Stress Analysis of a Total Hip Replacement Prosthesis

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Introduction and objectives

As human bodies age, the cartilage between joints that provides support and structure deteriorates. A very common place that this process occurs is in the hip joint. The cartilage can become damaged enough to cause extreme pain and inability to walk. A total hip replacement is a procedure that involves implanting a prosthesis in the femur that joins to the hip with a ball and socket type joint. The purpose of this report is to analyze the contact pressures and von Mises stresses throughout the implant due to normal daily activities to ensure that the implant will not fail under any circumstance. A convergence study will also be conducted to determine if the finite element model was properly meshed.

Method

Finite element analysis was run on a model of the total hip replacement prosthesis. The stem and outer cup were made of a titanium alloy (Commercially Pure CP-Ti UNS R50400 (SS)), which has a yield strength of 370 MPa and a Poisson's ratio of .37. The inner cup was made of PA Type Plastic, which has a yield strength of 103 MPa and a Poisson's ratio of .34. The prosthesis was analyzed during three activities – walking, stair climbing, and getting into a car. For each scenario, the person is assumed to have a body mass of 80 kg. The peak resultant forces due to each activity are shown below in Table 1.

Table 1: Peak forces acting on prosthesis for 80 kg person.

Activity	Peak Force (% BW)	Peak Force (N)
Walking with a rollator	144	1130
Getting into car	252	1978
Stair climbing with hand rail	555	4356

The peak force for each activity was applied to the ball of the stem in the downward direction. This simulates the force of the hip acting on the femoral head. The shaft of the stem and the outer cup were fixed to simulate being attached to bone. Two contact sets were applied; a no penetration contact set was applied to the ball of the stem and the inner surface of the plastic cup, and a bonded contact set was applied between the inner and outer cups.

A convergence study was performed in order to investigate the effect that mesh size has on the finite element analysis results. Simulations were run for the stair climbing loading configuration based on five different mesh sizes ranging from coarse to fine. The maximum von Mises stresses in the entire prosthesis were tracked and then compared to the number of elements in each mesh.

Results

The von Mises stress plots and contact pressure vector plots for each loading configuration are shown in figures below.

Figure 1: von Mises stress plot for walking with a rollator

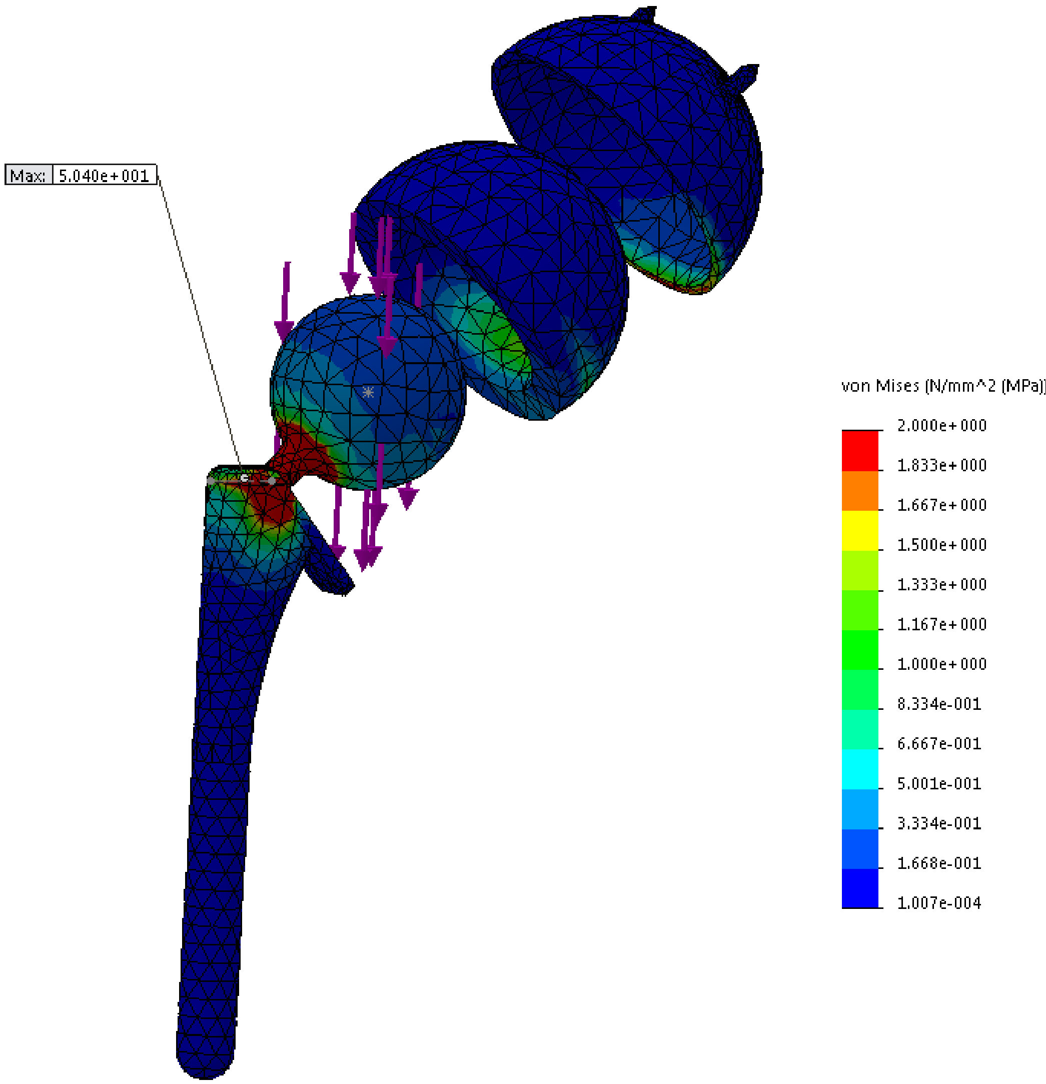

Figure 2: von Mises stress plot for getting into a car

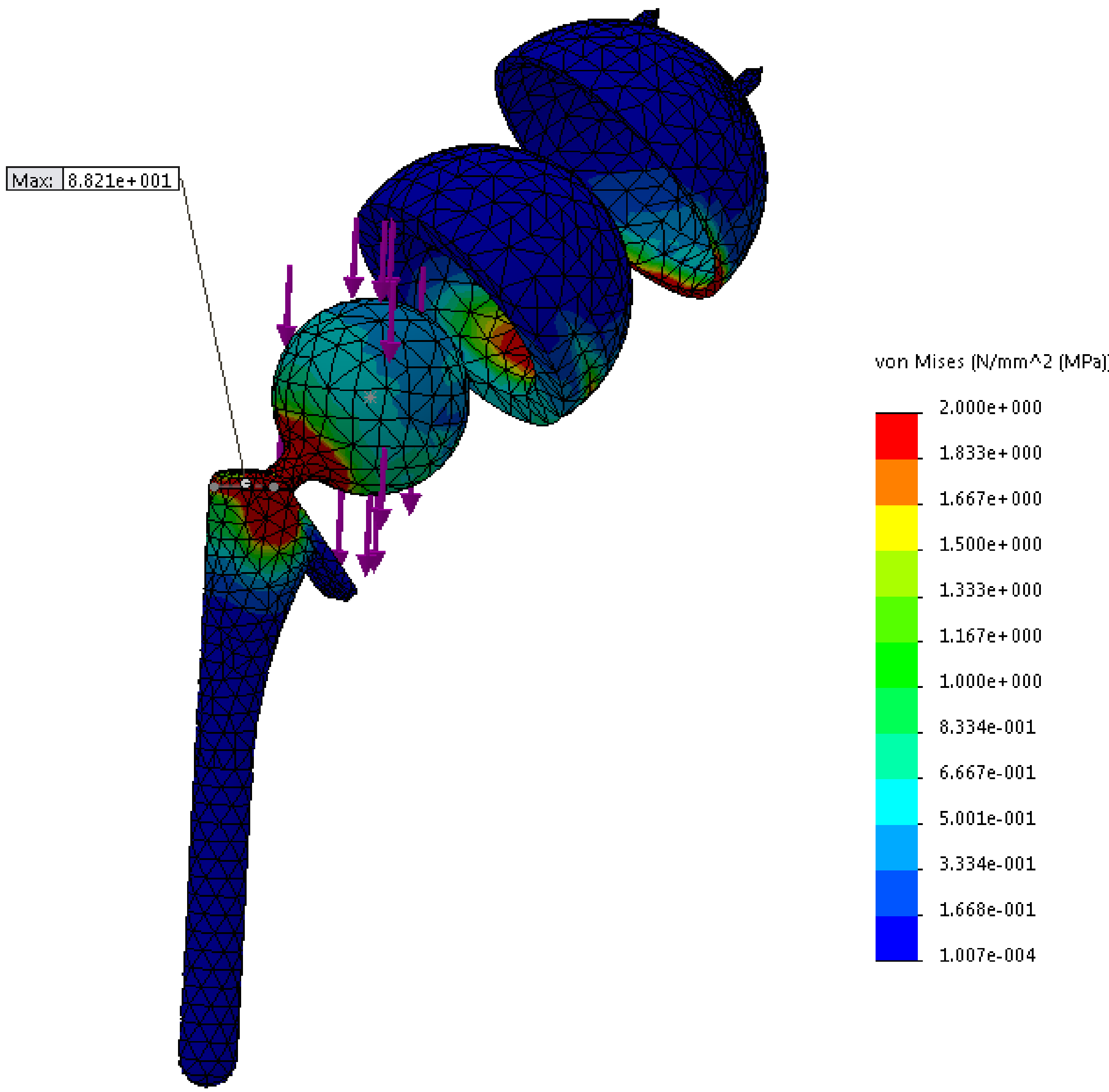

Figure 3: von Mises stress plot for stair climbing with a hand rail

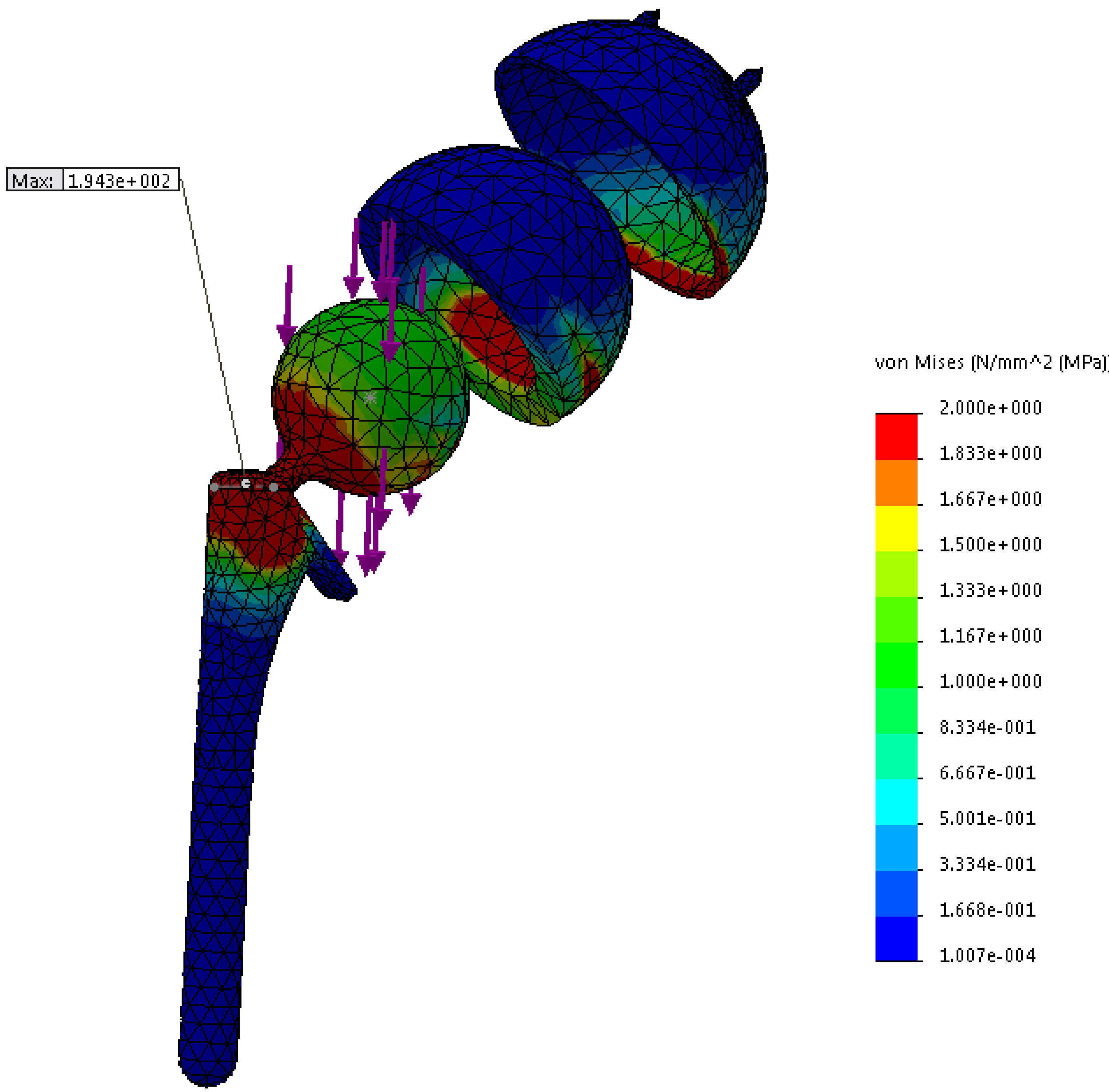

Figure 5: Contact pressure vector plot for walking with a rollator

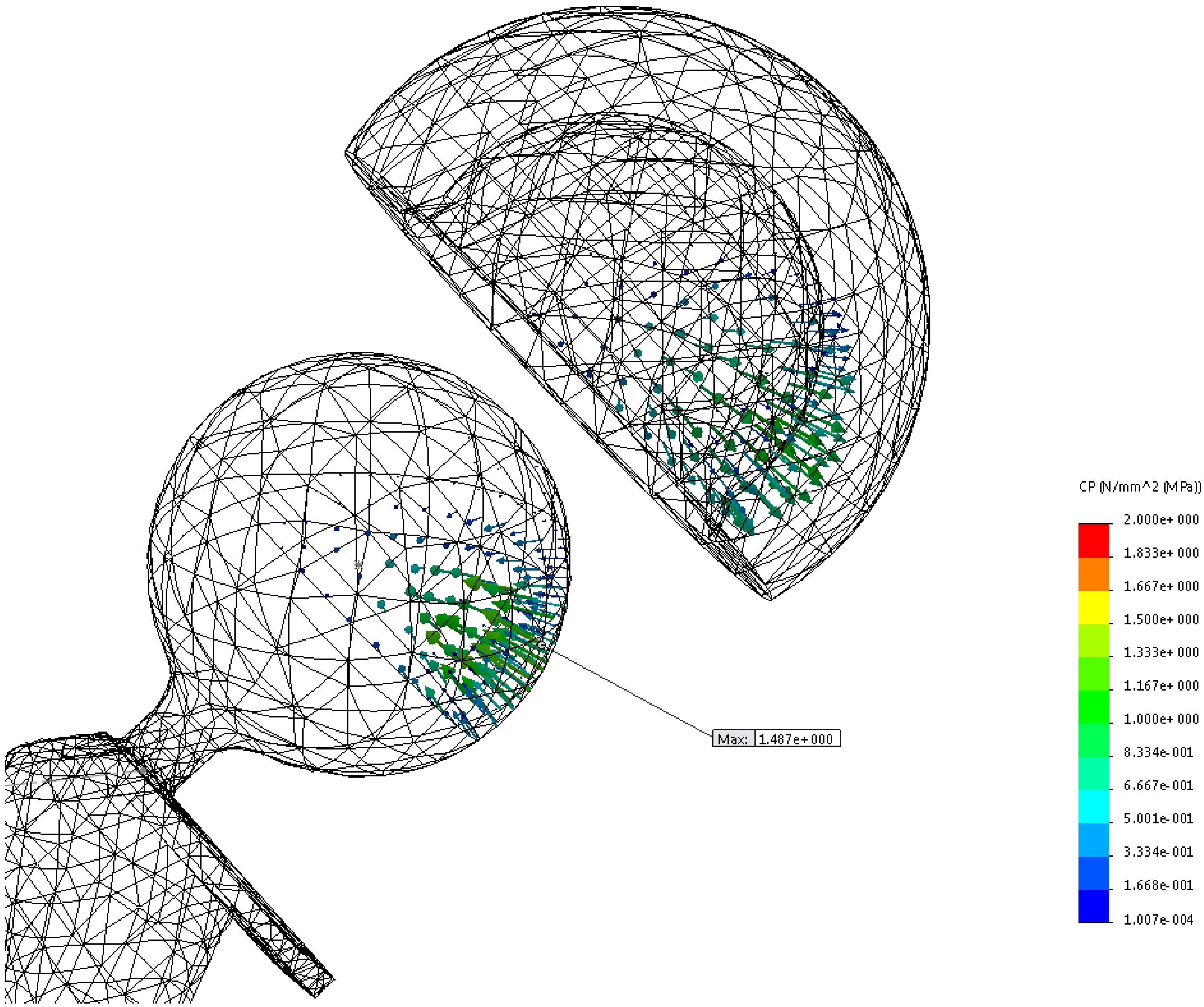

Figure 6: Contact pressure vector plot for getting into a car

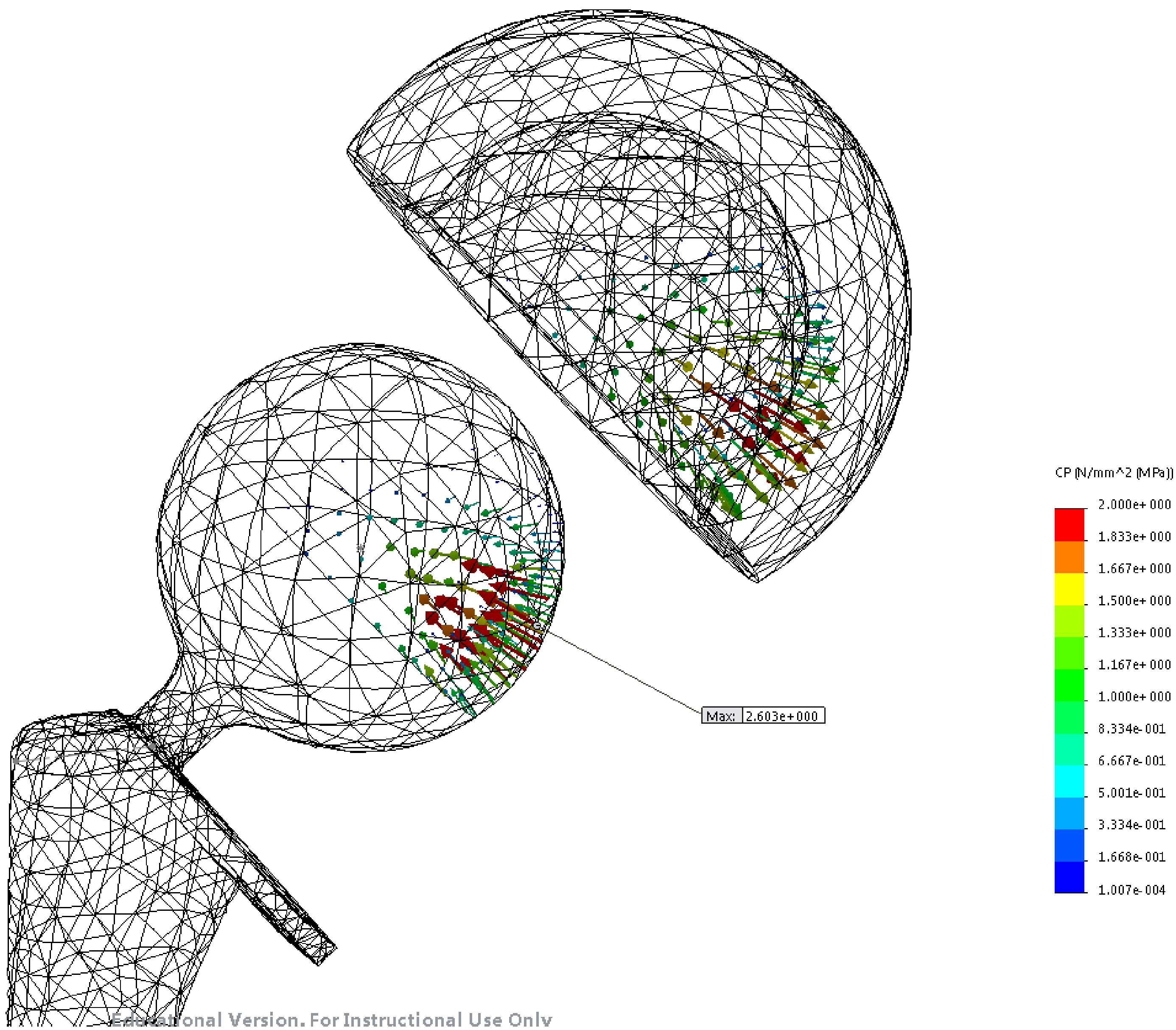

Figure 7: Contact pressure vector plot for stair climbing with a handrail

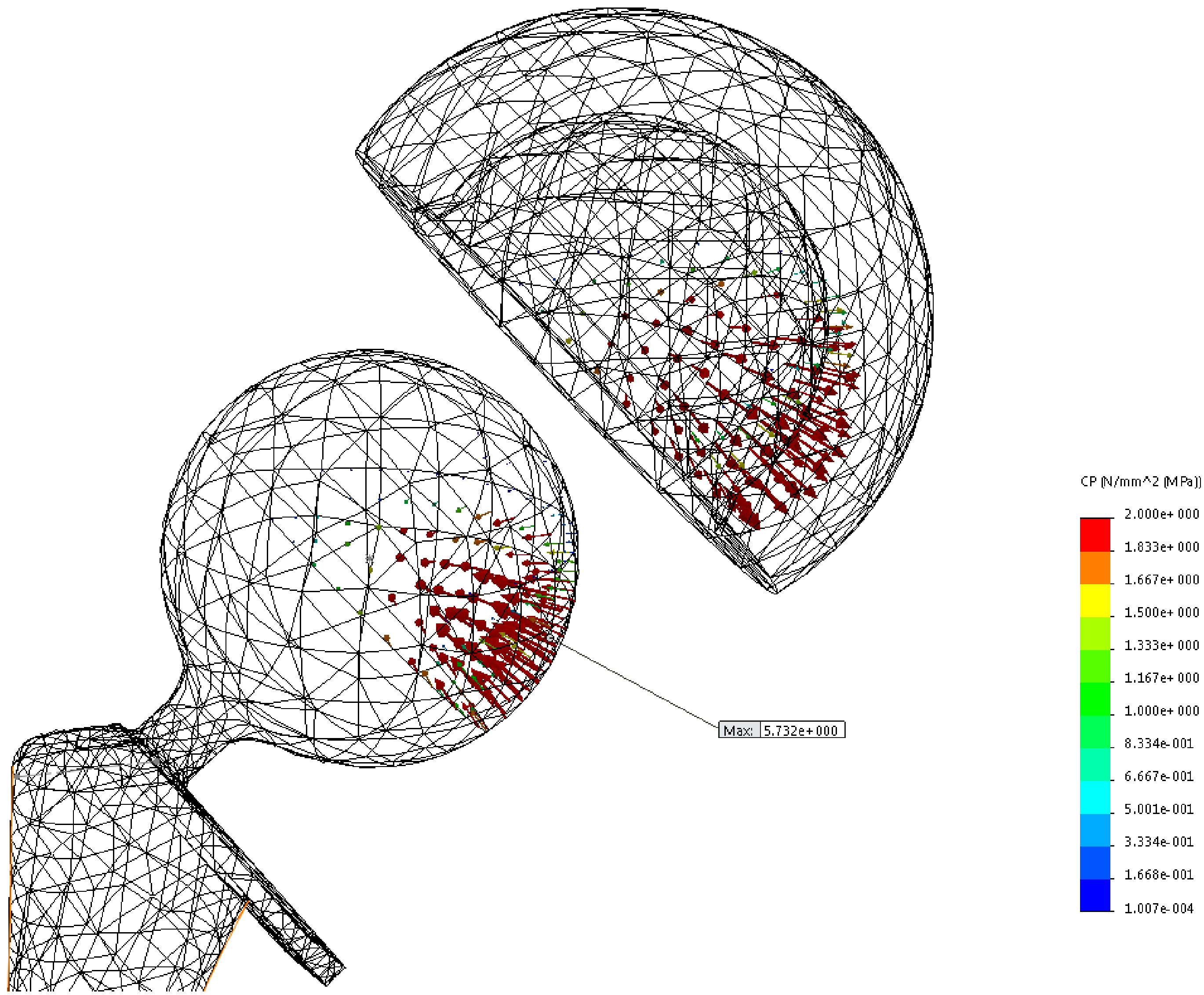

Table 2 shows the maximum von Mises stress and maximum contact pressure acting on the prosthesis.

Activity	von Mises stress (MPa)	Contact Pressure (MPa)
Walking with rollator	5.04	1.49
Getting into a car	8.82	2.60
Stair climbing with hand rail	19.43	5.73

For each loading configuration, the maximum von Mises stress was located near the neck where the ball connects to the stem. The maximum contact pressure occurs between the ball and the inner cup for each loading configuration. The yield strength of the materials was not exceeded under any loading configuration.

To test convergence, the maximum von Mises stress was tracked through five different simulations of the stair climbing loading configuration. Figure 4 shows how the maximum von Mises stress changes based upon the size of the mesh.

Figure 4: Effect of mesh size on convergence of maximum von Mises stress

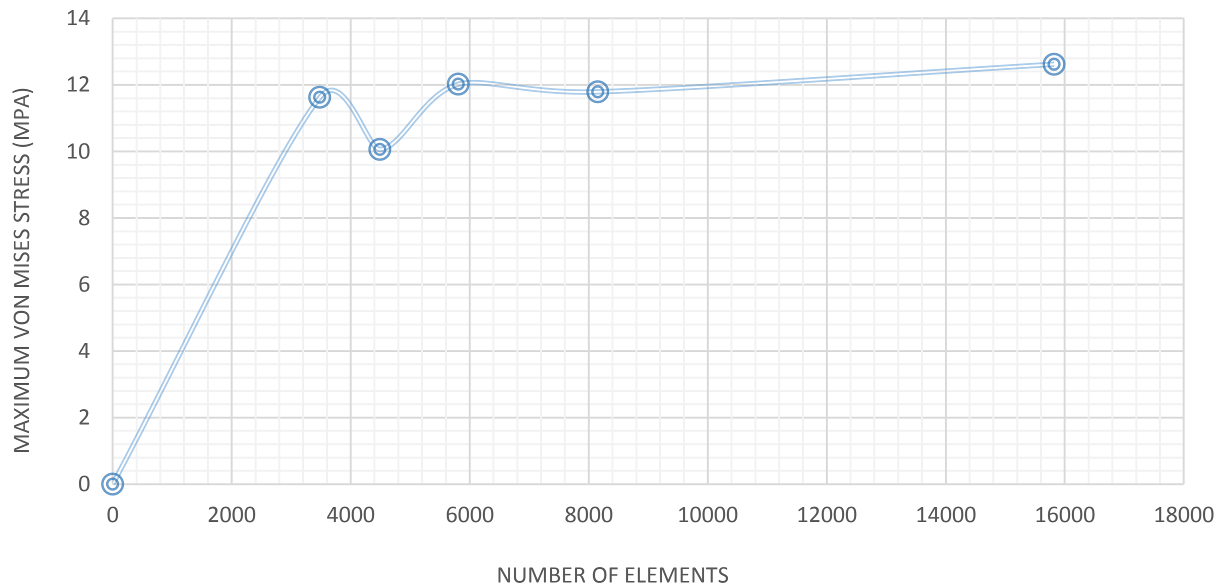

Table 2: Convergence information

Elements	Max von Mises Stress	Percent Difference between iterations
3483	11.63	0
4493	10.06	14.48
5810	12.02	17.75
8156	11.79	1.93
15821	12.62	6.80

Discussion

Based upon the simulation results, the maximum stress while walking with a rollator is 5.04 MPa. The maximum stress while getting into a car is 8.82 MPa, and the maximum stress while climbing stairs while using a handrail is 19.43 MPa. The point of maximum stress occurs at the same place on each part – the neck that connects the ball to the stem. The yield strength of the stem is 103 MPa, so the prosthesis is safe under all loading conditions. For the stair climbing configuration, the maximum von Mises stress converges to 12.62 MPa.

The results of this study show that the implant is safe under all loading conditions, however other loading configurations should be tested and compared to the results presented in this study. It is also recommended that other metrics for convergence such as the average stress on a surface.