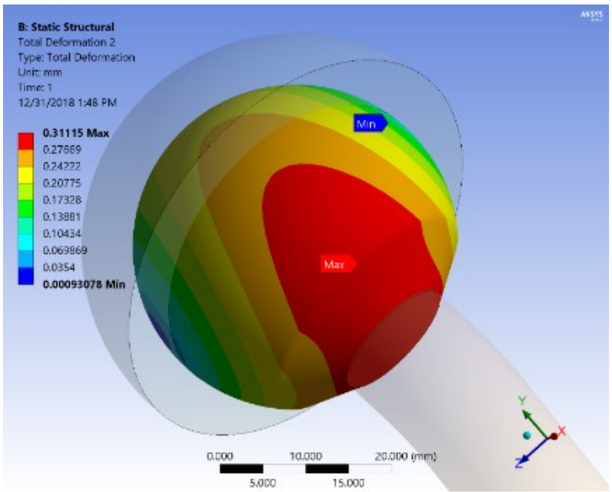

Figure 11. Alumina head total deformation at α= -10°.

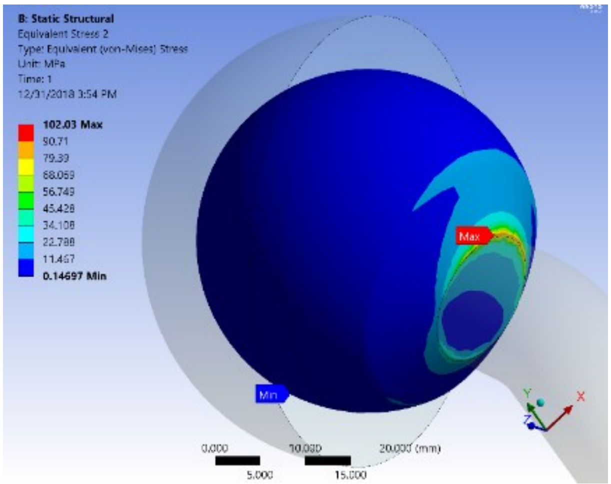

Figure 12. Alumina head stress at α= 0°.

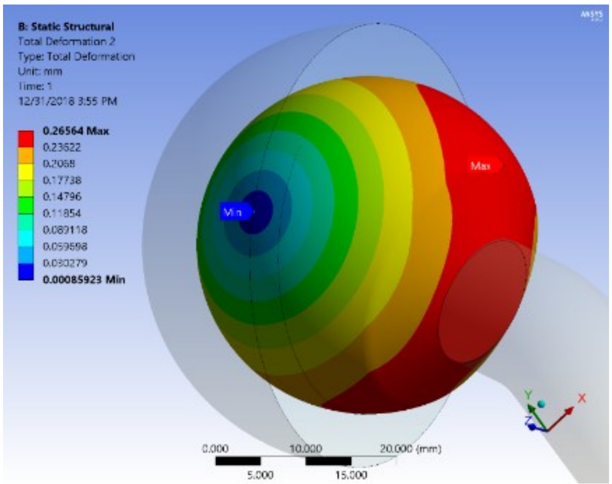

Figure 13. Alumina head total deformation at α= 0°.

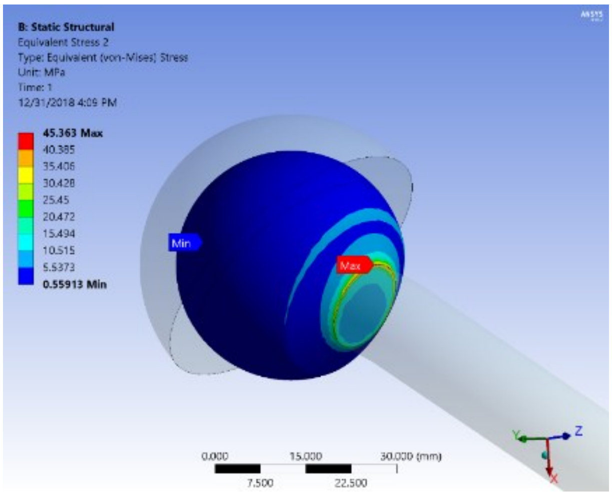

Figure 14. Alumina head stress at α= +30°.

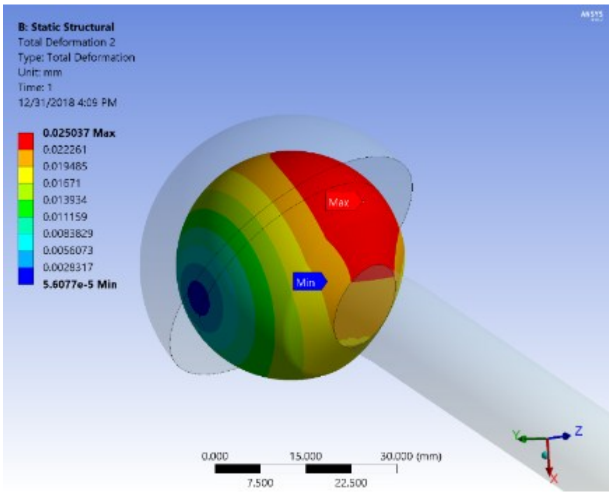

Figure 15. Alumina head total deformation at α= +30°.

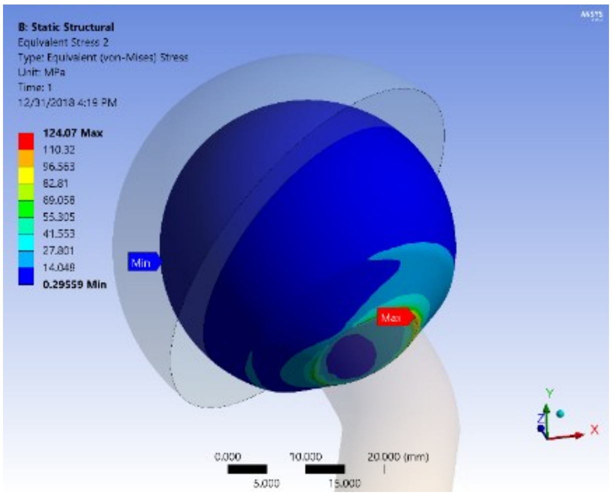

Figure 16. Cobalt-Chrome head stress at α= -10°.

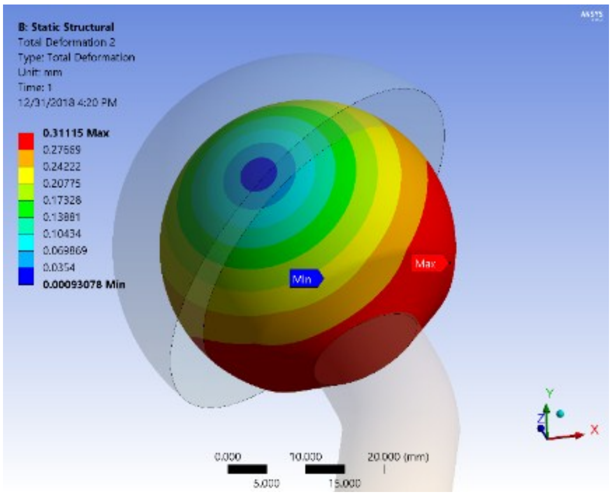

Figure 17. Cobalt-Chrome head total deformation at α= -10°.

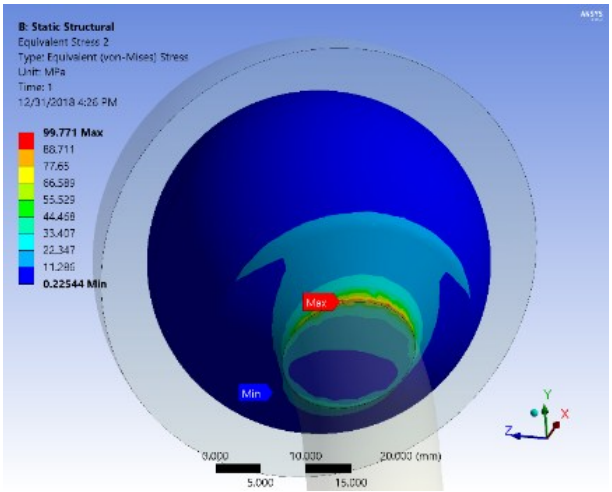

Figure 18. Cobalt-Chrome head stress at α= 0°.

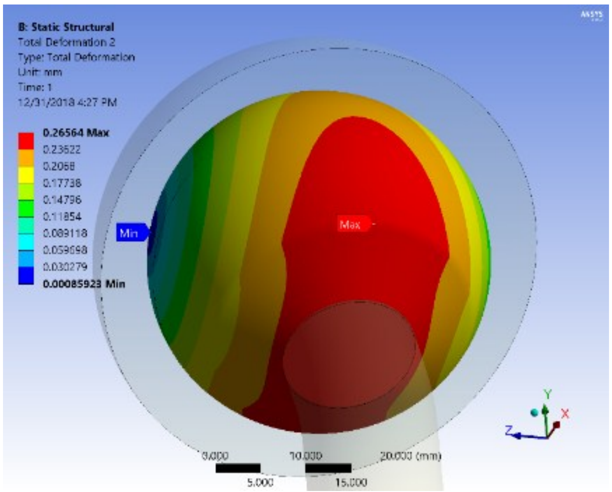

Figure 19. Cobalt-Chrome head total deformation at α= 0°.

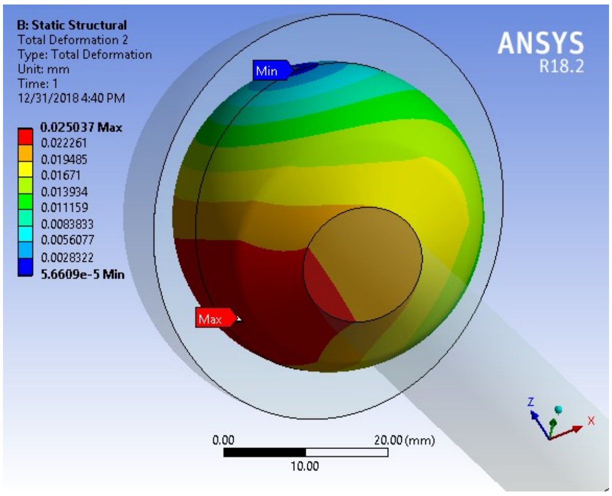

Figure 20. Cobalt-Chrome head total deformation at α= +30°.

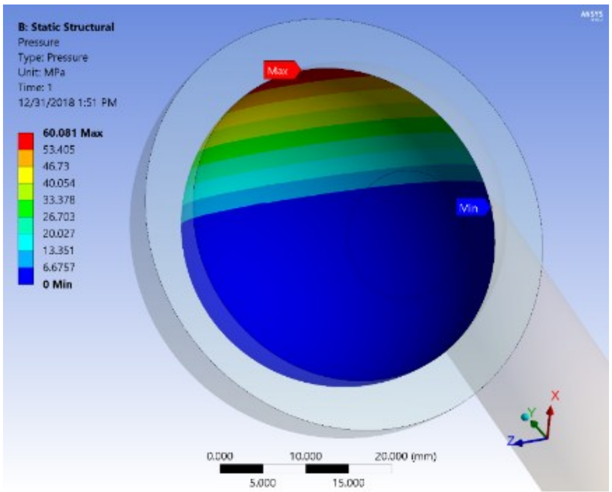

Figure 21. Pressure at α= -10°.

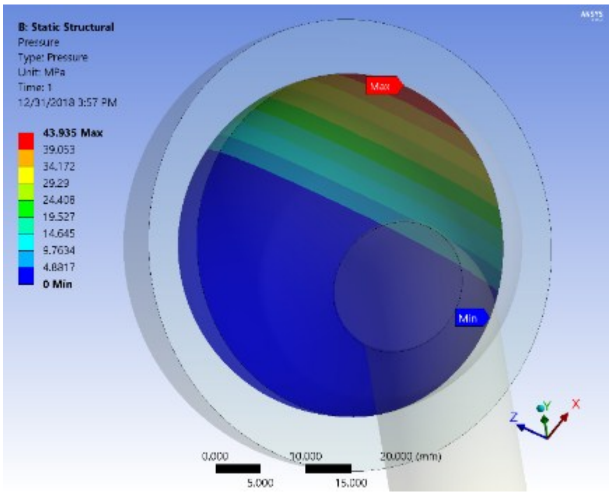

Figure 22. Pressure at α= 0°.

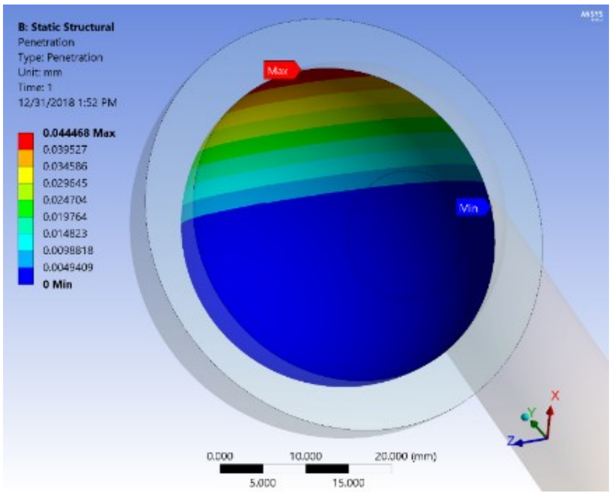

Figure 23. Penetration at α= -10°.

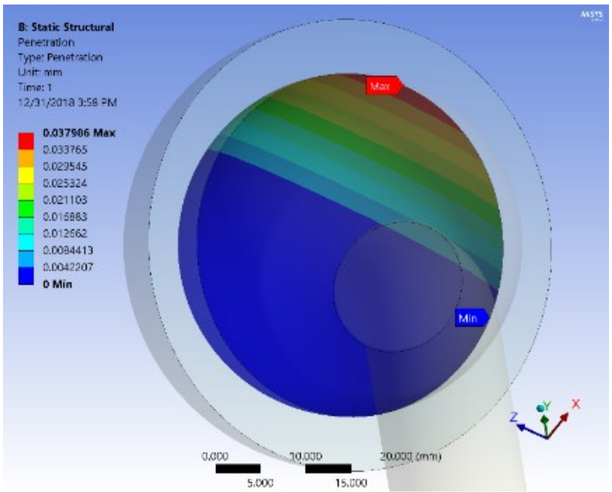

Figure 24. Penetration at α= 0°.

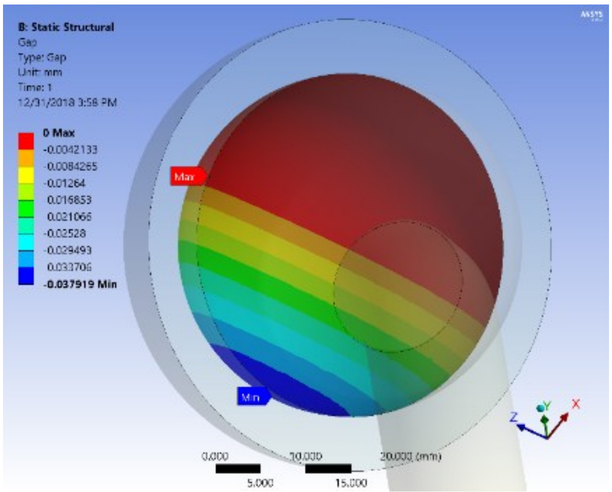

Figure 25. Gap at α= -10°.

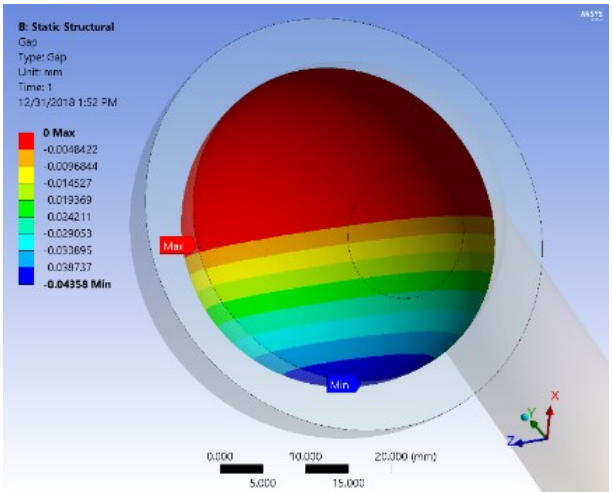

Figure 26. Gap at α= 0°.

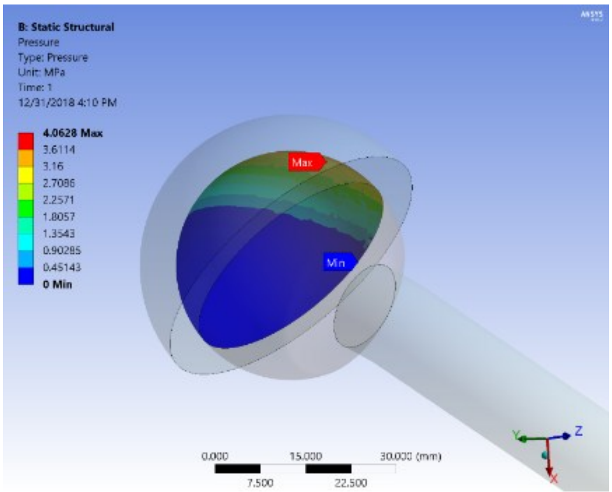

Figure 27. Pressure at α= +30°.

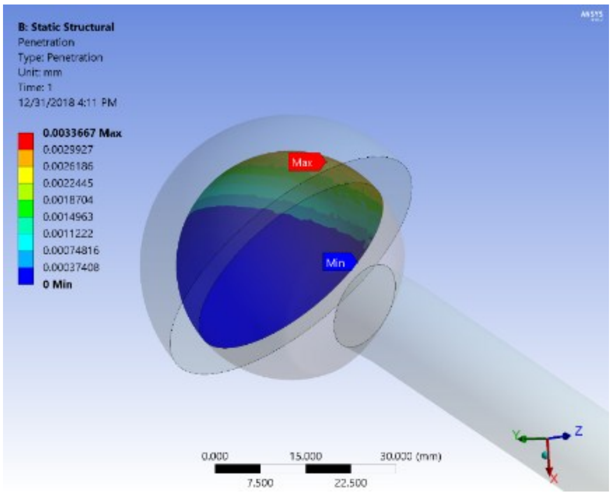

Figure 28. Penetration at α= +30°.

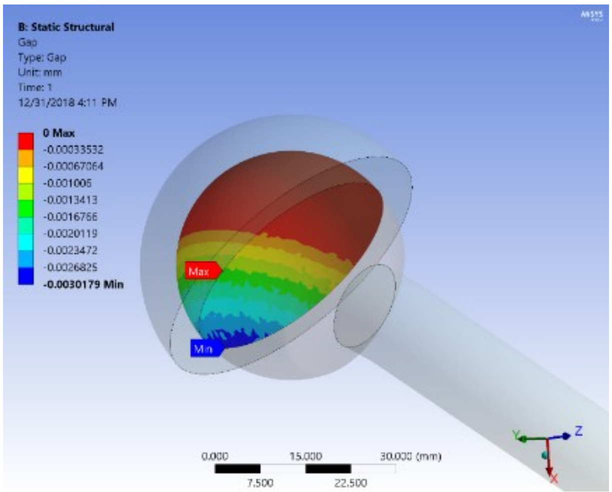

Figure 29. Gap at α= +30°.

Von mises stress variation is shown in Figure 30, 31 and 32, for HDPE liner it decreases as α increases, at β of 65° and 75° results are fully acceptable as stress start and end at lowest values, while 55° was considered partially acceptable as it starts and end at medium values. Alumina femoral head shows fully acceptable results at β of 55°, 65° and 75° as they are a mixture between low and medium values for the interval of movement. Cobalt-Chrome alloy femoral head shows fully acceptable results at β of 65° and 75° as it starts lowest at 75° and slightly higher at 65° but both angles end lowest, while 45° and 55° are considered partially acceptable, at 45° it is identical to 65° when starts but then pass through high value at α=0° and finally ends at medium value, at 55° it starts slightly higher than 65 but ends very low.
Deformation variation revealed in Figure 33, 34 and 35, for HDPE liner it decreases as α increases, at β of 65° and 75° results are fully acceptable as these two angles are close in results, at 65° the start is higher than 75° but the latter ends at higher deformation, While 55° was considered partially acceptable as it starts at medium deformation but ends at median values of 65° and 75°. Alumina femoral head shows fully acceptable results at β of 55°and 65° as the deformation starts at close values for all angles but ends lowest with 55 and 65. While acceptable results at 45° as it starts lowest but ends medium. Cobalt-Chrome ally femoral head shows fully acceptable results at β of 65° as it starts medium but ends lowest. While partially acceptable results at 45° and 55°, at 45° it starts lowest then end medium, at 55° it starts slightly higher than 45° but ends slightly higher than 65°.
Pressure variation is illustrated Figure 36, it is considered optimum at β of 55°, 65° and 75° as they start at common low point but ends lowest, while 45° was considered acceptable as it starts lowest but ends at medium value.

Gap variation is illustrated in Figure 37, it is considered fully acceptable at β of 55° and 65°, at 55° it starts lower than 65° but the latter ends lowest. While partially acceptable results at 45° as it starts lowest but ends at medium value.

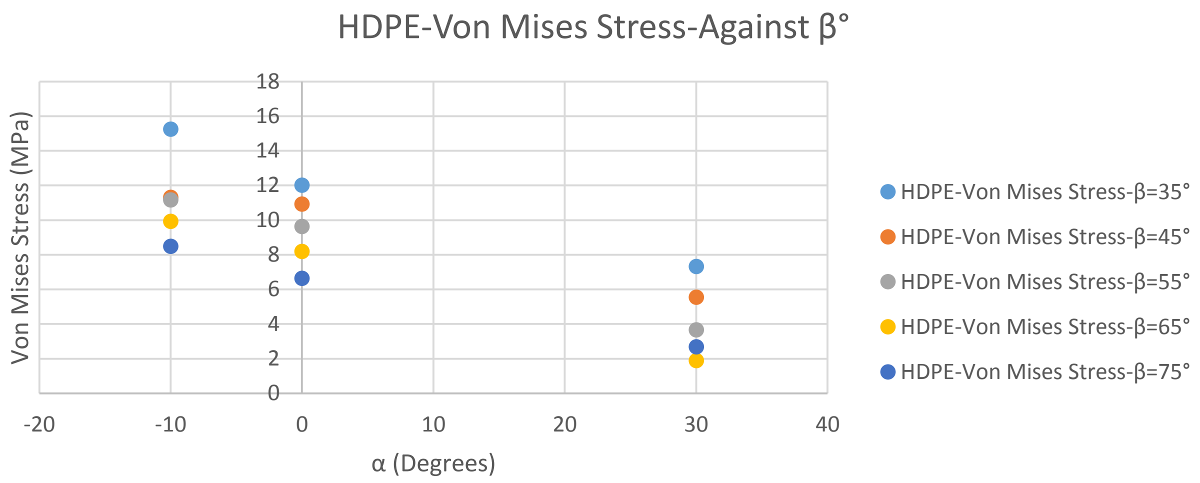

Figure 30. HDPE-Von Mises Stress- Against β°.

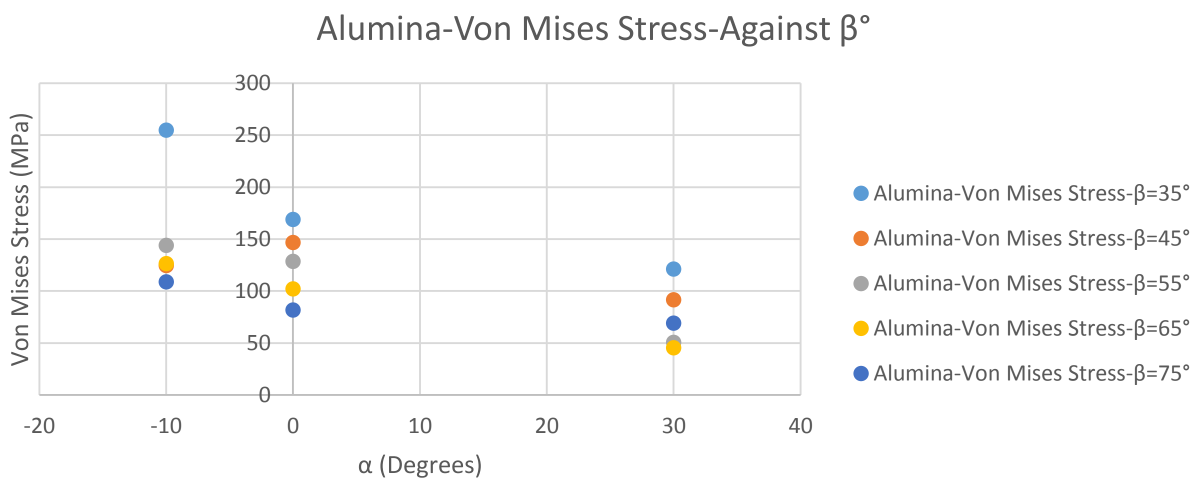

Figure 31. Alumina-Von Mises Stress- Against β° / Al_2O_3 Femoral head.

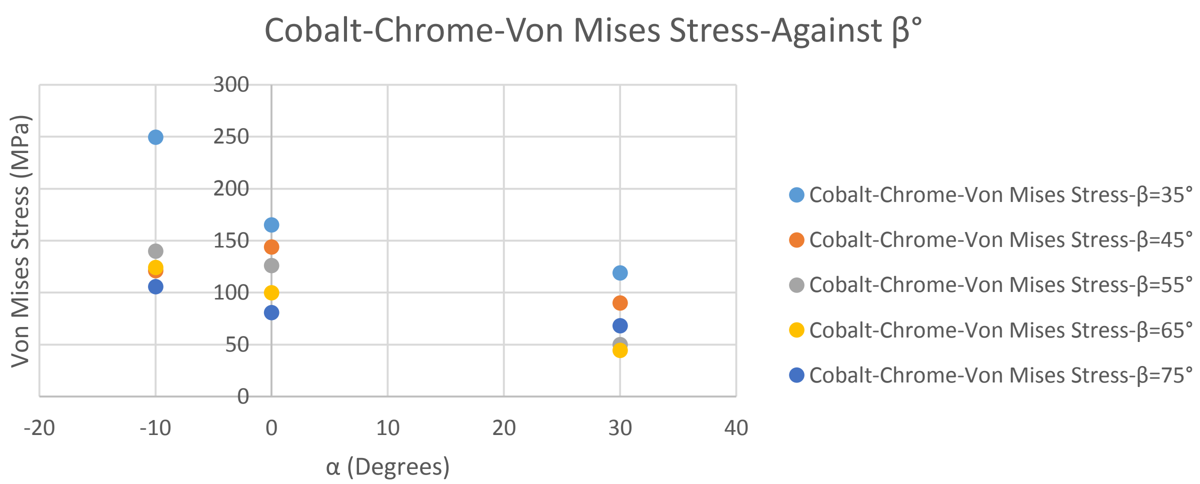

Figure 32. CoCr-Von Mises Stress- Against β° / CoCr Femoral head.

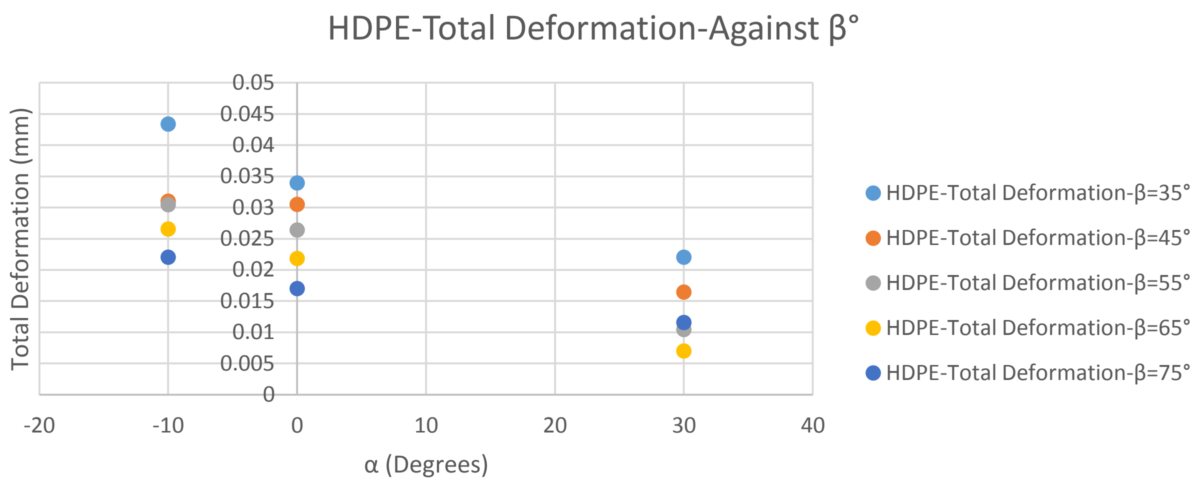

Figure 33. HDPE-Total Deformation-Against β° / Al_2O_3 Femoral head.

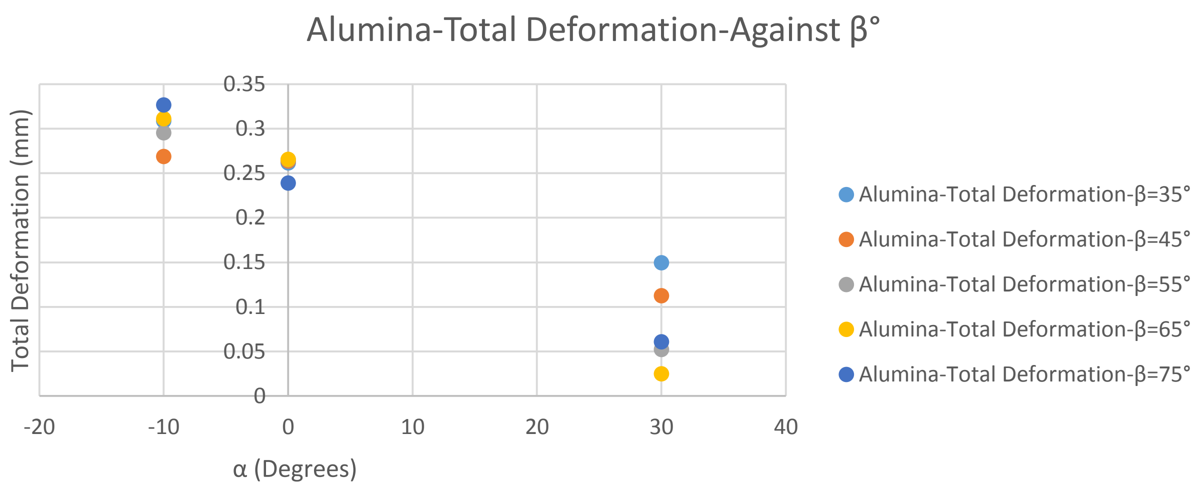

Figure 34. Alumina-Total Deformation-Against β°/ Al_2O_3 Femoral head.

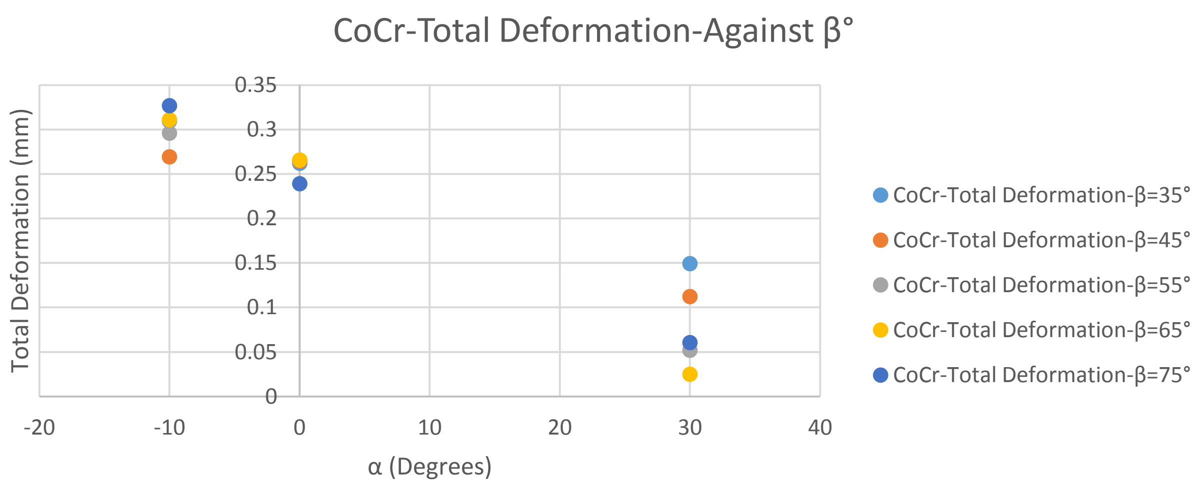

Figure 35. CoCr-Total Deformation-Against β°/ CoCr Femoral head.

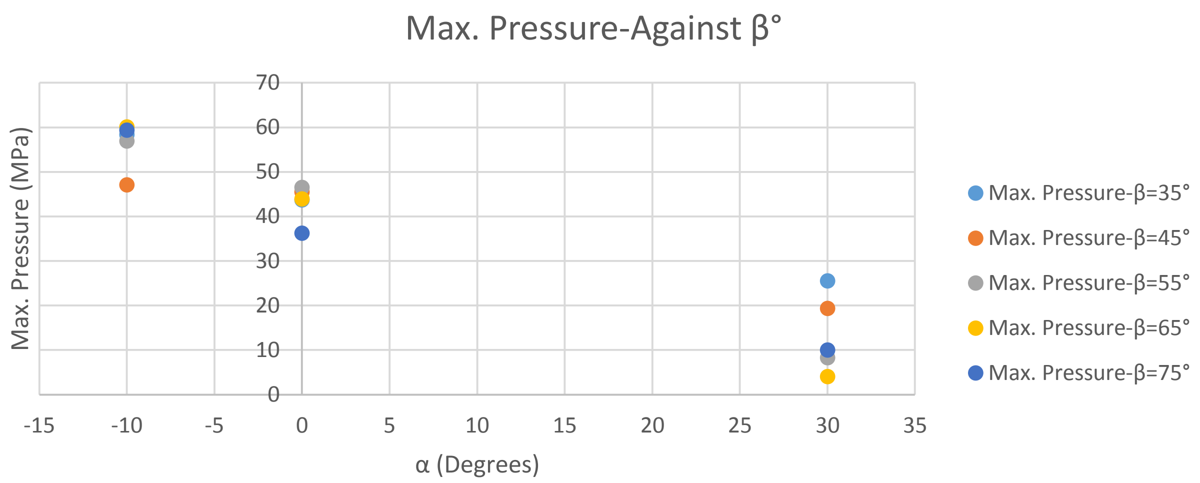

Figure 36. Max. Pressure-Against β° / Al_2O_3 Femoral head.

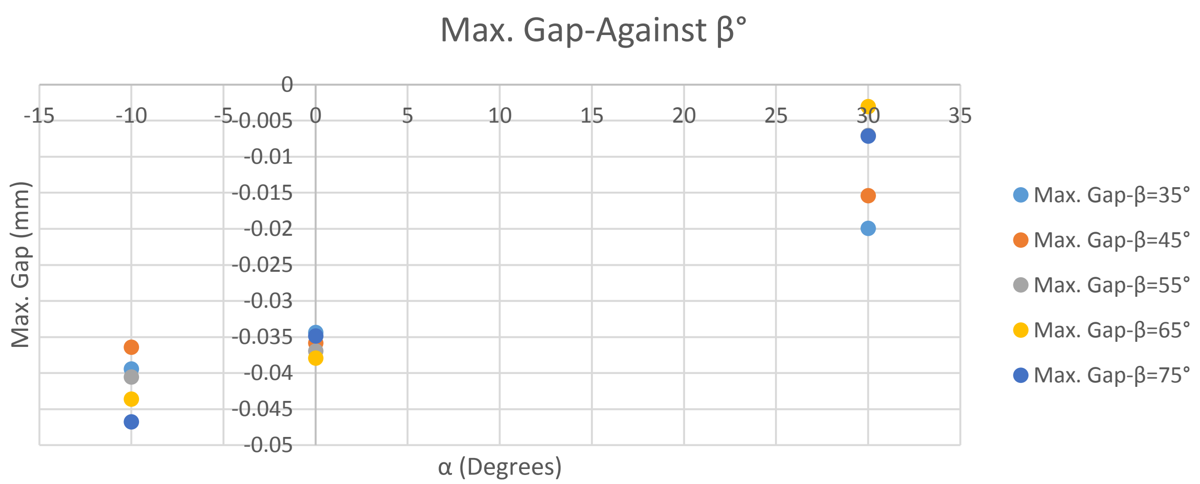

Figure 37. Max. Gap-Against β° / Al_2O_3 Femoral head.

Figure 38 shows Penetration variation, it is considered fully acceptable at β of 75°only and partially acceptable results at 45°,55° and 65°. The results are interconnected for this parameter and they are hardly compared which is a good result that holds wide range of acceptance.

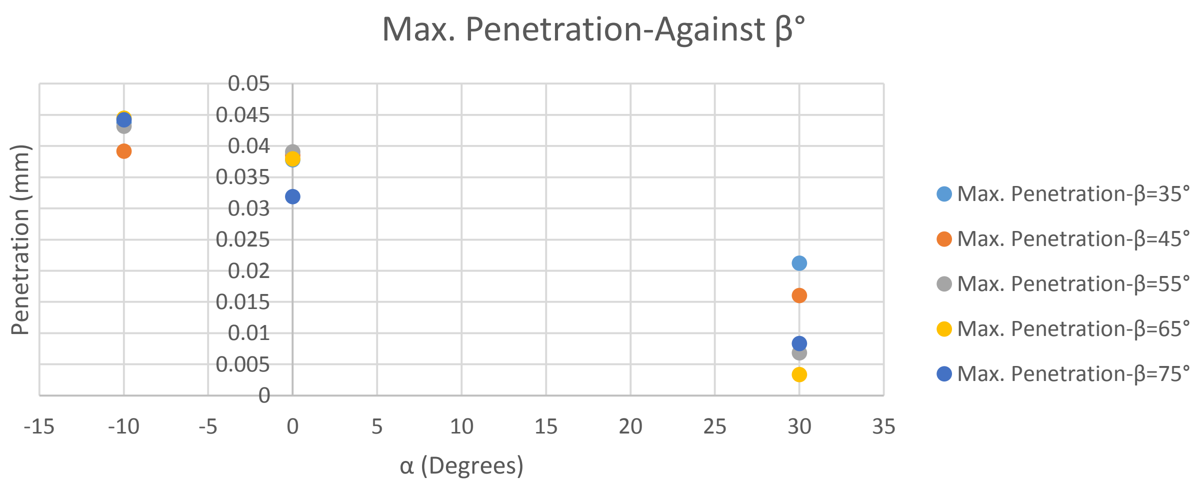

Figure 38. Max. Penetration-Against β° / Al_2O_3 Femoral head.

The following matrix (Table 4) will summarize the best parameters obtained for a specific β, it is based on results obtained from Numerical Analysis and was evaluated as follows: NA (Not Acceptable) =0, PA (Partially Acceptable) =0.5, FA (Fully Acceptable) =1.
It is obvious that the design with β=65° gives best compromise of Von-Mises stress, deformation, pressure, gap and penetration results. Note that the results of von-mises stress, deformation for HDPE liner with both femoral heads are identical. Pressure, Gap, Penetration results are identical for both couplings which shows that theses parameters are dependent on force and design only.

Table 4. Design selection matrix.

ALUMINA FEMORAL HEAD AGAINST HDPE LINER								
β°	Von-Mises Stress		Total Deformation		Pressure	Gap	Penetration	Ans
	HDPE	Al_2O_3	HDPE	Al_2O_3				
35	NA	NA	NA	NA	NA	PA	NA	0.5
45	NA	NA	NA	PA	PA	FA	PA	2.5
55	PA	FA	PA	FA	FA	NA	PA	4.5
65	**FA**	**FA**	**FA**	**FA**	**FA**	**FA**	**PA**	**6.5**
75	FA	FA	FA	NA	FA	NA	FA	5
COBALT-CHROME ALLOY FEMORAL HEAD AGAINST HDPE LINER								
β°	Von-Mises Stress		Total Deformation		Pressure	Gap	Penetration	Ans
	HDPE	CoCr	HDPE	CoCr				
35	NA	NA	NA	NA	NA	NA	NA	0
45	NA	PA	NA	PA	PA	PA	NA	2
55	PA	PA	PA	PA	FA	FA	PA	4.5
65	**FA**	**FA**	**FA**	**FA**	**FA**	**FA**	**PA**	**6.5**
75	FA	FA	FA	NA	FA	NA	FA	5

4. Conclusions
The following points are concluded from the finite element analysis work:
1. The angle of movement (α) at -10° is the most important as the results are maximum for Von-Mises stress, total deformation, pressure, penetration and gap.
2. The angle between femoral head and acetabulum (β) at 65° showed best compromise in terms of Von-Mises stress, Total Deformation, Pressure, Penetration and Gap.
3. The angle between femoral head and acetabulum (β) at 45° showed least pressure which contributes to comfortableness of patient.
4. Pressure, Gap and Penetration are functions of applied force only, as the materials changed the results were not affected.

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