

Computational modelling of forces acting on the femur in acetabular fractures: A finite element analysis study

Mark J. Berney^{a,*}, John Gibbons^{a,b}, Ms Karen Fitzgerald^c, Dr Philip Cardiff^d, Michael Leonard^e

^a Connolly Hospital, Dublin, Ireland

^b Tallaght Hospital, Dublin 24, Ireland

^c School of Mechanical & Materials Engineering, University College Dublin, Ireland

^d Bekaert Lecturer in Materials Processing, School of Mechanical & Materials Engineering, University College Dublin, Ireland

^e Consultant Surgeon in Trauma and Orthopaedics, Tallaght Hospital, Dublin 24, Ireland

ARTICLE INFO

Keywords:

Acetabulum
Trauma
Orthopaedic
Finite element

ABSTRACT

Background: The rising incidence of acetabular fractures in the elderly presents an increasing surgical challenge due to patient co-morbidities, complex fracture patterns and osteoporotic bone. Of interest in this study are those of the quadrilateral plate, which are more common in elderly patients with osteoporosis. Following such injuries, the weight-bearing surface of the femoral head moves medially. Non-operative management of these fractures can lead to the acetabulum articulating on the femoral neck increasing the risk of subsequent femoral neck fracture as a result of the altered biomechanics.

Using finite element analysis (FEA) this study seeks to understand the changing biomechanics of the proximal femur in such instances and to determine if there is a threshold of femoral head medialisation that can predict probability of femoral neck fracture.

Methods: A femoral neck FEA model was created from the CT and MRI scans of a healthy hip. Using FEA, the model was used to apply point loading to the femoral head at the anatomical weight bearing area and subsequent lateralization of this point down to the femoral neck-shaft junction. This simulates the changing forces acting on the femur as the head medialises into a fractured acetabulum.

Results: As the point of contact moved laterally the stress levels within the proximal femur increased steadily, particularly along the superior neck. Bending moment at the medial neck shaft junction also increased. This increase in stress levels can be seen as a corollary for risk of fracture within the femur.

Conclusion: With medialisation of the femur into a fractured acetabulum there is a significant change in the stress distribution within the femoral neck. Clinically, this indicates that patients with such injuries are at an increased risk of femoral neck fractures once they begin to mobilise after the initial injury, a devastating result. This model may be of use to treating surgeons in predicting the risk of femoral neck fracture.

1. Introduction

Acetabular fractures secondary to minor trauma in patients with osteoporosis is becoming increasingly common, Mears et al. (1999) predicted that by 2010 geriatric patients would represent the majority of acetabular fractures.^{1,2} A study by Ferguson et al. (2010), reviewing acetabular fractures between 1980 and 2007 found that the percentage of displaced acetabular fractures in patients > 60 years old increased from 10% to 24% of the total number of displaced acetabular fractures in patients of all ages.³ In elderly patients, with significant co-morbidities and lower functional demand, combined with more challenging

fracture patterns, the decision to operate must be made carefully. As such, acetabular fractures in the elderly continue to represent a complex surgical challenge to surgeons treating such injuries.

Acetabular fractures involving the quadrilateral plate are a heterogeneous group, not currently defined by a classification system. The relative incidence of such fractures is increasing secondary to the rise in osteoporotic acetabular injuries.⁴ These fractures are of interest to this study as fractures of the quadrilateral plate leads to medialisation of the femoral head. Consequently, the relative weight-bearing surface of the femoral head moves laterally changing the hip biomechanics (Fig. 1). In patients with such fractures treated non-operatively the subsequent

* Corresponding author.

E-mail addresses: Markberney@rcsi.com (M.J. Berney), jgibbo@gmail.com (J. Gibbons), karen.fitzgerald@ucdconnect.ie (M.K. Fitzgerald), philip.cardiff@ucd.ie (D.P. Cardiff), mikeleonard77@gmail.com (M. Leonard).

<https://doi.org/10.1016/j.jor.2019.06.004>

Received 27 November 2018; Received in revised form 22 April 2019; Accepted 2 June 2019

Available online 04 June 2019

0972-978X/ © 2019 Professor P K Surendran Memorial Education Foundation. Published by Elsevier B.V. All rights reserved.



Fig. 1. Fracture of the quadrilateral plate with medialisation of the left femoral head.



a

Fig. 2a. Fracture of quadrilateral plate with medialisation of femoral head.



b

Fig. 2b. Femoral neck fracture.



c

Fig. 2c. Post-operative imaging of acetabular ORIF and total hip arthroplasty.

medialisation of the femur can lead to the acetabulum articulating on the femoral neck once the patient begins to mobilise. As the National Referral Centre for Acetabular and Pelvic Trauma, this is a situation that has presented to the unit with ipsilateral femoral neck fractures after mobilization of the initially conservatively managed patient (Fig. 2a–c).

Little is understood of the stresses induced in the femur with the change in position within the acetabulum. The hypothesis of this study is that these femur fractures were due to the changing biomechanics within the hip.

Computational modelling has progressed significantly since Brekelman et al. (1972) first developed a 2D finite element model of the femur in the 1970s.⁵ Many modern model geometries are now created from patient-specific CT or MRI images.^{6,7} Material properties can now be assigned based on the Hounsfield unit of the voxels of CT images to better model the non-uniform distribution of bone properties relative to older models which assumed isotropic properties.^{8,9}

The study aim was to investigate the changing biomechanics acting on the proximal femur following acetabular fractures. The primary objective was to assess the changes in stress levels and distribution within the femur. The level of stress induced will be seen as a corollary of its risk of fracture. This will have direct clinical application with regards to predicting the fracture characteristics likely to cause fracture and the sites most at risk.

2. Methods

To simulate the medialisation of the femoral head into the acetabulum, this model was loaded at ten discrete points beginning on the superior surface of the femoral head (point of contact of acetabulum from CT) with subsequent points moving laterally down the neck. This simulates the changing point of contact between the acetabulum and femur in quadrilateral plate fractures, as described above. The changing forces acting on the femur were then analysed.

Previous work carried out by Cardiff et al. (2014) involved the creation of a 3-D model of the hip joint from the CT and MRI scans of a healthy 23-year old male subject with no congenital or acquired pathology.¹⁰ For this study, the proximal femur of this model was used. Volume meshing was then carried out to divide the model into small discrete elements for analysis using ABAQUS (ABAQUS FEA Version 6.14 by Dassault Systems), a commercially available FEA software system (Fig. 3).

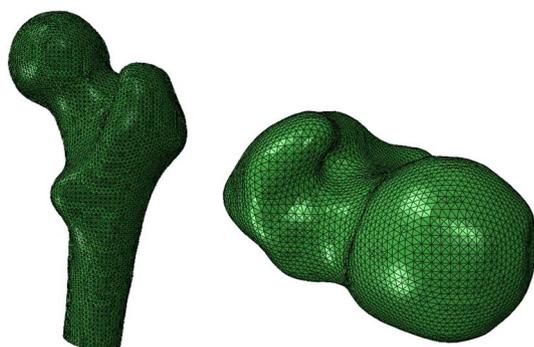


Fig. 3. Model geometry with meshing.

Material properties (Young's Modulus, Poisson ratio) were then applied to each element based on its Hounsfield unit. This technique has been widely used in recent literature and provides for closer approximation of bone properties in complex bone geometries when compared to homogenous material property application seen in earlier studies.^{5,7} To create this CT-based model, the software application BoneMat (BoneMat v 3.2) was used.

3. Model constraints

Before any model simulation can be created, boundary conditions and constraints must be set. For this analysis, it was decided that the femur would remain static with its base fixed and a point load would be applied at each reference point along the axis of interest. The position of the femur and loads is modelled as that of the mid-stance phase of gait when peak loads are reached during ambulation.¹¹ The load applied was 1917 N. This load was taken from Cardiff et al. (2014).¹⁰ A model was created for each point with the load applied at that point and the changing stress within the femur analysed (Figs. 4 and 5). In this way, the changing load on the femur when it medialises into the acetabulum was modelled.



Fig. 4. Image showing boundary constraints (fixed base) and points of contact superiorly.

4. Data collection

Ten simulations were carried out. Each simulation modelled a point load on the femur and the stresses induced by this load were analysed using the ABAQUS FEA software.

For each model the visual representation of the von Mises stress distribution in the femur was recorded, both in the antero-posterior view and a cranio-caudal view of femoral head and neck. Von Mises stress is a value used to determine if a given material will yield or fracture. The von Mises yield criterion states that if the von Mises stress of a material under load is equal or greater than the yield limit of the same material under simple tension then the material will yield. These models of the stress within the femur provides a very useful insight into how the stress is distributed within the femur when placed under loading conditions. In each simulation, the von Mises stress was recorded at all ten points. This was carried out to determine the changing stresses along the femoral neck with the change in the position of the point of contact for the load (Table 1).

5. Assumptions

Only the proximal femur geometry was used. The acetabular component was excluded. The other components of the hip; cartilage, and synovial fluid were also excluded. With regard to boundary conditions, the femur was modelled as a free-standing static structure which was only fixed at its base. Also, the load was modelled at a single point of contact rather than a distributed load across the femoral head and neck.

6. Results

Reviewing the stress contours on the simulations (see Appendix) it can be seen that the peak stress when the femur is loaded at Point 1 and Point 2 is on the inferior aspect of the femoral neck. This is due to compression in that region secondary to the bending moment of the load acting on the femoral head. In all points loaded, the stress on the neck is focused more on the postero-inferior portion of the neck rather than anteriorly. As the point of loading moves laterally the stress levels measured on the neck increase. It is interesting to note that as the loading point moves laterally the stress induced in the inferior portion of the femoral neck decreases. This is most likely due to reduced compressive force in this area as the bending arm of the load decreases as the point of contact moves laterally. Altering the stress distribution acutely makes the femoral neck more susceptible to fracture as there is no time for bone remodelling in accordance with Wolff's Law.

When reviewing Figs. 6 and 7, the large peaks of stress demonstrate the point at which the load is being applied for each plot. This distortion from large point stresses (up to 500 MPa) makes interpreting the graph more challenging. However, it can be seen that loads at the head-neck junction and points on the medial neck (Points 4–8) produce greater levels of stress along the femoral neck (Points 5–8). This is significant as it suggests that the medialisation of the femoral head does indeed induce increased stress levels within the femoral neck.

7. Discussion

The primary objective of this study was to investigate the changing biomechanics within the proximal femur caused by the medialisation of the femoral head in acetabular fracture involving the quadrilateral plate. Reviewing the images showing the stress distribution, it can be seen that as the load on the femur moves laterally the level of stress increases along the femoral neck. The true distribution of the stress on the femoral neck

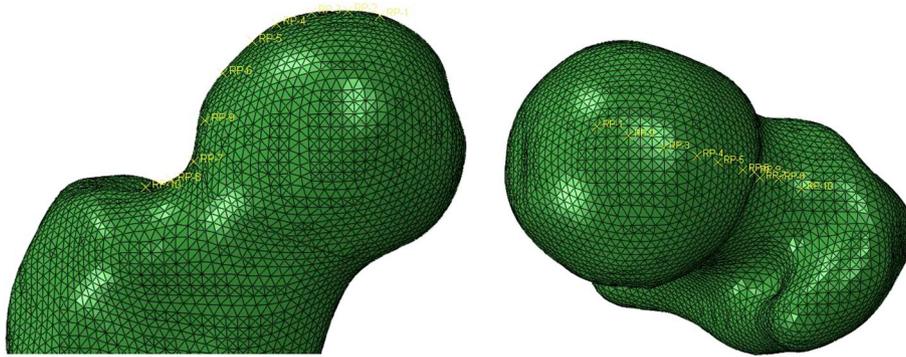


Fig. 5. Points of contact 1–10 in AP and cranio-caudal views.

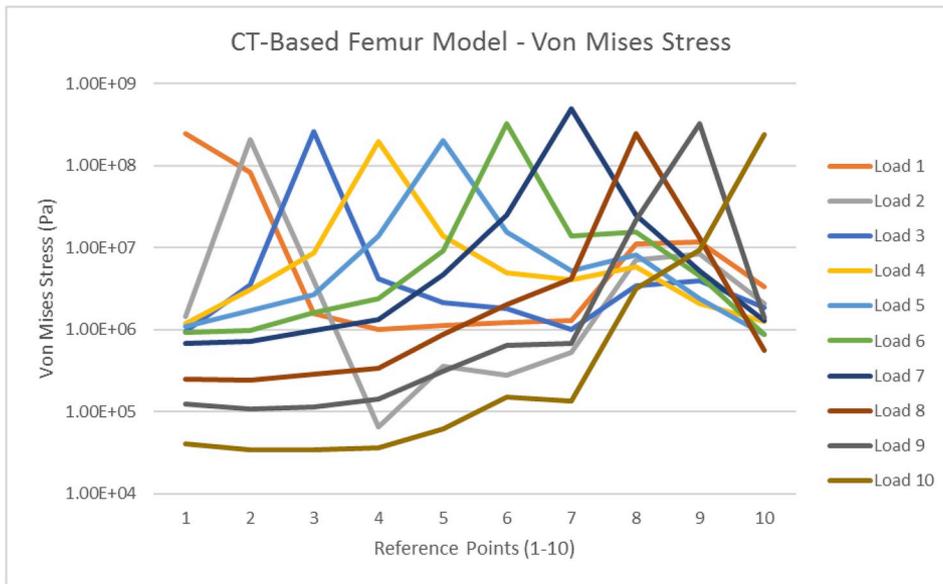


Fig. 6. Plots of Von Mises Stress for each Load applied (Points 1–10).

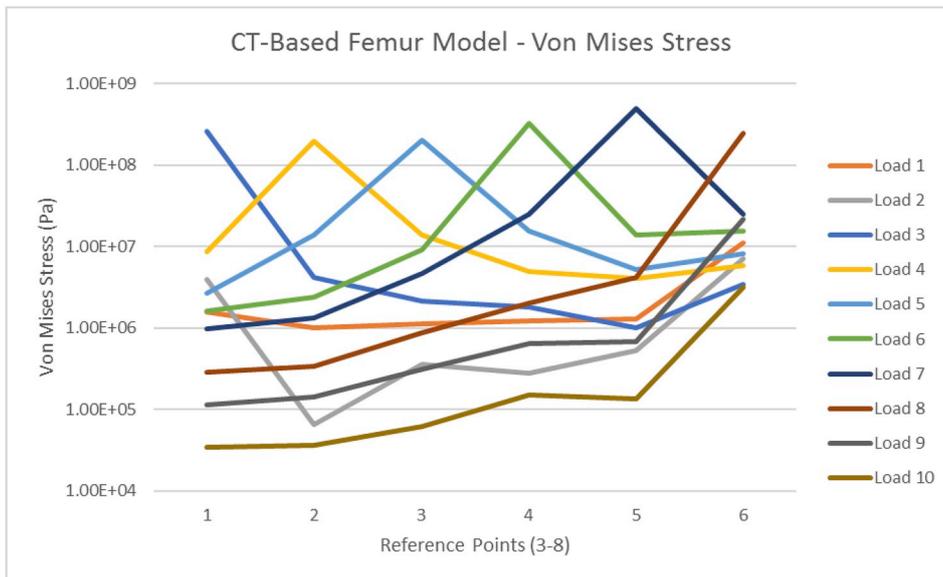


Fig. 7. Plots of Von Mises Stress for each Load applied (showing only points 3–8).

in such injuries is made difficult to appreciate in these models due to the significant distortion caused by the area of very high stress at the point of contact, however, in Fig. 6 above demonstrating the distribution of stress along the femoral neck with each load, it can be seen that the loads on the lateral aspect of the femoral head and femoral neck (Point 5–7) cause increased stress along the whole of the neck when compared to loading on the medial aspect of the head (Point 1–3) or the far lateral position (Point 9 and 10). Interestingly, when the load moves laterally away from the neck (Points 9 and 10) the stress on the neck is significantly less than more medial loads. This would suggest that while the acetabulum articulating with the femoral neck leads to increase stress within the neck of the femur, if the femur medialises so that the acetabulum begins to articulate with the lateral neck-shaft junction, the stress levels within the neck decrease again. Certainly, this is not likely to present in a clinical setting but is rather a point of note from these simulations.

From a clinical stand-point this study demonstrates that medialisation of the femoral head in acetabular fractures does increase stress on the femoral neck as the acetabulum articulates with it on weight bearing. The femur is designed to take the load in the normal anatomical position with the lines of the trabeculae such that load-bearing in this position is optimised.¹² When the load is moved laterally in an acute manner the femur does not have the time to remodel according to Wolff's Law and therefore this level of increased stress on the femoral neck may very likely predispose it to fracture particularly in the elderly who are already at increased risk of femoral neck fracture due to pre-existing osteoporosis.

FEA analysis is an increasingly powerful tool in the armamentarium of engineers and orthopaedic surgeons who are keen to gain a better understanding of the biomechanical behaviour of systems within the body as they relate to orthopaedic issues. This study presents a new approach to gaining an understanding of the changing biomechanics within the hip caused by acetabular fractures. As discussed in the introduction, acetabular fractures are complex in nature and with an increasingly ageing population, the best course of management is not always clear. This study can be seen as a proof of concept in the development of FEA analyses for the investigation of the effect such fractures have on the proximal femur. The strengths of this study include the use of a model geometry created from the CT of a real hip rather than an idealised model. Similarly, the use of a CT-based model with material properties based on bone density on CT-scan provides an excellent model to closely approximate the true properties of the femur.

In conclusion, this study gives a better understanding of the changing biomechanics within the proximal femur caused by acetabular fractures. It supports the hypothesis that there is increased stress locally on the femoral neck when the femoral head medialises through the fractured acetabulum. This level of increased stress on the femoral neck must be responsible for the femoral neck fractures that were seen in our patients. The management of acetabular fractures in the elderly is challenging with no universally agreed approach. If the decision is made to manage a patient conservatively then early assisted weight-bearing as tolerated is recommended to avoid the recognised complications of immobilisation.¹³ Our study highlights the importance of recognising the increased risk of femoral neck fracture with femoral head medialisation. This information has the potential to be of value to the treating surgeon when deciding on the treatment plan and when counselling the patient and their families. However, further studies will need to be undertaken to gain a more in-depth understanding of this issue which may then be used to guide management of such injuries in the future.

Sources of financial support

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest

The authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. For this type of retrospective study formal consent is not required. This article does not contain any studies with animals performed by any of the authors.

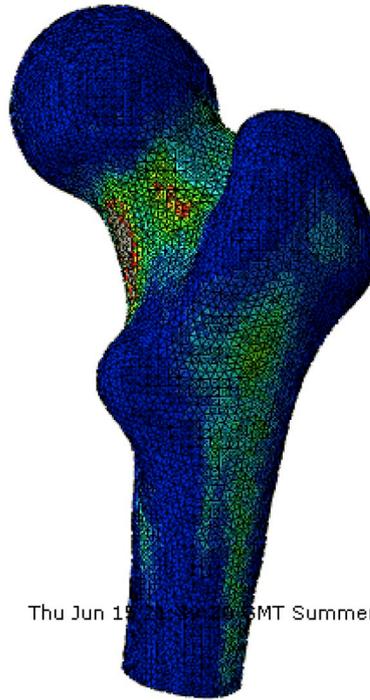
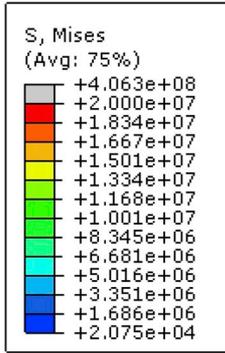
Acknowledgements

None.

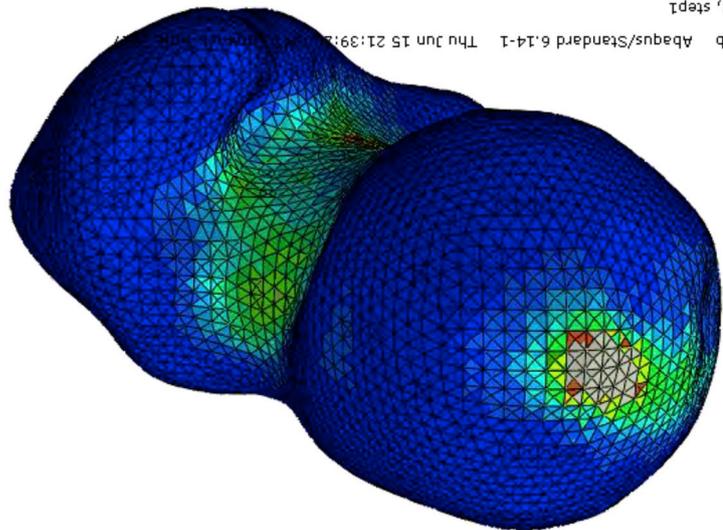
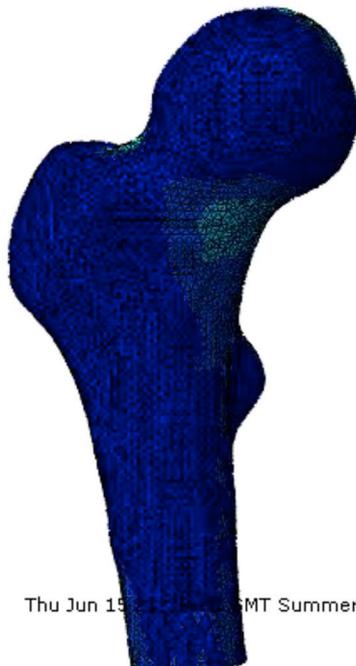
Appendix

Results

Contour Stress Scale: 0–20 MPa (20,000,000 Pa).



Pt1
ODB: Pt1.odb Abaqus/Standard 6.14-1 Thu Jun 15 21:39:22 GMT Summer Time 2017
Step: Step-2, step1
Increment 1: Step Time = 1.000
Primary Var: S, Mises



db Abaqus/Standard 6.14-1 Thu Jun 15 21:39:22 GMT Summer Time 2017
2, step1
1: Step Time = 1.000
r: S, Mises

14-1 Thu Jun 15 21:39:22 GMT Summer Time 2

in

Image 1. Visual Representation of von Mises Stress Under Load at Point 1

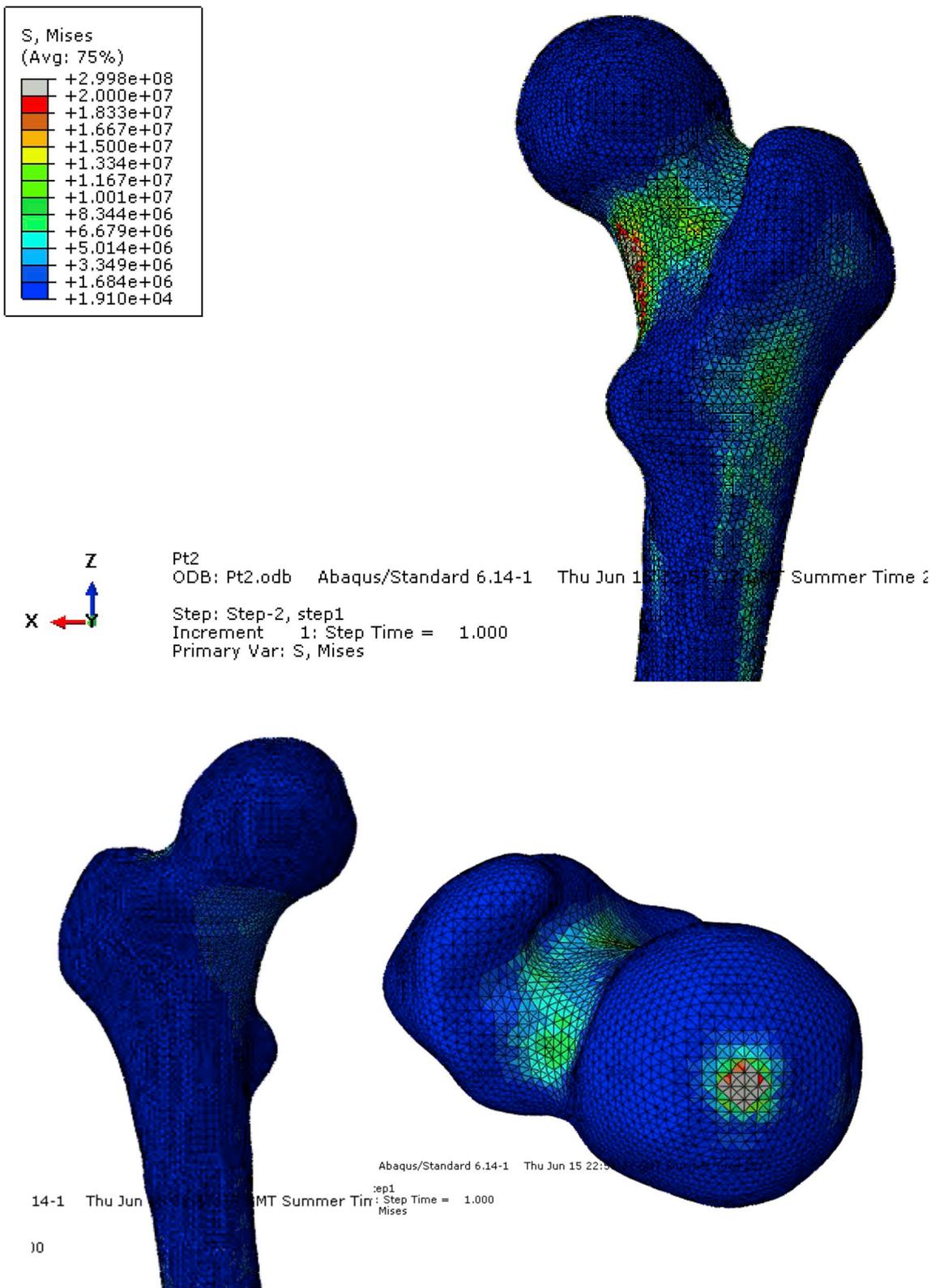


Image 2. Visual Representation of von Mises Stress Under Load at Point 2

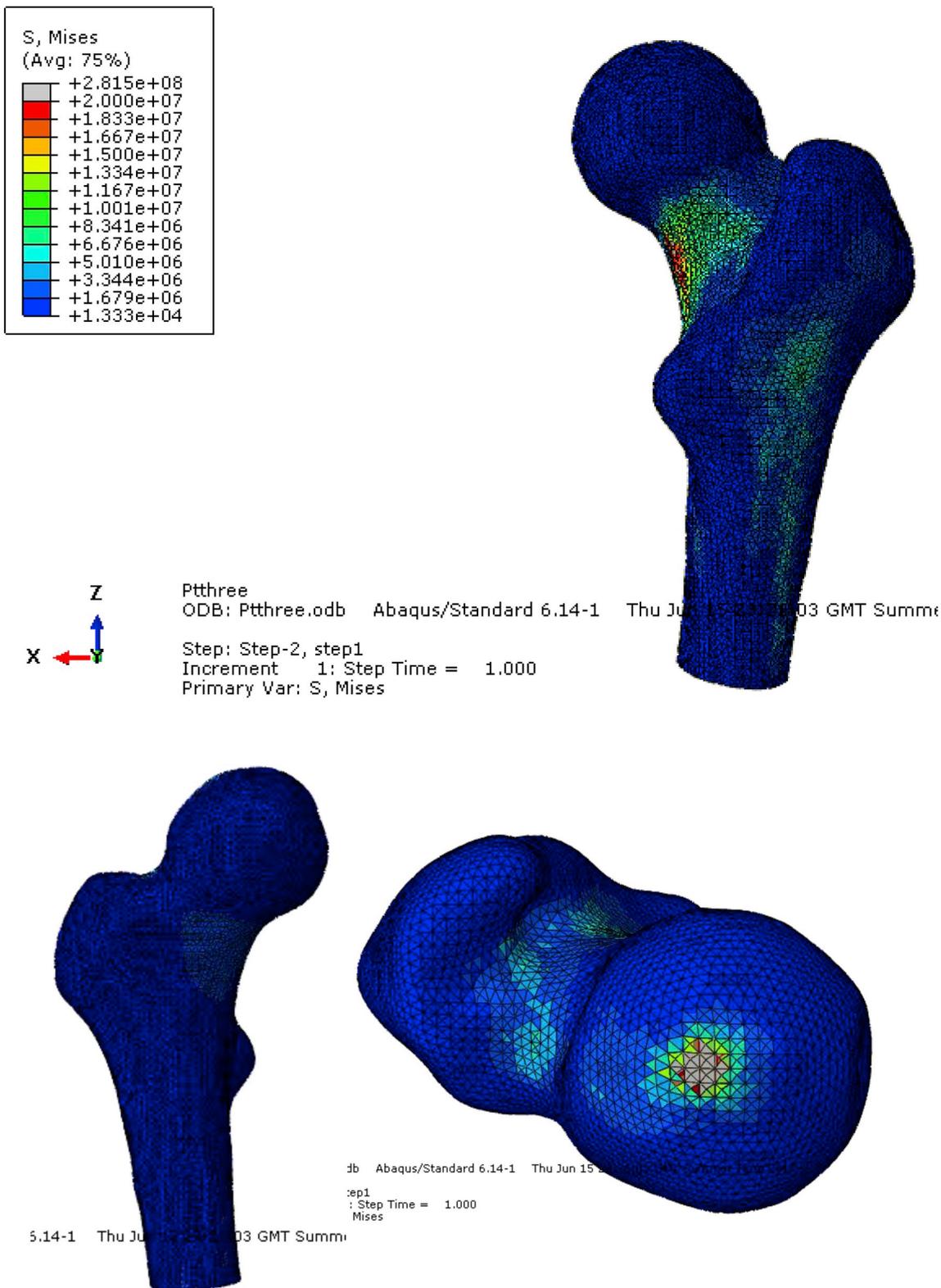


Image 3. Visual Representation of von Mises Stress Under Load at Point 3

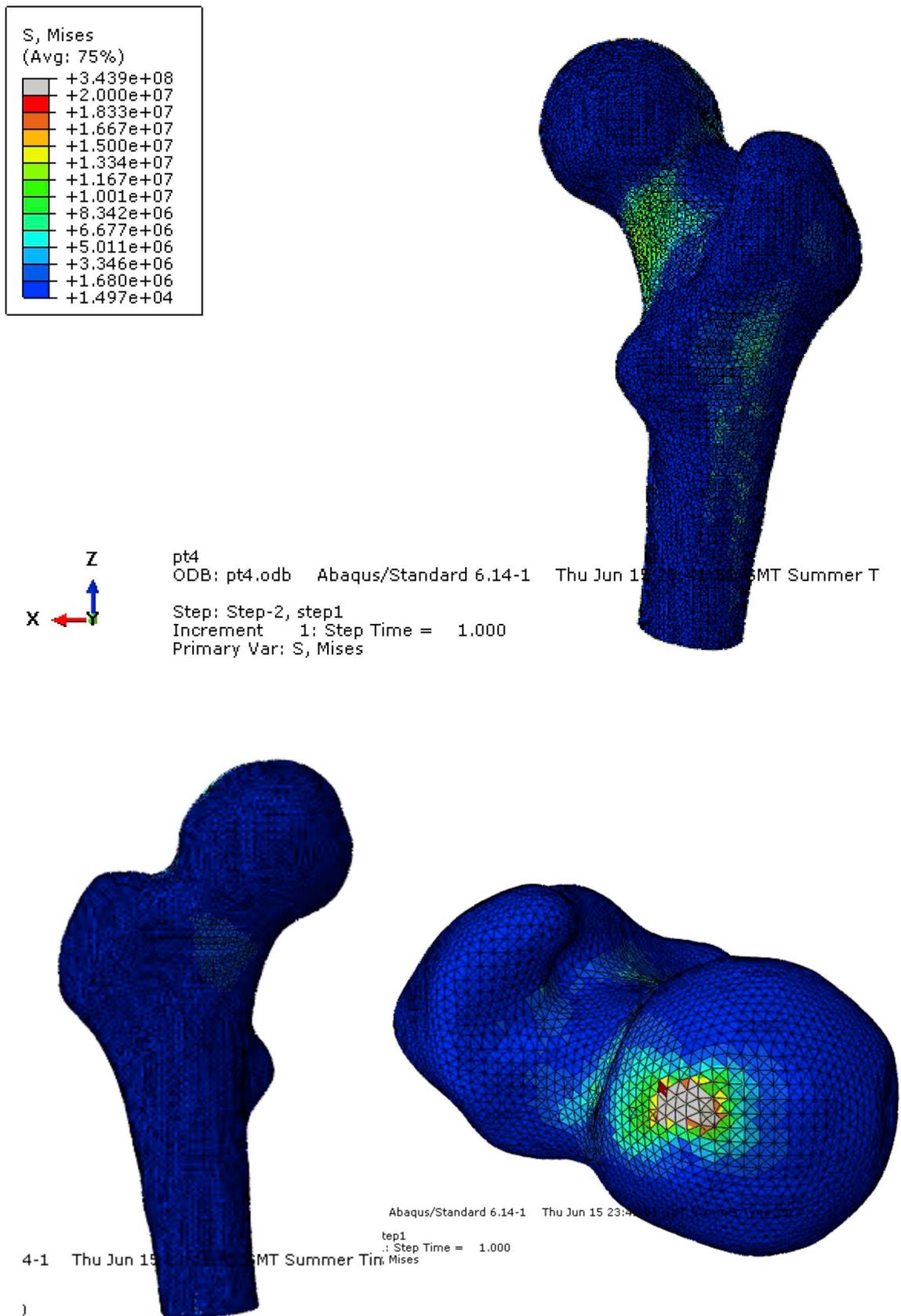


Image 4. Visual Representation of von Mises Stress Under Load at Point 4

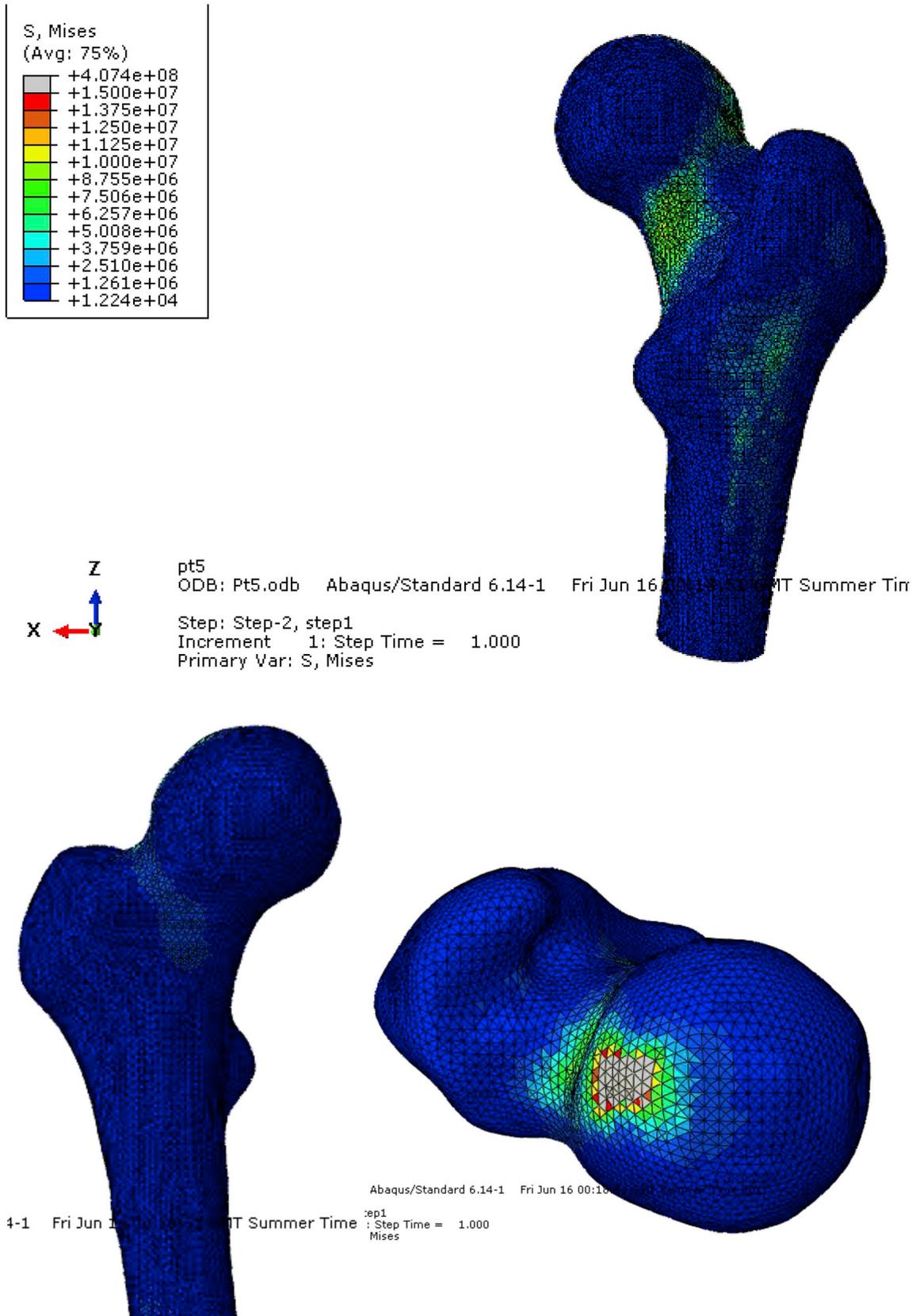


Image 5. Visual Representation of von Mises Stress Under Load at Point 5

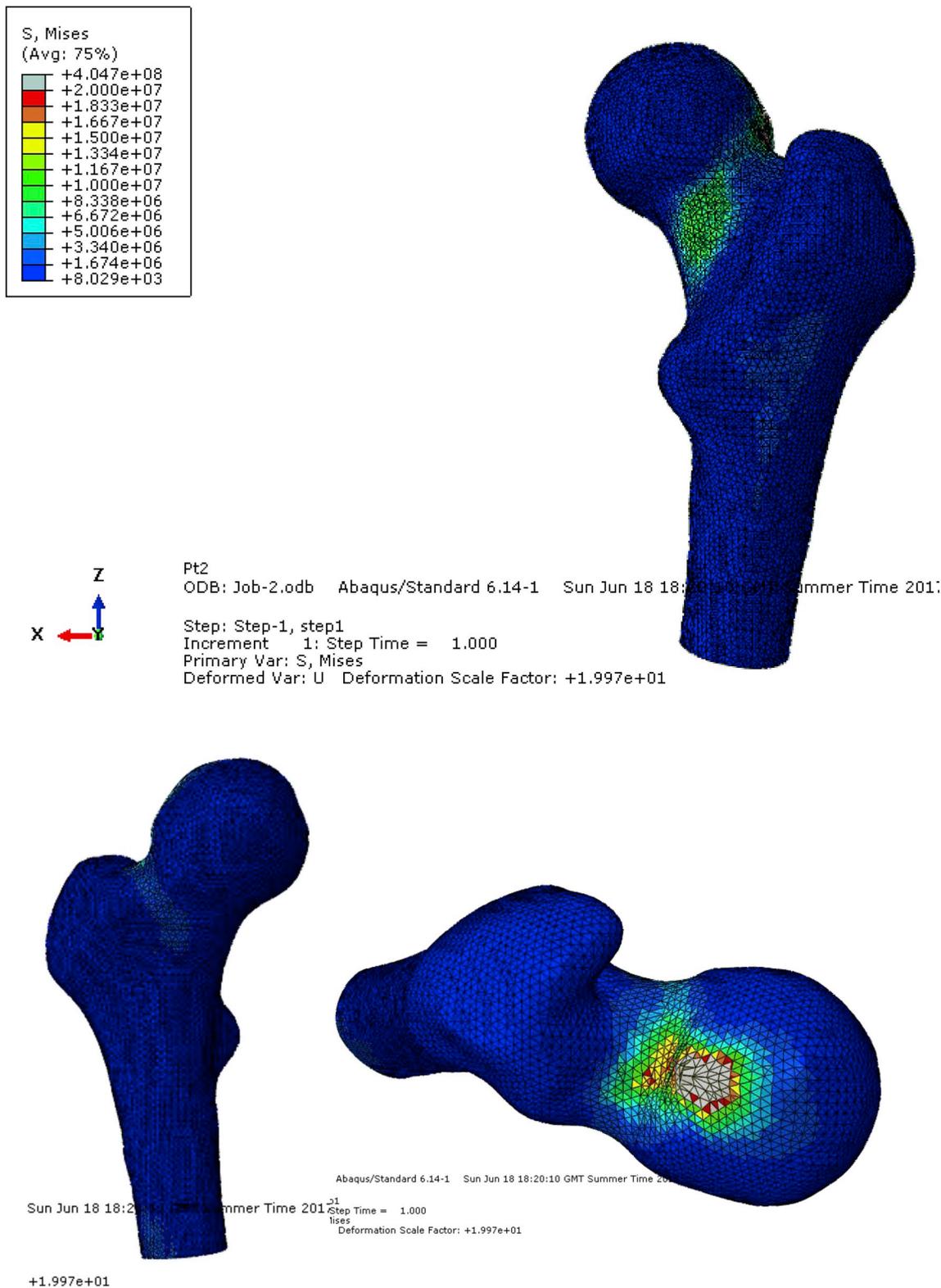


Image 6. Visual Representation of von Mises Stress Under Load at Point 6

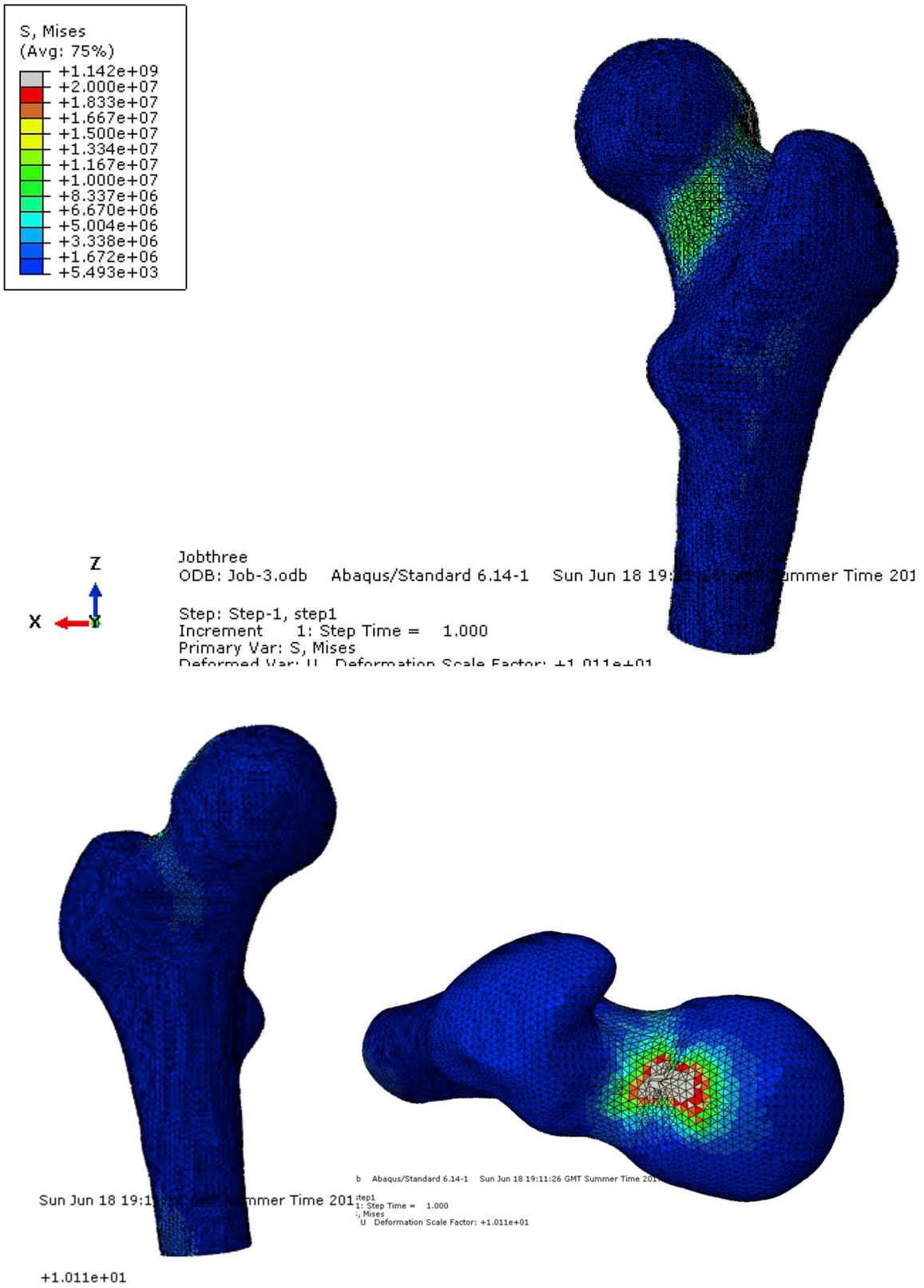


Image 7. Visual Representation of von Mises Stress Under Load at Point 7

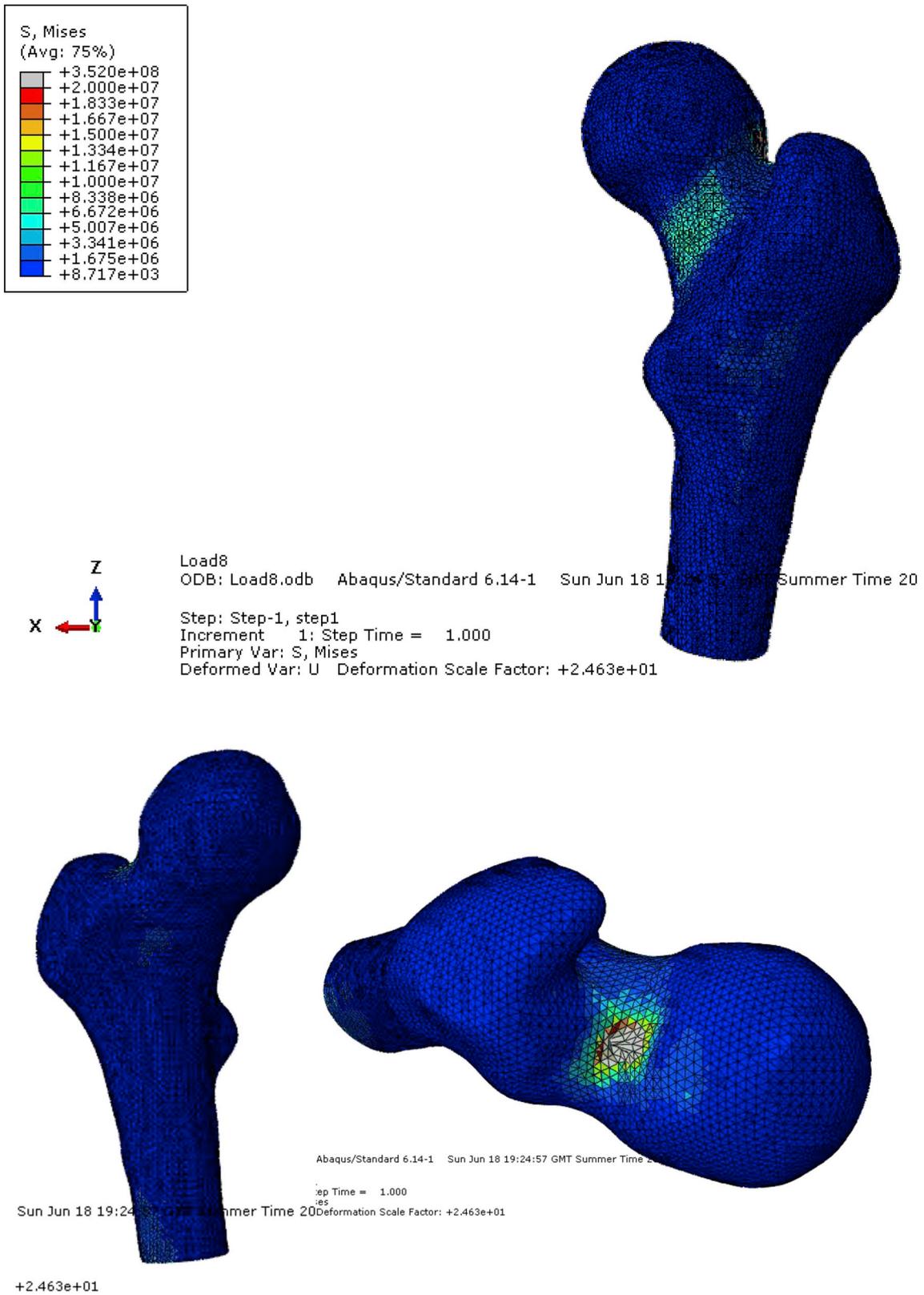


Image 8. Visual Representation of von Mises Stress Under Load at Point 8

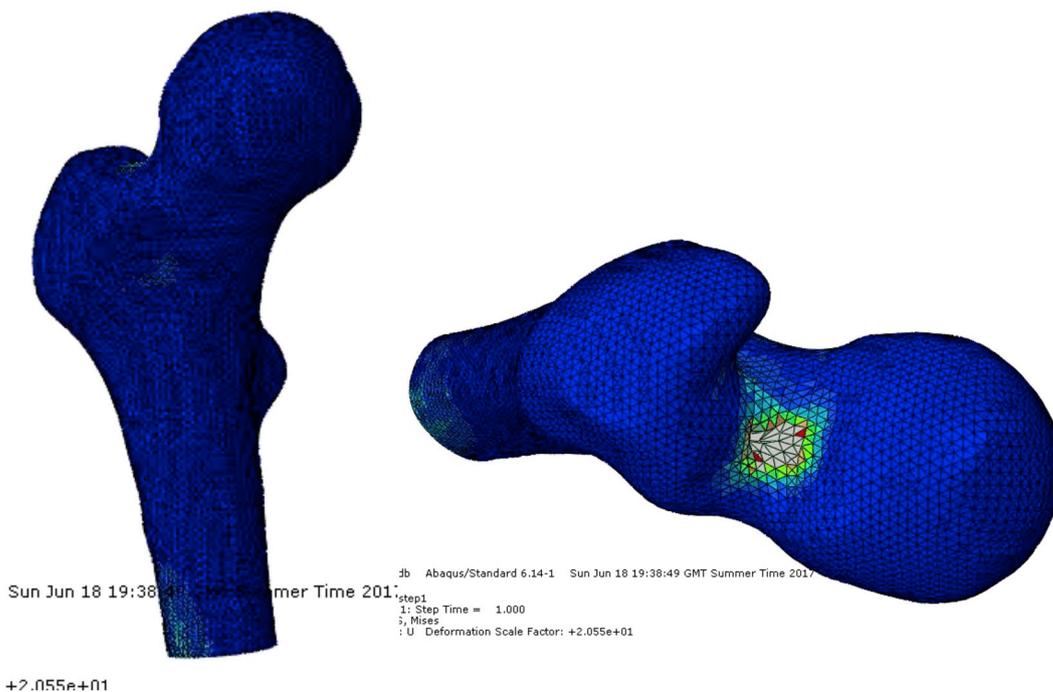
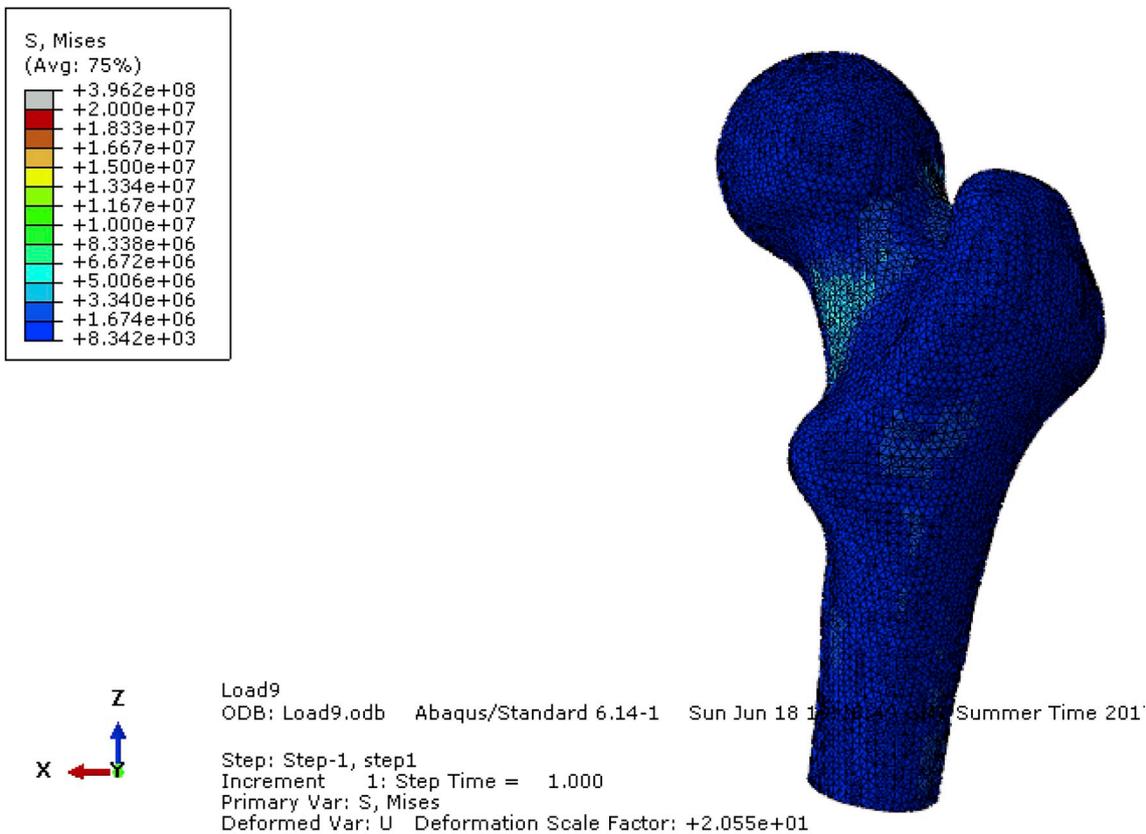


Image 9. Visual Representation of von Mises Stress Under Load at Point 9

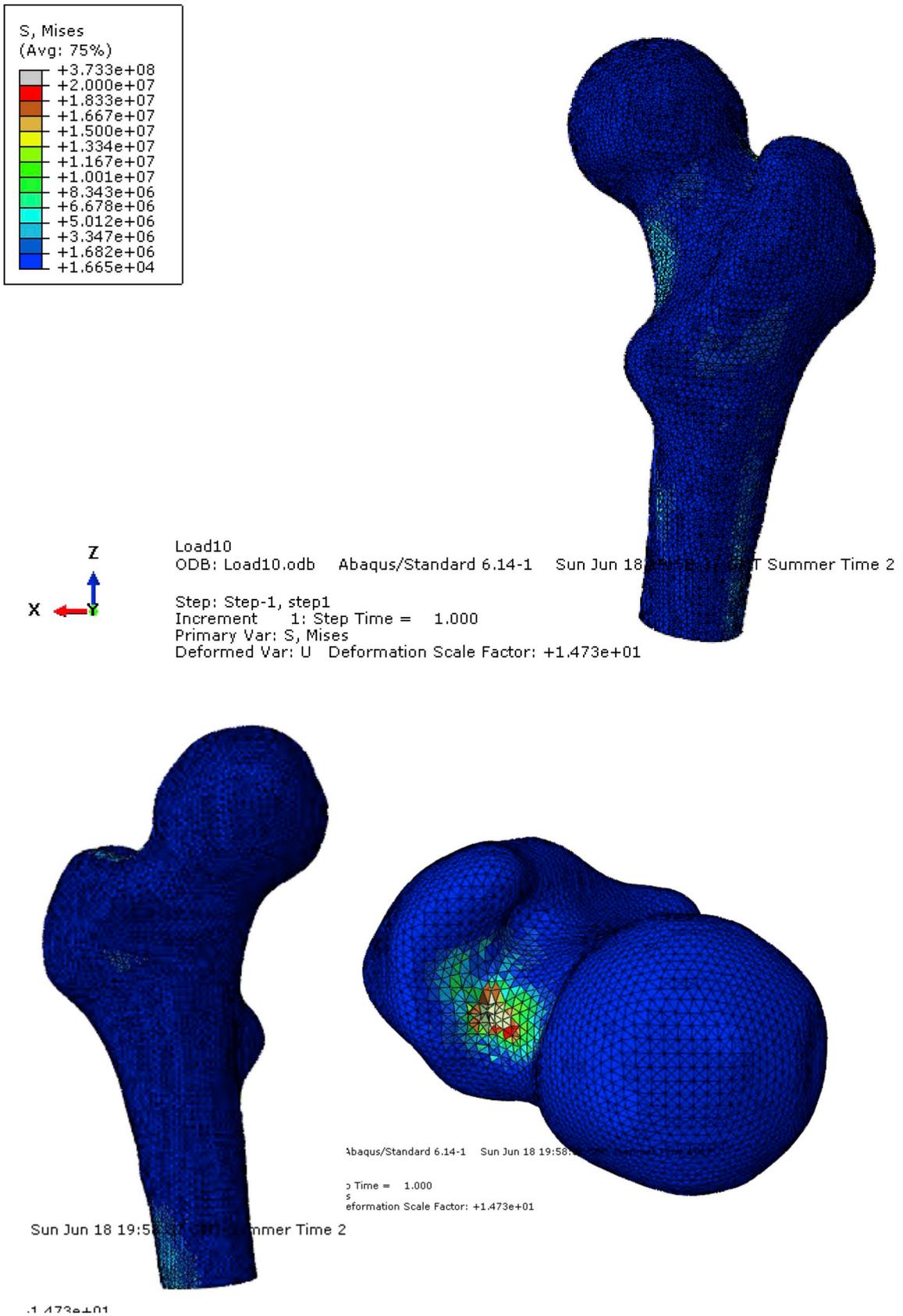


Image 10. Visual Representation of von Mises Stress Under Load at Point 10

Table 1
Von Mises Stress measured at Point 1–10 with each Load applied.

| | LOAD 1 | LOAD 2 | LOAD 3 | LOAD 4 | LOAD 5 | LOAD 6 | LOAD 7 | LOAD 8 | LOAD 9 | LOAD 10 |
|----------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| POINT 1 | 2.44E + 08 | 1.47E+06 | 9.42E+05 | 1.20E+06 | 1.10E+06 | 9.35E+05 | 679885 | 250074 | 123408 | 40269 |
| POINT 2 | 8.25E+07 | 2.07E + 08 | 3.50E+06 | 3.10E+06 | 1.70E+06 | 9.81E+05 | 712684 | 242087 | 108250 | 34212 |
| POINT 3 | 1.56E+06 | 4.00E+06 | 2.60E + 08 | 8.60E+06 | 2.70E+06 | 1.60E+06 | 994447 | 291188 | 114746 | 34961 |
| POINT 4 | 1.00E+06 | 6.64E+04 | 4.20E+06 | 1.96E + 08 | 1.40E+07 | 2.39E+06 | 1.33E+06 | 337502 | 143843 | 36280 |
| POINT 5 | 1.12E+06 | 358773 | 2.14E+06 | 1.40E+07 | 2.00E + 08 | 9.27E+06 | 4.68E+06 | 868995 | 312977 | 61751 |
| POINT 6 | 1.22E+06 | 281974 | 1.80E+06 | 5.00E+06 | 1.55E+07 | 3.24E + 08 | 2.53E+07 | 2.00E+06 | 651717 | 153486 |
| POINT 7 | 1.29E+06 | 529984 | 1.00E+06 | 4.10E+06 | 5.30E+06 | 1.40E+07 | 4.98E + 08 | 4.20E+06 | 682031 | 135656 |
| POINT 8 | 1.10E+07 | 7.20E+06 | 3.40E+06 | 5.90E+06 | 8.20E+06 | 1.55E+07 | 2.50E+07 | 2.49E + 08 | 2.20E+07 | 3.18E+06 |
| POINT 9 | 1.17E+07 | 8.40E+06 | 3.96E+06 | 2.10E+06 | 2.40E+06 | 4.50E+06 | 5.30E+06 | 1.30E+07 | 3.30E + 08 | 9.45E+06 |
| POINT 10 | 3.35E+06 | 2.06E+06 | 1.88E+06 | 1.27E+06 | 8.81E+05 | 8.81E+05 | 1.30E+06 | 5.67E+05 | 1.40E+06 | 2.40E + 08 |

References

- White G, Kanakaris NK, Faour O, Valverde JA, Martin MA, Giannoudis PV. Quadrilateral plate fractures of the acetabulum: an update. *Injury*. 2013;44(2):159–167.
- Mears DC. Surgical treatment of acetabular fractures in elderly patients with osteoporotic bone. *J Am Acad Orthop Surg*. 1999;7(2):128–141.
- Ferguson TA, Patel R, Bhandari M, Matta JM. Fractures of the acetabulum in patients aged 60 years and older: an epidemiological and radiological study. *J Bone Jt Surg Br*. 2010;92(2):250–257.
- Laflamme GY, Hebert-Davies J, Rouleau D, Benoit B, Leduc S. Internal fixation of osteopenic acetabular fractures involving the quadrilateral plate. *Injury*. 2011;42(10):1130–1134.
- Brekelmans WA, Poort HW, Slooff TJ. A new method to analyse the mechanical behaviour of skeletal parts. *Acta Orthop Scand*. 1972;43(5):301–317.
- Ota T, Yamamoto I, Morita R. Fracture simulation of the femoral bone using the finite-element method: how a fracture initiates and proceeds. *J Bone Miner Metab*. 1999;17(2):108–112.
- Yosibash Z, Padan R, Joskowicz L, Milgrom C. A CT-based high-order finite element analysis of the human proximal femur compared to in-vitro experiments. *J Biomech Eng*. 2007;129(3):297–309.
- Bessho M, Ohnishi I, Matsuyama J, Matsumoto T, Imai K, Nakamura K. Prediction of strength and strain of the proximal femur by a CT-based finite element method. *J Biomech*. 40(8):1745–1753.
- Chen G, Schmutz B, Epari D, Rathnayaka K, Ibrahim S, Schuetz MA, et al. A new approach for assigning bone material properties from CT images into finite element models. *J Biomech*. 43(5):1011–1015.
- Cardiff P, Karac A, FitzPatrick D, Ivankovic A. Development of a hip joint model for finite volume simulations. *J Biomech Eng*. 2014;136(1):011006.
- Bergmann G, Deuretzbacher G, Heller M, et al. Hip contact forces and gait patterns from routine activities. *J Biomech*. 2001;34(7):859–871.
- Li B, Aspden RM. Material properties of bone from the femoral neck and calcaneus of patients with osteoporosis or osteoarthritis. *Osteoporos Int*. 1997;7(5):450–456.
- Harper CM, Lyles YM. Physiology and complications of bed rest. *J Am Geriatr Soc*. 1988;36(11):1047–1054.