Project 2

FEA Analysis of Hip Replacement

John Carey

Introduction and Objectives

In this project a hip replacement prosthesis was analyzed. The analysis centered on FEA analysis of the hip joint using Solidworks under three loading conditions, walking, Climbing Stairs, and getting in and out of a car. The forces were found using orthoload.com. The purpose of this project was to complete 2 studies and a recommendation. Study 1 was used to fine tune loading conditions and mesh types for hip replacement using one of the loading conditions. Once the most accurate loading condition and mesh was found Study 2 was to use those constraints to evaluate all three of the loading conditions. Finally, a recommendation was the be given using the data from study 2 as to whether the current design was acceptable and if any recommendations could be made.

Methods

The methods used in this project relied heavily on data received from orthoload.com. Forces were given in percentage of body weight with max forces, forces in the x, y and z plane, and pictures of the angles of the forces applied.

Two different hip implants had force databases, the Hip I and Hip II with a collective database and Hip II with its own database of forces. Looking at the diagrams Hip III had a similar anatomy as the implant we are analyzing, so forces were chosen for Hip III implants

Figure 1. Choice was made to use data for HIP JOINT III as it had the backing similar to the proposed concept joint

The activity suggested the loading condition on the joint. We are working with walking, climbing stairs and getting in and out of the car for loading conditions. Most activities showcased data from multiple patients. An attempt to randomly select 3-5 patients per activity was made and the average and maximum forces were calculated.

Stairs - Max Force and Moments Cartensian BW%

Patient	Condition	Max F	Max FX	Max FY	Max FZ	Max Mom	Mx	My	Mz
h4l	Up - Handrail Contralateral	232	40	-60	-220	0.45	-3	-3.2	0.05
h7r	Up - Handrail Ipsilateral	302	90	-20	-290	0.4	-0.3	0.4	0.2
h4l	Down - Contralateral	285	50	-30	-280	0.45	-0.2	0.2	-0.15
h2r	Up and Down	326	110	-90	-290	0.21	-0.22	0.18	-0.7
h66	Up and Down	293	80	-100	-280	0.16	-0.16	-0.12	0.7

Average		287.6	74	-60	-272	0.334	-0.776	-0.508	0.02
Max		326	110	-20	-220	0.45	-0.16	0.4	0.7
sd		34.6742	28.80972	35.35534	29.49576	0.138672	1.244299	1.516285	0.510637

Car in and out- Max Force and Moments Cartensian BW%

Patient	Condition	Max F	Max FX	Max FY	Max FZ	Max Mom	Mx	My	Mz
hsr	Passenger In	223	75	70	205	NA	NA	NA	NA
kwr	Driver In	297	75	60	280	NA	NA	NA	NA
pfl	Passenger Out	204	50	70	190	NA	NA	NA	NA
kwr	Driver Out	240	75	60	225	NA	NA	NA	NA
pfl	Driver In	252	80	60	250	NA	NA	NA	NA

Average		243.2	71	64	230	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Max		297	80	70	280	0	0	0	0
sd		35.09558	11.93734	5.477226	35.88175	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Walking - Max Force and Moments Cartensian BW%

Patient	Condition	Max F	Max FX	Max FY	Max FZ	Max Mom	Mx	My	Mz
Hr10r		247	80	-40	-220	0.35	0.3	0.21	0.2
h1l		243	70	-30	-220	0.3	0.3	0.15	0.1
H2R		269	70	-40	-270	0.28	-0.35	0.28	0.05
H8L		311	110	-50	-260	0.25	0.22	-0.1	-0.1
h6r		244	90	-60	-220	0.16	-0.16	0.11	0.5

Average		262.8	84	-44	-238	0.268	0.062	0.13	0.15
Max		311	110	-30	-220	0.35	0.3	0.28	0.5
sd		28.96895	16.7332	11.40175	24.8998	0.070498	0.298865	0.143701	0.223607

Tables 1, 2 and 3. Forces in body weight percentage for 3 loading conditions

Forces were converted to Newtons by taking the body weight percentage and multiplying them by the body weight of 80kg and the gravitational constant 9.81 $\frac{m}{s^2}$

Stairs - Max Force and Moments Cartensian - Newtons 80 kg

Patient	Condition	Max F	Max FX	Max FY	Max FZ	Max Mom	Mx	My	Mz
h4l	Up - Handrail Contralateral	1820.736	313.92	-470.88	-1726.56	36	-3	-3.2	0.05

h7r	Up - Handrail Ipsilateral	2370.096	706.32	-156.96	-2275.92	0.4	-0.3	0.4	0.2
h4l	Down - Contralateral	2236.68	392.4	-235.44	-2197.44	0.45	-0.2	0.2	-0.15
h2r	Up and Down	2558.448	863.28	-706.32	-2275.92	0.21	-0.22	0.18	-0.7
h66	Up and Down	2299.464	627.84	-784.8	-2197.44	0.16	-0.16	-0.12	0.7
Average		2257.085	580.752	-470.88	-2134.66	7.444	-0.776	-0.508	0.02
Max		2558.448	863.28	-156.96	-1726.56	36	-0.16	0.4	0.7
sd		272.1231	226.0987	277.4687	231.4827	15.96376	1.244299	1.516285	0.510637

Walking - Max Force and Moments Cartensian - Newtons

Patient	Condition	Max F	Max FX	Max FY	Max FZ	Max Mom	Mx	My	Mz
Hr10r		1938.456	627.84	-313.92	-1726.56	0.35	0.3	0.21	0.2
h1l		1907.064	549.36	-235.44	-1726.56	0.3	0.3	0.15	0.1
H2R		2111.112	549.36	-313.92	-2118.96	0.28	-0.35	0.28	0.05
H8L		2440.728	863.28	-392.4	-2040.48	0.25	0.22	-0.1	-0.1
h6r		1914.912	706.32	-470.88	-1726.56	0.16	-0.16	0.11	0.5
Average		2062.454	659.232	-345.312	-1867.82	0.268	0.062	0.13	0.15
Max		2440.728	863.28	-235.44	-1726.56	0.35	0.3	0.28	0.5
sd		227.3483	131.3222	89.48097	195.4136	0.070498	0.298865	0.143701	0.223607

Car in and out- Max Force and Moments Cartensian Newtons

Patient	Condition	Max F	Max FX	Max FY	Max FZ	Max Mom	Mx	My	Mz
hsr	Passenger In	1750.104	588.6	549.36	1608.84	NA	NA	NA	NA
kwr	Driver In	2330.856	588.6	470.88	2197.44	NA	NA	NA	NA
pfl	Passenger Out	1600.992	392.4	549.36	1491.12	NA	NA	NA	NA
kwr	Driver Out	1883.52	588.6	470.88	1765.8	NA	NA	NA	NA
pfl	Driver In	1977.696	627.84	470.88	1962	NA	NA	NA	NA
Average		1908.634	557.208	502.272	1805.04	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Max		2330.856	627.84	549.36	2197.44	0	0	0	0
sd		275.4301	93.68422	42.98527	281.6	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Tables 4,5, and 6. Forces in Newtons for 3 loading conditions

Additionally, the angle of the force was important to the loading condition. Max Forces were broken into components of the x, y and z plane. Angles were measured by hand and component forces for each loading condition were found

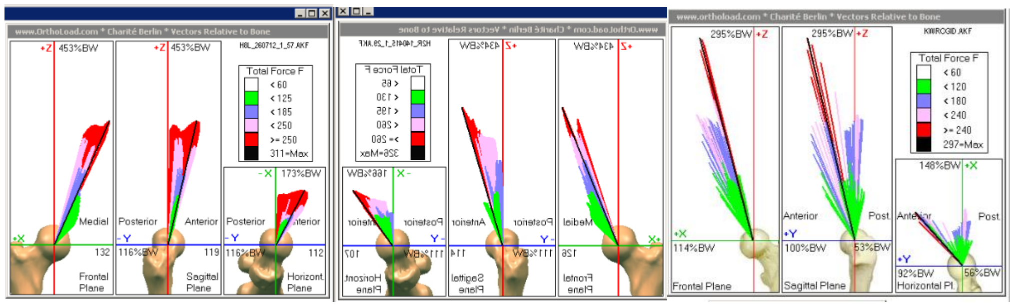

Figure 2. Angle data for max forces for walking (23.4 in the xz plane

14.8 in the yz plane), stairs (22 xz plane and 14 yz plane) and getting in and of car (17.4 xz and

14.6 in the yz plane)

Calculations of component forces could then be made using the max force in Newtons as the magnitude

Walking

Frontal plane (α) = 23.4

Sagittal plane = (β) 14.8

Magnitude of 2440.728 N (max force for walking)

$$X = 2440.728 \text{ N} \cdot \sin a = 969.329 \text{ N}$$

$$-Y = 2440.728 \text{ N} \cdot \sin \beta = -623.47 \text{ N}$$

$$-Z = \sqrt{2440.728^2 - x^2 - y^2} = -2151.47 \text{ N}$$

Stairs

Frontal plane (α) = 22

Sagittal plane = (β) 14

Magnitude of 2558.448 N (max force for stairs)

$$X = 2558.448 \text{ N} \cdot \sin a = 958.411 \text{ N}$$

$$-Y = 2558.448 \text{ N} \cdot \sin \beta = -618.94459 \text{ N}$$

$$-Z = \sqrt{2558.448^{\,2} - x^2 - y^2} = -2289.982 \text{N}$$

Car in and out

Frontal plane (α) =17.4

Sagittal plane = (β) 14.6

Magnitude of 2330.856 N (max force for car in and out)

$$-X = 2330.856 \text{ N} \cdot \sin\alpha = -697.02102 \text{ N}$$

$$-Y = 2330.856 \text{ N} \cdot \sin\beta = --587.53738 \text{ N}$$

$$-Z = \sqrt{2330.856^{\,2} - x^2 - y^2} = -2145.192583\text{N}$$

With loading conditions now known, we need to derive other boundary conditions. Several conditions were attempted as detailed in study 1, but the prevailing condition was a fixed condition at the bottom of the hip replacement mimicking the impact on the ground, or the force of the muscles holding the implant in place. The load was prescribed to the back of the joint ball, similar to the force conditions shown on orthpodia.com. The acetabular cup was bonded to the metal backing using the connections feature

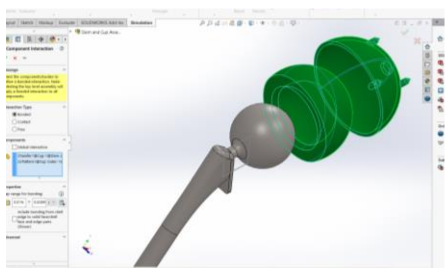

Figure 3. Bonding of the acetabular cup to the backing

The face of the ball was connected to the cup with an "on spherical faces connection." This was chosen due to the rotating ball and joint nature of the socket. Originally translations were set to 0, 0, 0 but through an iterative process that translations were changed in study 1.

The stem and head and metal backing components were assigned a material choice of titanium alloy (Commercially Pure CP-Ti UNS R50400 (SS)). With an Elastic Modulus (E) = 1.05 x 10^{11} $\frac{N}{m^2}$ and a poisons ratio (v) = .37

The acetabular cup was assigned PA Type 6 plastic With an Elastic Modulus (E) = 2.62 x 10^{9} $\frac{N}{m^2}$ and a poisons ratio (v) = .34

Meshes were created using first a standard mesh, then a curvature-based mesh, and finally a curvature-based mesh with enhanced controls around the neck of the stem/head. This was due to the finding in study 1 that this area had the highest Von Mises stresses.

The forces were applied with a force in the external loads. The direction was chosen to be "selected direction" and the component forces were added into each direction

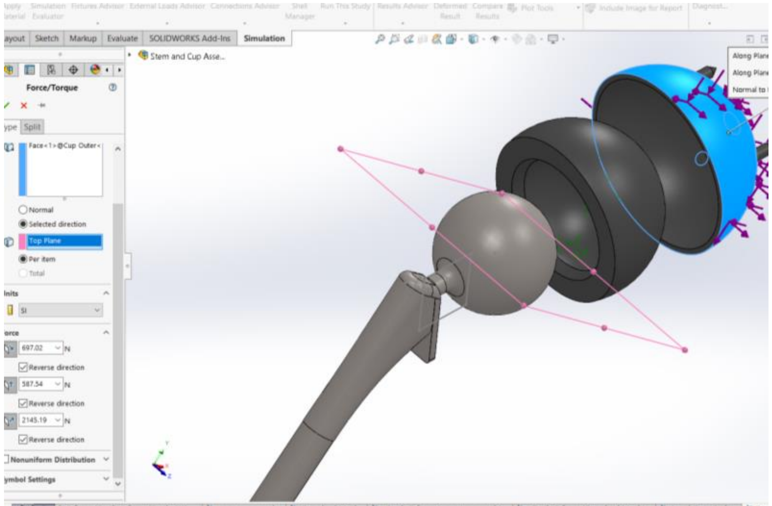

Figure 4. Forces were loaded by broken down component forces in the x, y and z plane. Arrows were compared to the orthopedia angle diagrams to ensure proper loading.

Study 1

Study one was used to measure the von mises stresses of three different meshes under one loading condition. The loading condition of walking was used and the forces and angles for that were applied to this study. In addition, several loading conditions were attempted to find the best result.

The first mesh was the standard mesh with a mid-range coarseness setting. The first loading condition used had the metal backing fixed and the force prescribed through the face of the ball from the ball and stem. This approach was quickly found unrealistic.

Still using the standard mesh, the bottom of the stem was now fixed and the force applied from the back of the metal backing.

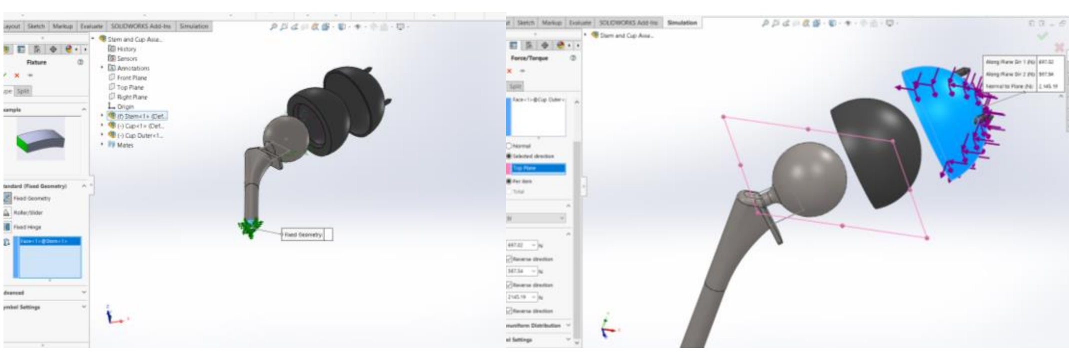

Figure 5. Fixtures and loads applied

The 0 translation of the joint still seemed inaccurate, so a test run with 0,0,0 translation on the "on spherical faces" connection was run and the displacements inside the cup were found.

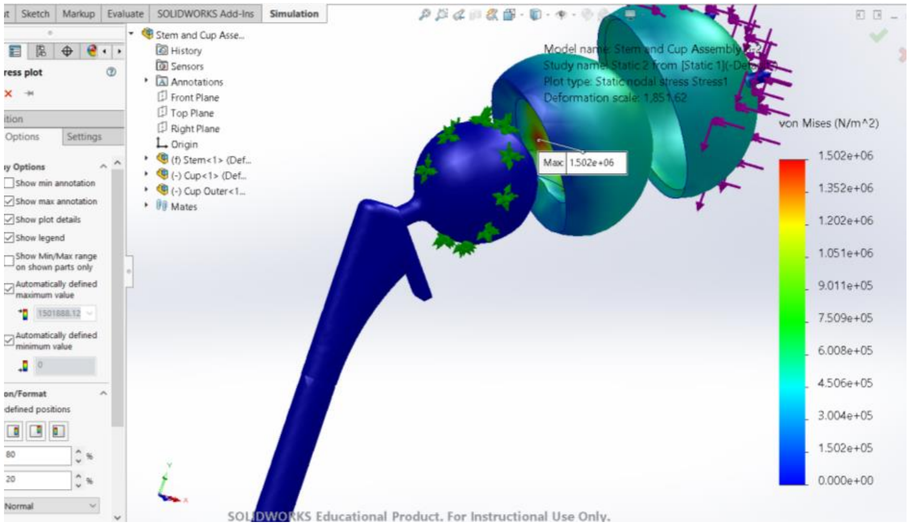

Figure 6. Displacement map inside the cup

These displacements were then put into the translations for the on spherical faces fixture.

We got a standard mesh Von Mises Map that looked correct, with the max Von Mises on the neck stem connecting to the ball face

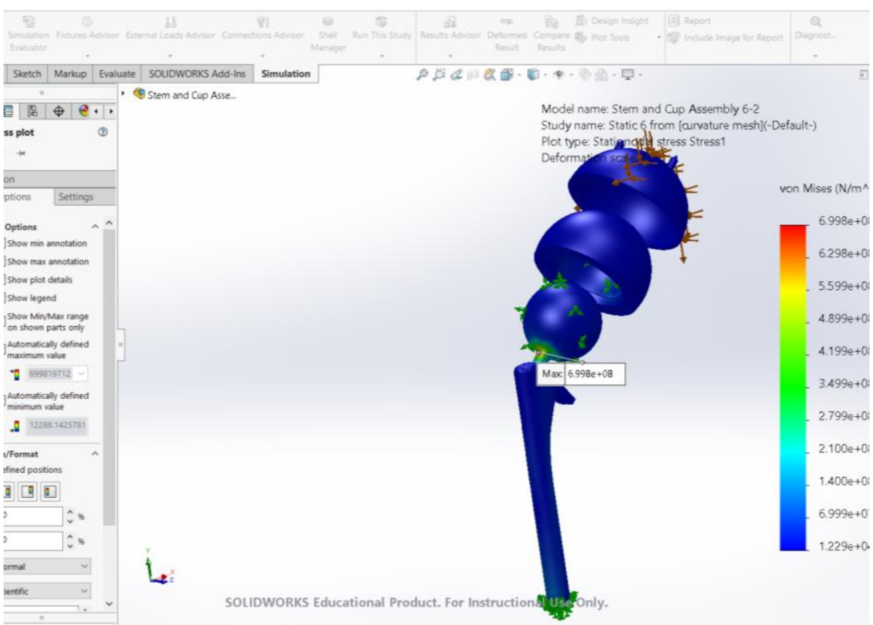

Figure 7. Max Von Mises with the loading conditions and a standard mesh

Using the same force and boundary conditions, the mesh was changed to a curvature based mesh with medium coarseness.

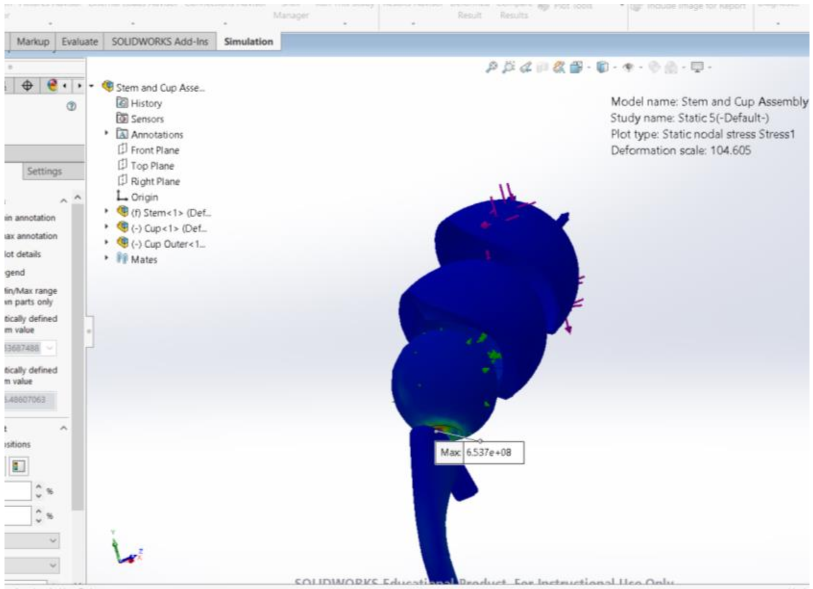

Figure 8. Max Von Mises with the loading conditions and a curvature-based mesh

With both the standard mesh and the curvature-based mesh showing max Von Mises stresses around the neck, a fine mesh control was added around the neck using a curvature based mesh

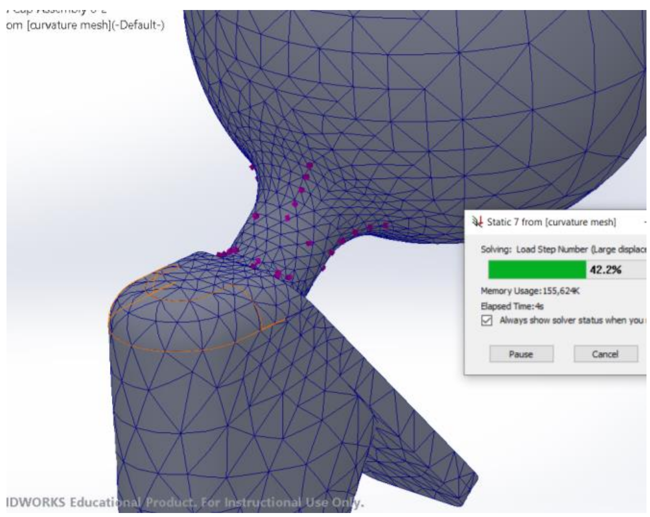

Figure 9. Increase mesh controls around the neck

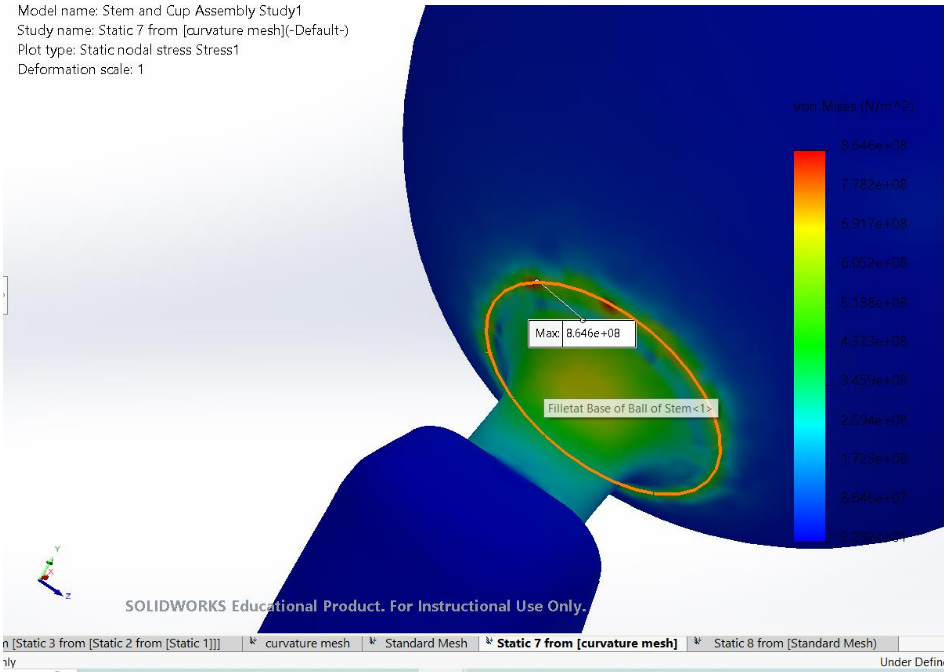

Figure 10. Max Von Mises with the loading conditions and a curvature based with finer mesh controls around neck

Study 1 results

Mesh Type	Number of nodes	Number of elements	Max Von Mises	Location of max von mises
Standard	15684	9005	6.998E+08	fillet at base of stem lateral side
Curvature Based	19967	11788	6.537E+08	Loft of stem lateral side
Curvature with finer Mesh around neck	24463	15378	8.65E+08	Points of radius connecting stem to Ball Lateral Side

The results of the three meshes showed that the curvature-based mesh with finer controls around the neck area showed higher Von Mises Stresses. Using this mesh would only increase our factor of safety, so the decision to use a curvature-based mesh with fine controls around the neck in study 2 was made.

Study 2

Study 2 used the exact same mesh as was defined in study 1, a curvature-based mesh with fine controls around the neck, and applied all three loading conditions, walking, stairs, and getting in and out of a car

In and Out of a car

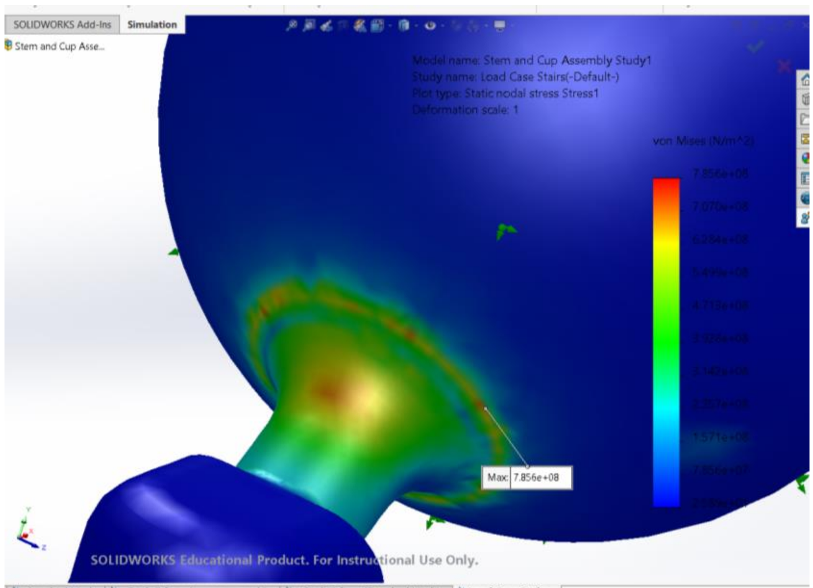

Figure 11. Von Mises Stress for getting in and out of car

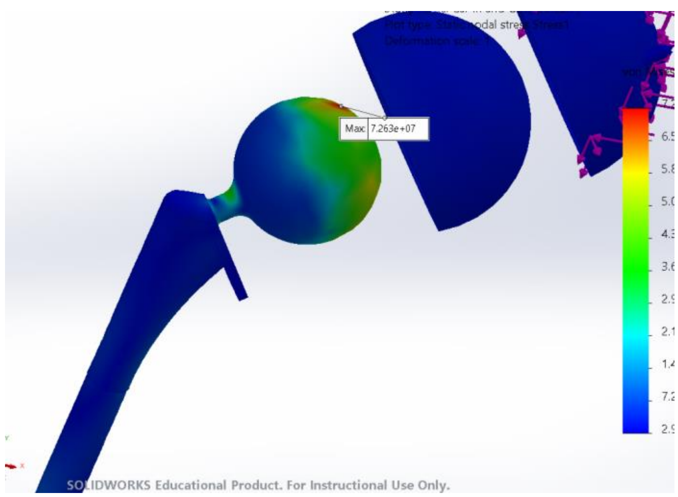

Figure 12. Contact Pressure for getting in and out of car

Stairs

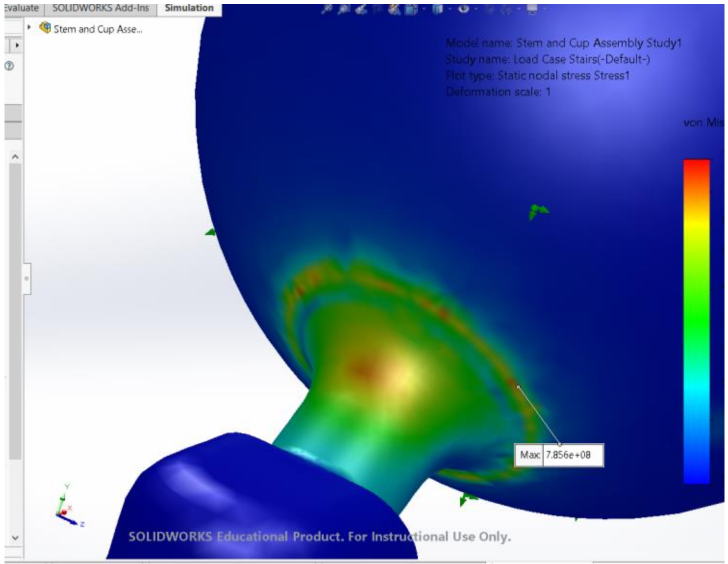

Figure 13. Von Mises Stresses for going up and down stairs

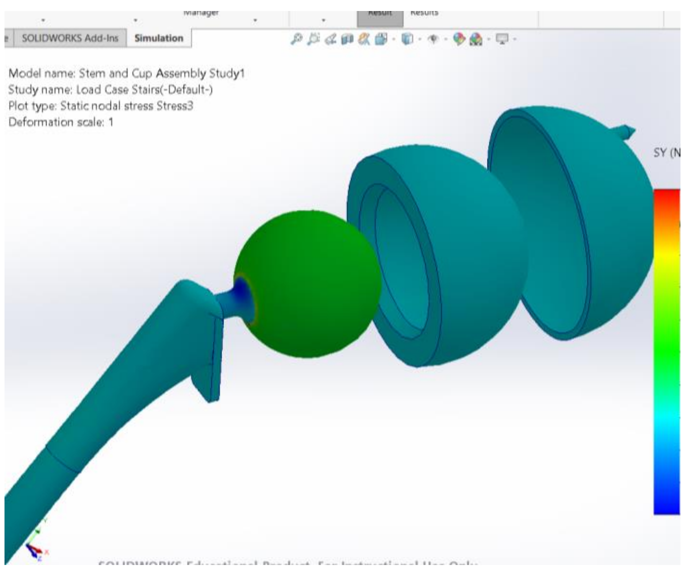

Figure 14. Contact Pressure for going up and down stairs

Walking

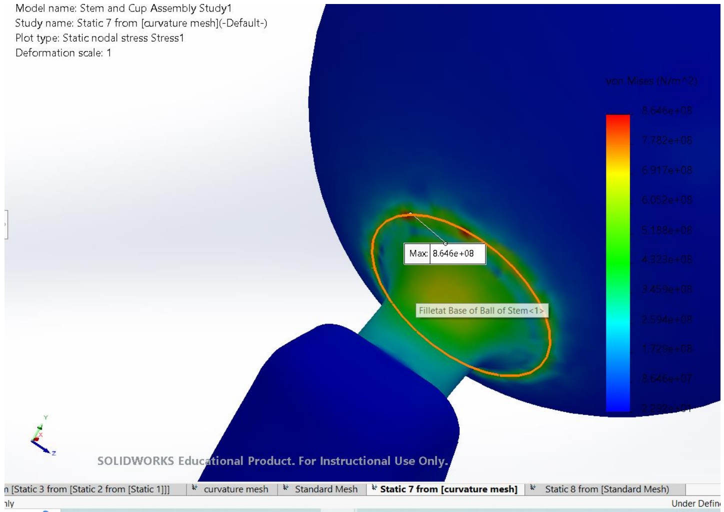

Figure 15. Von Mises Stresses for walking

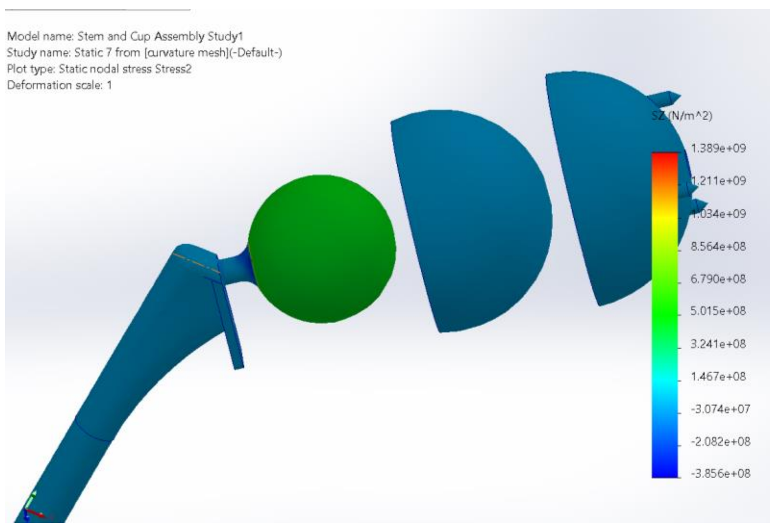

Figure 16. Contact Pressure for walking

Von Mises Stresses for each activity ranged from 7.589 x 10^8 $\frac{N}{m^2}$ to 8.65 x 10^8 $\frac{N}{m^2}$

Study 2 - Results

Input	Mesh Type	Number of nodes	Number of elements	Max Von Mises	Location of max von mises

Stairs	Curvature with finer Mesh around neck	25151	15199	7.586E+08	Points of radius connecting stem to Ball Lateral Side
Car	Curvature with finer Mesh around neck	25151	15199	7.856E+08	Loft of stem lateral side
Walking	Curvature with finer Mesh around neck	24463	15378	8.65E+08	Points of radius connecting stem to Ball Lateral Side

Recommendation

With Von Mises Stresses that range from 7.589 x 10^8 $\frac{N}{m^2}$ and 8.65 x 10^8 $\frac{N}{m^2}$, I cannot recommend this hip replacement as is. Changing the materials and redesigning the neck of the prosthetic would be deemed necessary are further FEA analysis would need to be done. An increase in the radius of the neck may be in order. With a yield strength of 3.7 x 10^8 $\frac{N}{m^2}$, the titanium alloy would experience plastic deformation and may fail completely.

Discussion and Conclusion

In this project I obtained FEA analysis of a hip replacement prosthetic under 3 different loading conditions. The maximum Force that was seen was from walking of 311 percent of the body weight of the patient. This translated to a Von Mises Stress of 8.65 x 10^8 $\frac{N}{m^2}$, which exceeds the yield strength of the titanium alloy, given at 3.7 x 10^8 $\frac{N}{m^2}$. Although this could mean a redesign of the part is needed, which was the formal recommendation, there are alternative explanations for the failure in analysis.

The first possible explanation could be a misinterpreting of the force data or the components of the force. It was assumed that to find the force when at 311 percent of the body weight (87 kg) that the equation to find the force would be 3.11 x 80 kg x 9.81$\frac{m}{s^2}$, since the force = mass time acceleration, but it is possible that since orthoload.com already describes it as a force that gravitational acceleration is already included in the Body weight Percentage. If my calculations have increased the force by 9.81 times, that would certainly lead to exaggerated Von Mises Stresses.

Another possible explanation could be incorrect boundary conditions set up in SolidWorks. Though a fixed support at the bottom of the hip replacement shaft may work theoretically, in real world conditions there would be muscle, bone and other tissue that allowed displacement and reduced the force impact.

Still another explanation could be that a direct maximum force is not the ideal loading condition for this exercise.

Since all three meshes put the Maximum Stress Location in roughly the same area, the loft of the stem, it is reasonable to assume this is the weakest point of the design and the area most likely to fail. Although all three meshes pointed to the same area of stress concentration, the concentration was higher as the mesh was refined.

Citations

OrthoLoad.com

SolidWorks' Material Database