Human Foot Hitting a Soccer Ball Analysis Using Finite Element Methods

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Abstract: *This paper is related to using Finite Element Analysis to analyze the stresses in the human foot bones when hitting a soccer ball. The result is a determination of the optimal position to hit the ball to have minimal stresses in the foot bones. The results will not only show the direction the ball will travel, but how far it will travel as well. The stresses in the human leg bones are determined for each impact and compared. The primary goal of this research was to show the advantages of utilizing finite element analysis applications in sports. The results will show that accurate results can be attained if the simulations mimic the real case. All simulations are ran using Abaqus/Explicit*.

Keywords: *Abaqus/Explicit, Soccer, Velocity, Human Leg Bones, Finite Element Analysis*

1. Introduction

Soccer game, more commonly known as football, is a team sport played between two teams on a rectangular field with a spherical ball. It is played by 250 million players in over 200 countries, making it the world’s most popular sport. Players are not allowed to use their hands (except for goalkeepers), but mostly use their feet, head or torso to hit the ball.

In this analysis, we are simulating how much stress is in the human feet bones when hit a ball on three different relative positions in between the foot and the ball. For the simplicity of the simulation we have designed only the human feet bones with their properties for a middle age man. The soft tissues (ligament, tendon, joint capsule, flesh) were not modeled because it doesn’t affect this simulation too much. The ultimate goal of this paper is to do more simulations with soft tissues and footwear added to see how that reduce the stress in the bones.

This model has been solved in about 12 hours with 4-core, 24GB memory PC.

The first simulation will show the stress when the ball will be hit by tip of the foot, second will be a lateral hit and last a dorsal hit. These three relative hit positions are shown in Figure 1, Figure 2 and Figure 3 below.

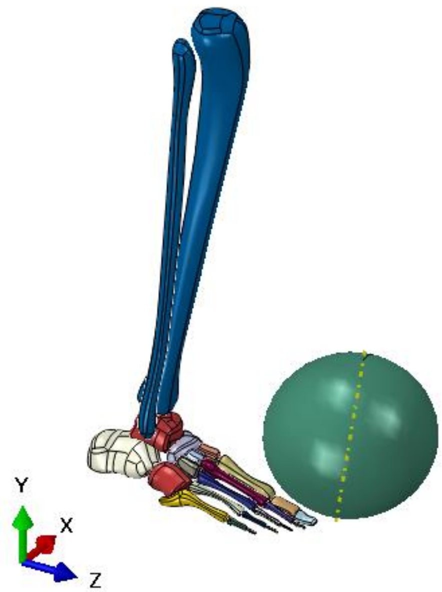

Figure 1. Tip hit.

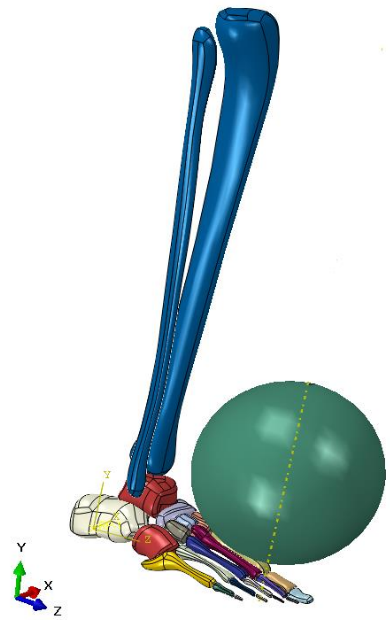

Figure 2. Lateral hit.

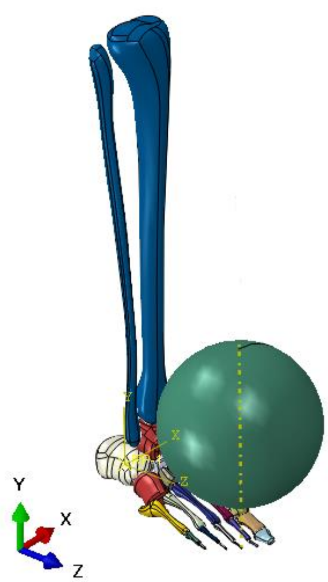

Figure 3. Dorsal hit.

To do this using Abaqus/Explicit Dynamic Simulation, we have created our model, the human leg bones, in Autodesk Inventor software and imported in Abaqus/CAE as a step file. Further, we have created in Abaqus a rigid leg, to be attached to our test model, a soccer ball, a gate and the field. The procedure is as the velocity boundary condition applied to the rigid leg move the human leg which hit the ball toward the gate.

In the next chapter will be explained more about the procedure and properties of the parts.

The unit system used in all simulations are US Units as shown in Table 1 below.

Table 1. Units used for this simulation.

US Unit (ft)	
Length	ft
Force	lbf
Mass	slug
Time	s
Stress	lbf/ft^2
Density	$slug/ft^3$

2. Model

2.1. Human Leg Bones

Human leg bones were designed using the real medium age dimensions. The material properties for the bones are shown in Table 2.

Table 2. Human Leg Bones Material Properties.

Material Properties - FOOT				
Human Bones				
Density	1750	Kg/m^3	3.395561	$slug/ft^3$
Young's Modulus	12	GPa	2.5063E+08	lbf/ft^2
Poisson's Ratio	0.3		0.3	

In Figure 4, we have the human leg bones created for this simulation in Autodesk Inventor software and imported as a step file in Abaqus/CAE. In Figure 5, is shown the human foot anatomy. We used that to create the part to part tie constraint directly in the input file created in Abaqus/CAE.

To mesh the human leg bones, we have used C3D10M elements. In Figure 6, is shown the mesh of one of the bones in the model.

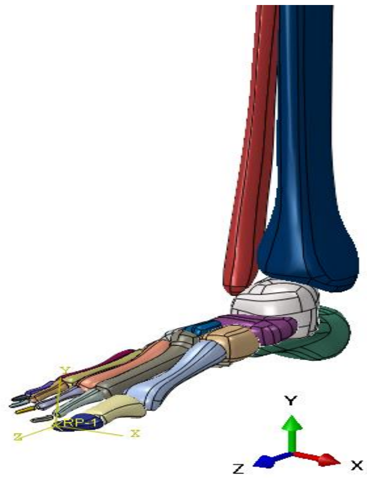

Figure 4. Human leg bones model.

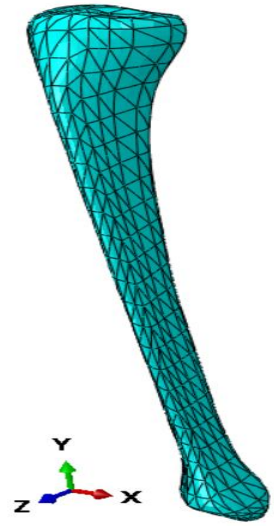

Figure 5. Tibia mesh.

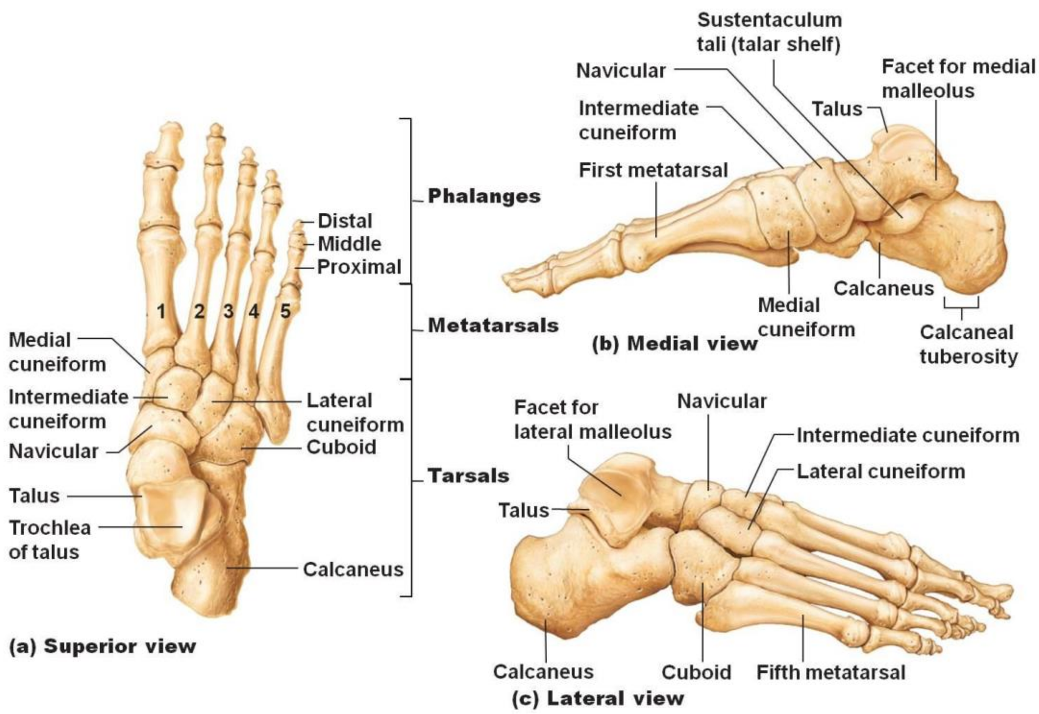

Figure 6. Human foot bones anatomy.

2.2. Rigid Leg

We have created a rigid leg to be tied to the human leg bones, as shown in Figure 7, to apply the velocity boundary condition that will move the human leg to hit the ball. In Figure 8 is shown the rigid leg mesh. For the mesh, we used the rigid body elements R3D4.

For the Rigid leg, we have also created an entity set, R1, with a node representing the "knee" and the degree of freedom 3 and 4 were fixed.

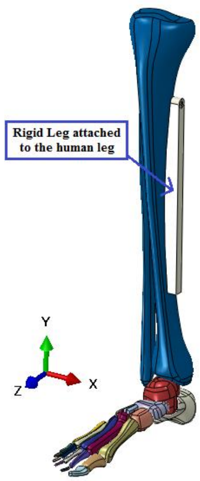

Figure 7. Rigid leg tied to Human leg.

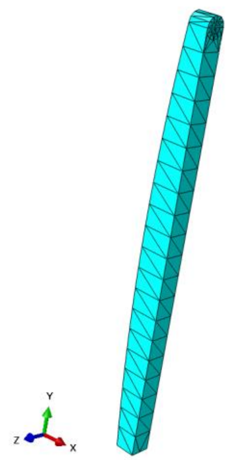

Figure 8. Rigid Leg Mesh.

2.3. Soccer Ball

The ball diameter is 0.721785 ft (220 mm), the dimensions correspond to FIFA (International Federation of Football Association) standards. We meshed the ball with shell elements, S4R, with a thickness of 0.0328084ft (10 mm). Material properties for the ball are in Table 3, below. We have created an entity set, Pressure, that includes all the elements of the ball, and to this we will apply gravitational force at Earth's surface equal to 32.1740 ft/s^2 (9.8m/s^2). Figure 9, below, represents the ball's mesh.

Table 3. Material Properties of the Ball.

Material Properties - BALL				
Rubber				
Density	1.522	g/cm^3	2.9531675	slug/ft^3
Young's Modulus	10	GPa	2.0885E+08	lbf/ft^2
Poisson's Ratio	0.48		0.48	

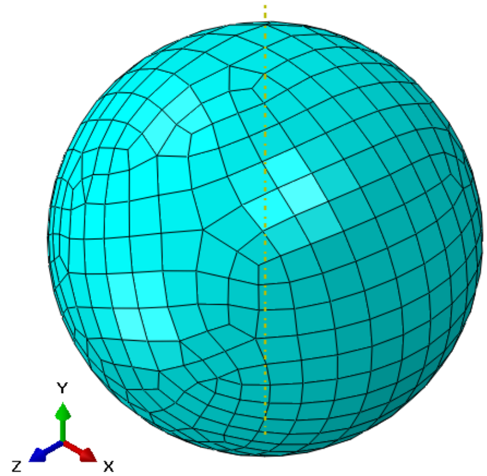

Figure 9. Mesh of the Ball.

2.4. Ground

The ground is created as a rigid body, meshed with rigid elements, R3D4 as we can see in Figure 10. For the ground, we have created an entity set, R2, which contains the reference node, with all degrees of freedom fixed.

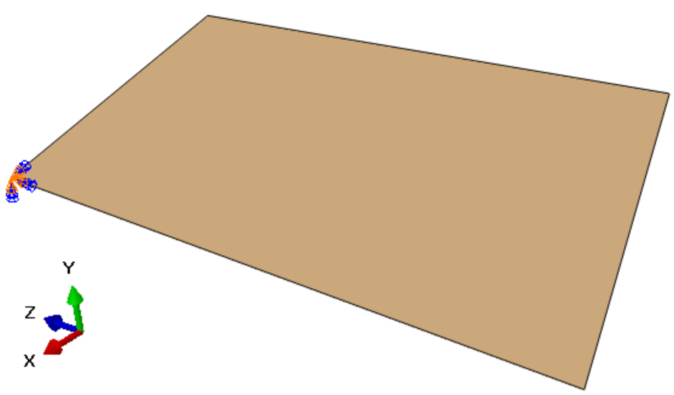

Figure 10. Ground and reference node.

2.5. Gate

The gate is created also as a rigid body, meshed with rigid elements, R3D4. The entity set created for the gate, R3, which contains the reference node, have all degree of freedom fixed. In Figure 11 is shown the reference node for the gate. The material properties used for the gate are presented in Table 4 below.

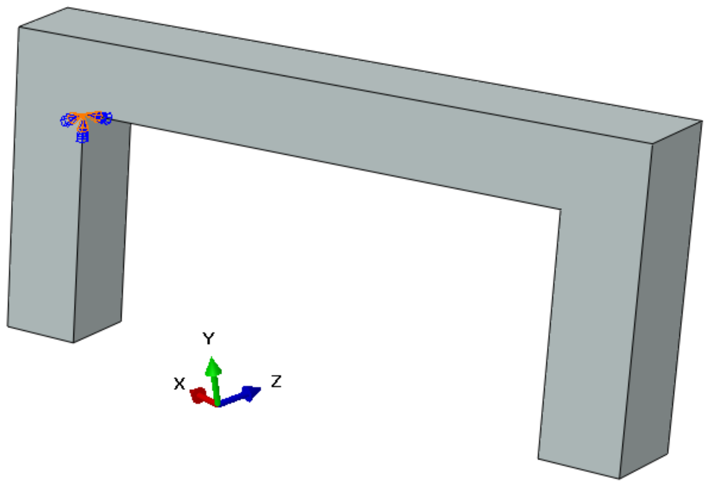

Figure 11. Reference node for the gate.

Table 4. Material properties of the gate.

Material Properties - GATE				
Steel				
Density	7700	Kg/m^3	3.395561	$slug/ft^3$
Young's Modulus	210	GPa	4.3859E+09	lbf/ft^2
Poisson's Ratio	0.3		0.3	

2.6. Input File

In the next figures are shown how the input file for these simulations was created. We can observe part to part tie definitions, rigid bodies, amplitude velocity, and final code for Abaqus/Explicit Dynamic simulation.

```
Set-Proximal1
*SURFACE, TYPE=ELEMENT, name=PROXIMAL2
Set-Proximal2
*SURFACE, TYPE=ELEMENT, name=PROXIMAL3
Set-Proximal3
*SURFACE, TYPE=ELEMENT, name=PROXIMAL4
Set-Proximal4
*SURFACE, TYPE=ELEMENT, name=PROXIMAL5
Set-Proximal5
*SURFACE, TYPE=ELEMENT, name=NAVICULAR
Set-Navicular
*SURFACE, TYPE=ELEMENT, name=TALUS
Set-Talus
*SURFACE, TYPE=ELEMENT, name=TIBIA
Set-Tibia
*SURFACE, TYPE=ELEMENT, name=HUMAN_LEG
Set-Human_leg
*TIE, name=one, adjust=no, type=surface to surface, position tolerance=0.05
CALCANEUS, TALUS
CALCANEUS, CUBOID
TALUS, NAVICULAR
FIBULA, TIBIA
TIBIA, TALUS
FIBULA, TALUS
NAVICULAR, MEDIAN_CUNEIFORM
NAVICULAR, INTERMEDIATE_CUNEIFORM
NAVICULAR, LATERAL_CUNEIFORM
LATERAL_CUNEIFORM, CUBOID
MEDIAN_CUNEIFORM, METATARSAL1
MEDIAN_CUNEIFORM, METATARSAL2
LATERAL_CUNEIFORM, INTERMEDIATE_CUNEIFORM
INTERMEDIATE_CUNEIFORM, METATARSAL2
LATERAL_CUNEIFORM, METATARSAL3
CUBOID, METATARSAL4
CUBOID, METATARSAL5
METATARSAL1, PROXIMAL1
PROXIMAL1, MIDDLE1
METATARSAL2, PROXIMAL2
PROXIMAL2, MIDDLE2
METATARSAL3, PROXIMAL3
PROXIMAL3, MIDDLE3
METATARSAL4, PROXIMAL4
PROXIMAL4, MIDDLE4
METATARSAL5, PROXIMAL5
PROXIMAL5, MIDDLE5
GATE, GROUND
*TIE, name=one, adjust=no, type=surface to surface, position tolerance=0.5
RIGID_LEG, HUMAN_LEG
```

Part to Part Tie Contact

MATERIALs USED

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*Material, name=Bone
*Density
 3.687,
*Elastic
 3.09104e+08, 0.3
*Material, name=Rubber
*Density
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*Elastic
 2.08854e+08, 0.48
*Material, name=Steel
*Density
 14.9405,
*Elastic
 4.38594e+09, 0.3
**
** INTERACTION PROPERTIES
**
*SURFACE INTERACTION,NAME=ALFRICTION
*FRICTION
0.1,
**
** BOUNDARY CONDITIONS
**
** Name: BC-1 Type: Displacement/Rotation
*Boundary
R1, 2, 2
R1, 3, 3
R1, 4, 4
R1, 5, 5
** Name: BC-2 Type: Displacement/Rotation
*Boundary
R2, 1, 1
R2, 2, 2
R2, 3, 3
R2, 4, 4
R2, 5, 5
R2, 6, 6
** Name: BC-3 Type: Dis
*Boundary
R3, 1, 1
R3, 2, 2
R3, 3, 3
R3, 4, 4
R3, 5, 5
R3, 6, 6
```

STEP DEFINITION

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** STEP: Step-1
**
*Step, name=Step-1, nlgeom=YES
*Dynamic, Explicit
, 0.2
*Bulk Viscosity
0.06, 1.2
** Mass Scaling: Semi-Automatic
**              Whole Model
*Fixed Mass Scaling, dt=1.5e-05, type=below min
**
** BOUNDARY CONDITIONS
**
** Name: VEL_BC-1 Type: Velocity/Angular velocity
*Boundary, amplitude=TWO, type=VELOCITY
R1, 1, 1, 650.
** Name: VEL_BC-2 Type: Velocity/Angular velocity
*Boundary, amplitude=ONE, type=VELOCITY
R1, 6, 6, 30.
**
** LOADS
**
** Name: DISTFORCE-1   Type: Pressure
*Dsload
DISTFORCE-1, P, 1.
** Name: GRAVITY-1   Type: Gravity
*Dload
Pressure, GRAV, 32.174, 0., -1., 0.
**
** INTERACTIONS
**
** Interaction: General_Contact
*CONTACT
*CONTACT INCLUSIONS, ALL EXTERIOR
*CONTACT PROPERTY ASSIGNMENT
,,ALFRICTION
*SURFACE PROPERTY ASSIGNMENT,PROPERTY=FEATURE EDGE CRITERIA
, NO FEATURE EDGES
**
```

3. Analysis and Discussion

The procedure used in all three simulations is to add an amplitude velocity on the entity set R1, which will result in hitting the ball by the human leg. In this case, we will observe also the movement of the ball toward the gate.

Computational power is required to run such complex simulations, in our case around several hours to run one simulation. This makes us to maintain the simulation time very low at 0.2 seconds. All simulations were completed without errors and for eye impression was specified on result figures the projected trajectory of the ball.

Further, we will analyze each case and observe the movement of the ball toward the gate and stresses created by the kick in human foot bones.

In Figure 12 below, is shown basic demonstration how simulations will basically work.

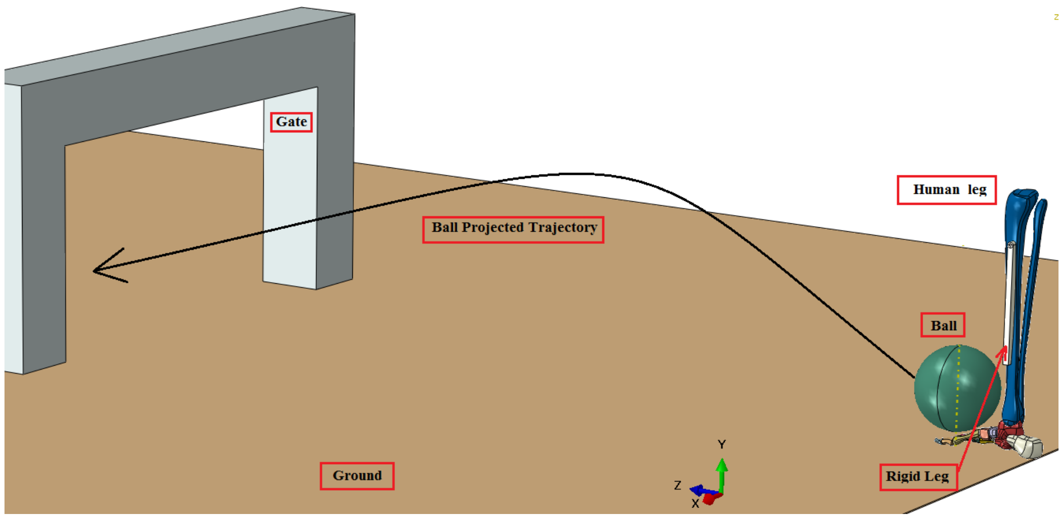


Figure 12. Final Assembly.

3.1. Dorsal Hit

After many trials to find the best velocities, extreme velocities applied to the set R1 are 650 rad/s in DOF 4 and 300 rad/s in DOF 3 in case of the ball dorsal hit.

In Figure 13 and Figure 14 we can observe the stress results after hitting the ball. First figure was captures at increment 2797, just at the beginning at the hit. Second figure was captured at the end of the 0.2 second simulation time, maximum stress captured on Navicular bone with value of 1.240E+07 lbf/ft^2 shown in Figure 15.

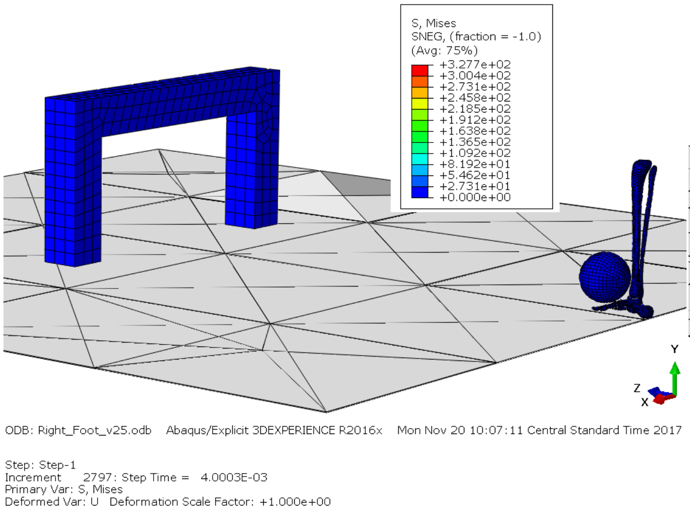


Figure 13. Stress at Increment 2797.

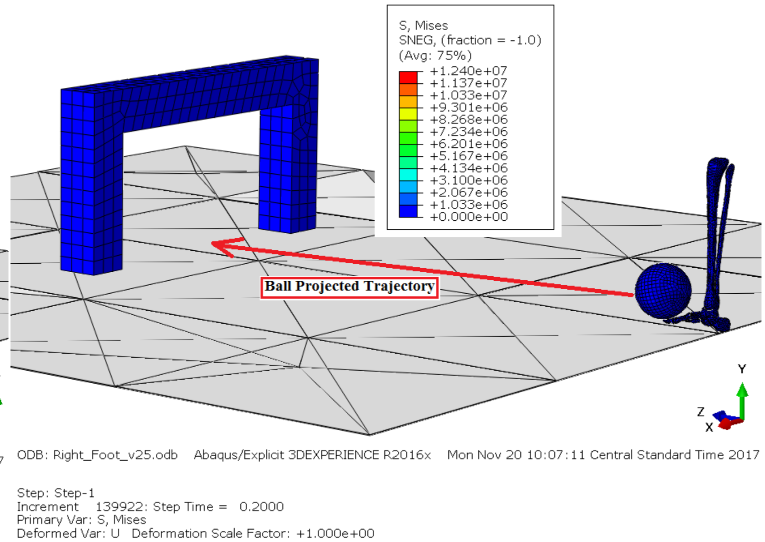


Figure 14. Stress at the end of simulation.

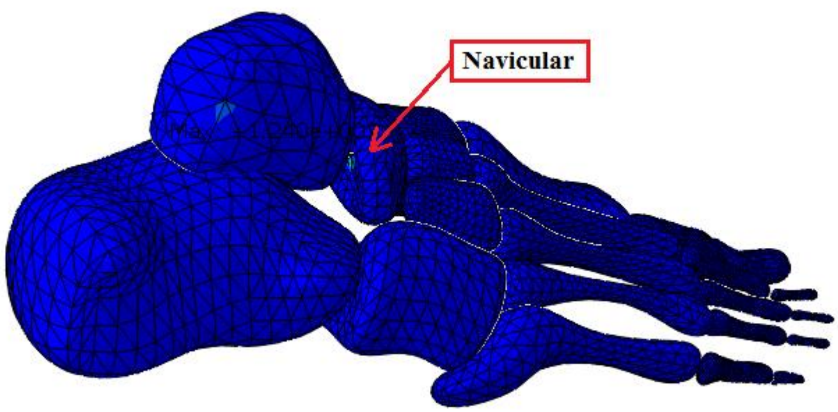
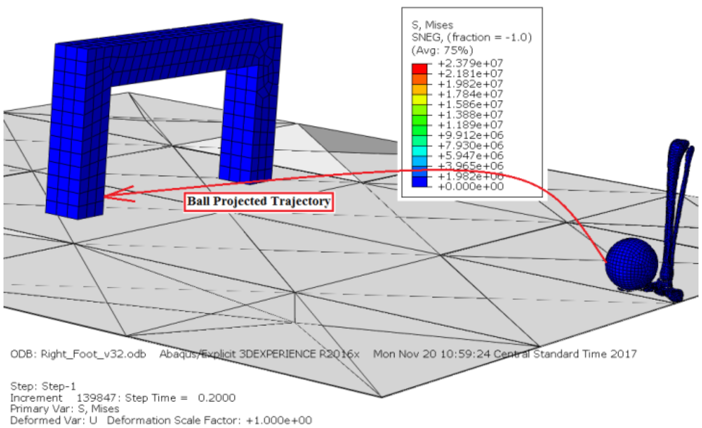


Figure 15. Maximum Stress in Dorsal Hit.

3.2. Lateral Hit

After many trials to find the best velocities, extreme velocities applied to the set R1 are 3000 rad/s in DOF 3, 650 rad/s in DOF 4 and 700 rad/s in DOF 5, in case of the ball lateral hit. Velocity applied in DOF 5 gives a rotational side movement to the human foot that makes to laterally hit the ball.

In Figure 16 we can observe the stress results at the end of simulation, maximum stress captured on Navicular bone and it was 2.379E+07 lbf/ft^2 shown in Figure 17.



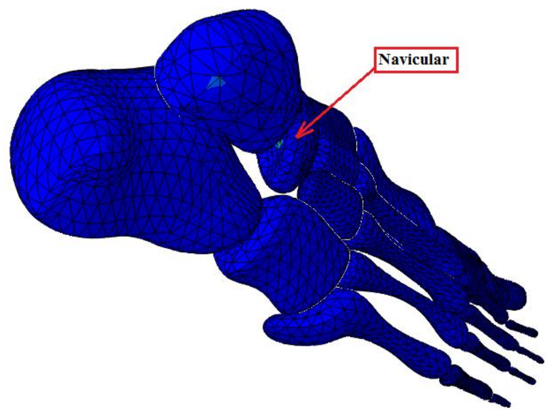


Figure 16. Stress at end of simulation.

Figure 17. Max stress in lateral hit.

3.3. Tip Hit

After many trials to find the best velocities, extreme velocities applied to the set R1 are 650 rad/s in DOF 4 and 300 rad/s in DOF 3 in case of the ball tip hit.

In Figure 18 we can observe the stress results at the end of simulation, maximum stress captured on Navicular bone and it was 1.989E+07 lbf/ft^2 shown in Figure 19.

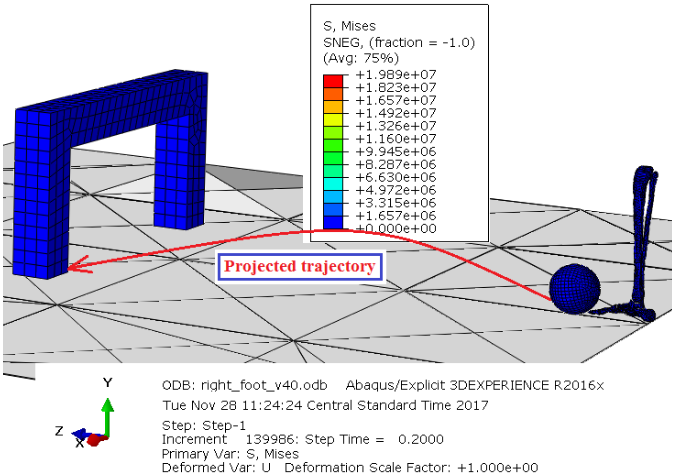


Figure 18. Stress at end of simulation.

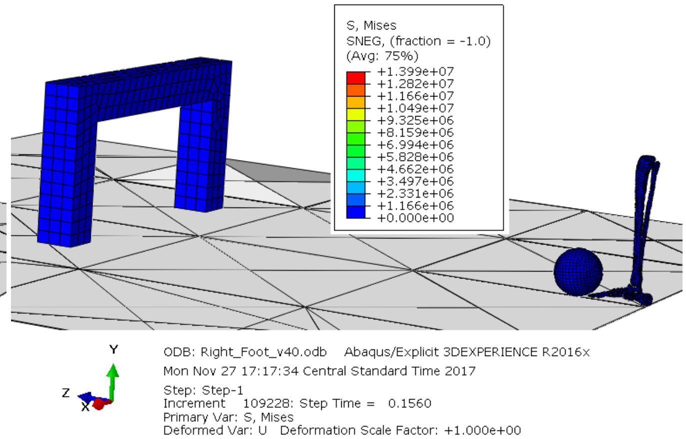


Figure 19. Stress at Increment 109922.

4. Conclusion

From our three cases where we have simulated the human foot hitting a soccer ball, one with dorsal face of the foot, one with the lateral face and one with the tip of the foot, we found that the maximum stress was captured on Navicular bone. Because we would need a very large computational time to simulate it for a long time, we set up our time to 0.2 seconds. Maximum stress level was in case of lateral hit, and less stress in case of dorsal hit. In practice we can observe the same "pain" in the bones after real hitting a soccer ball, of course not at the same velocities.

5. References

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