The Effect of Density and Shear Modulus on Acceleration at the Center of Gravity of a Simplified Human Head Model due to Impact

Justin Morse
ENGN 2340

December 13, 2013

Introduction

In my thesis research, I am using a complex finite element model of the human head, the NRL/Simpleware Head Model [1], to investigate brain injury in girls' lacrosse due to stick impacts. Part of the study involves simulating collisions between a lacrosse stick and head form surrogate that were performed in the laboratory. These experiments are intended to replace acceleration data collected in-game; these data are limited in girls' lacrosse because helmets are forbidden, making measurement difficult. A good match of peak acceleration and curve shape over time provides a way to justify that the model can capture the accelerations observed in lacrosse head impacts. Additionally, impact experiments on cadavers in literature [2] are used to validate the pressure dynamics in the brain resulting from impacts of similar force. Together, these methods are the best we currently have to justify the use of this finite element head model to investigate intracranial dynamics in lacrosse.

Accurate measurements of the material properties of living tissue are difficult to obtain, so the accuracy of models currently available is questionable. This study will help determine how much the results of an acceleration study are affected by material properties. The full head model is too complex and its computational requirements too high to easily accomplish a parametric study of material parameters. In this investigation, a hyperelastic sphere with a stiff, linear elastic shell representing the skull, will be impacted with a rigid surface. The acceleration at the center of mass of the sphere will be plotted against impact force. The density and shear modulus of the hyperelastic portion of the sphere will be varied to determine the effect of each parameter on the force-acceleration relationship.

Methods

Model Description

Due to the axisymmetry of the problem, a two-dimensional model is used to reduce computational cost. The model is a half-circle with a smaller, concentric partition to allow for a different material property in the outer shell (Figure 1). This shape was meshed using the medial axis algorithm with 10,147 linear quadrilateral elements with hybrid formulation to overcome volumetric locking.

Displacement in the x_1 direction was prescribed zero along the vertical edge of the half-circle to enforce the axisymmetry of the problem. Motion in the x_2 direction was unrestrained and an initial velocity was prescribed to the sphere in the negative x_2 direction. The total radius of the sphere was 7.5 cm and the shell had a thickness of 6 mm, characteristic values of the human head and skull.

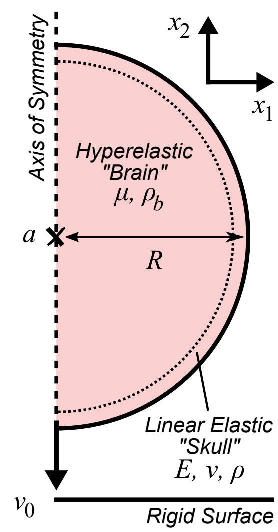


Figure 1: The sphere model, with center of mass is denoted by the "X". The independent variables are the initial velocity, v_0, shear modulus of the brain, μ, and density of the brain, ρ_b. The dependent variable is peak acceleration at the center of mass, a.

Experimental Design

The sphere impacted the surface initial velocities of 5, 8, 11, 14, 17 m/s, a range of speeds characteristic of lacrosse stick swings. The Neo-Hookean constitutive relation described the inner sphere material, and the two parameters varied were the "brain" density and shear modulus. Since the material should be near-incompressible, the bulk modulus, K, was approximated by Abaqus as nearly infinite. The outer shell had a constant material property resembling bone adapted from a past simulation study [3]. This was a linear elastic model, with $E = 6.5$ GPa, $\nu = 0.22$, and $\rho = 1412$ kg/m^3.

Dimensional Analysis of Parameters

Several dimensionless groups govern the solution, and a relationship is given in equations 1. Additional variables not mentioned in Figure 1 are the radius of the sphere over where acceleration is averaged upon measurement, r_0, bulk modulus of the brain, K, sphere radius, R, skull thickness, d, skull elastic modulus, E, skull Poisson ratio, ν, skull density ρ_s, time, t, and total mass, m.

$$\frac{aR}{v_0^2} = f\left(\frac{\mu t^2}{\rho_b R^2}, \frac{E}{K}, \frac{m}{\rho_s d^3}, \nu\right) \tag{1}$$

The left-hand group of equation 1 shows acceleration and initial velocity are positively related, which is expected. The acceleration is also inversely related to total radius. On the right side, moving terms containing radius to the bottom demonstrates that acceleration is also directly related to shear modulus, but inversely related to density. Simulations varying these parameters will attempt to confirm and provide more information about this.

Variation of Parameters in Simulation

The range of shear moduli was centered about $\mu_b = 22.53$ kPa, an established shear modulus of "general brain" material from Moore et al. [3]. The shear modulus values ranged from $0.01\mu_b$ to $10\mu_b$. The range of densities was based on $\rho_b = 1040$ kg/m^3, the value for brain tissue from Moore et al. and was bounded by $0.01\rho_b$ and $10\rho_b$. All parameter values used are listed in Table 1.

Value	1	2	3 (Brain)	4	5
Shear Modulus (Pa)	225.30	2253.00	22530.00	71246.12	225300.00
Density (kg/m^3)	10.40	104.00	1040.00	3288.77	10400.00

Table 1: Parameter values used during the study. One parameter was varied at a time, while the other was kept at the normal brain value.

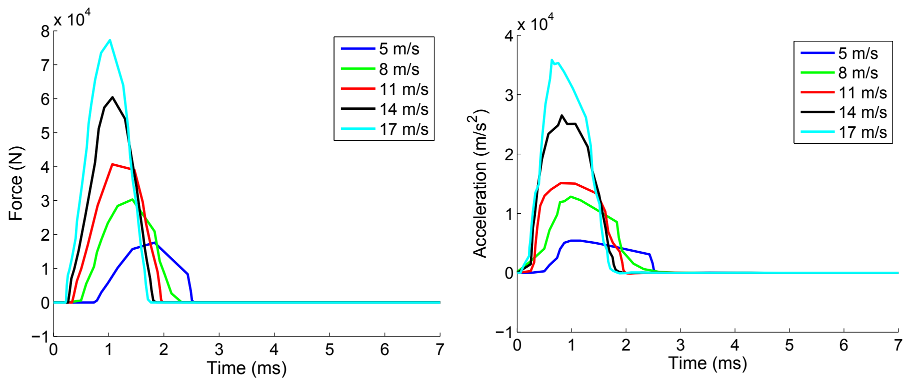
Acceleration will be multiplied by the ratio of the current model's mass to that of the "normal brain" model before being plotted. This will ensure that the effect of density is being examined, not just the varying mass.

Analysis & Data Processing

The mesh was generated, as well as other pre-processing performed, with Abaqus/CAE 6.12-2. Implicit dynamic analyses were performed with Abaqus/Standard 6.12-2. Displacement data from a small circle of radius $r_0 = 4.5$ mm around the center of mass was extracted and averaged using Abaqus/CAE. Post-processing, including calculating accelerations from displacements and plotting, was performed by scripting in MATLAB.

Results

Force and acceleration measurements over time for the "normal brain" model ($\mu = 22.53$ kPa and $\rho_b = 1040$ kg/m^3) are presented in Figure 2.



(a) Input Force

(b) Acceleration

Figure 2: Measured input force and center-of-mass acceleration of simulation with "normal brain" parameter values.

With increasing initial velocity, impact force peaks increase relatively linearly. A similar trend is seen with the peak values of acceleration. Acceleration curves are slightly more spread out, but the initial increase is more sharp. The mass of each model and its mass ratio with the "normal brain" model is given in Table 2.

Density Value	1	2	3 (Brain)	4	5
Mass (kg)	0.57	0.70	1.98	5.07	14.84
Mass Ratio	0.29	0.35	1.00	2.56	7.48

Table 2: Total masses of models with varying density.

Scatter plots of acceleration at the center of mass versus input force are shown in Figure 3 and Figure 4 for variation of the shear modulus and density, respectively.

Acceleration increases with input force in all cases. Additionally, the trends are nearly coincident for each parameter value. The trends appear close to linear within the range of forces seen in this situation.

Discussion

A significant difference in acceleration versus force was not seen with changes in either shear or bulk modulus. This indicates that material properties do not play a large role in the behavior during the sudden and short-lived impact duration. Deformations in the center of mass region were small during the timespan of interest; many material models and parameters would behave similarly at these small strains. The acceleration at the center of gravity is largely a function of the rigid body movement of the object, and less a function of intracranial

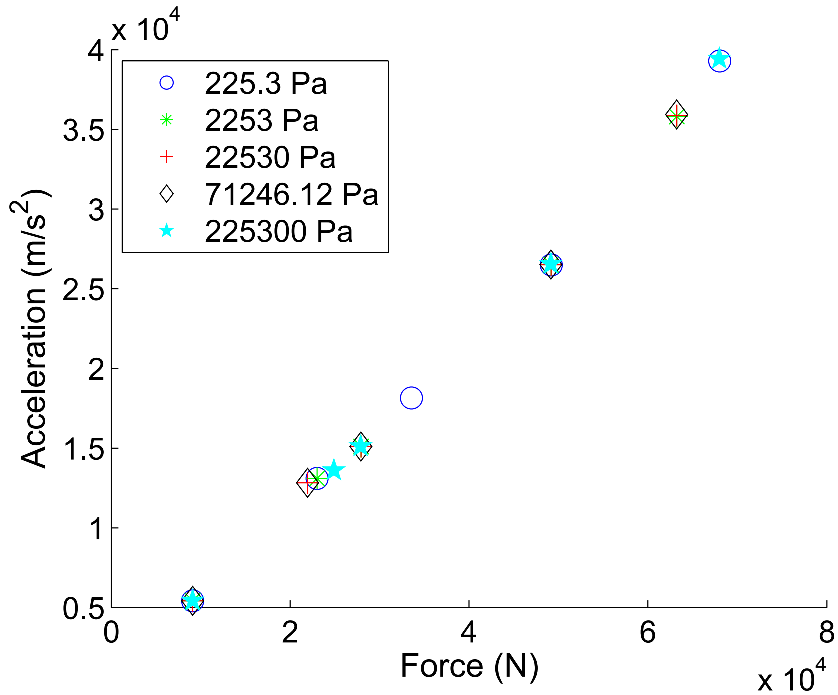


Figure 3: Scatter plot of acceleration at the center of mass versus input force for each simulation in which shear modulus was varied. Each symbol denotes a different shear modulus value. Acceleration values have been scaled by mass ratios, as previously described.

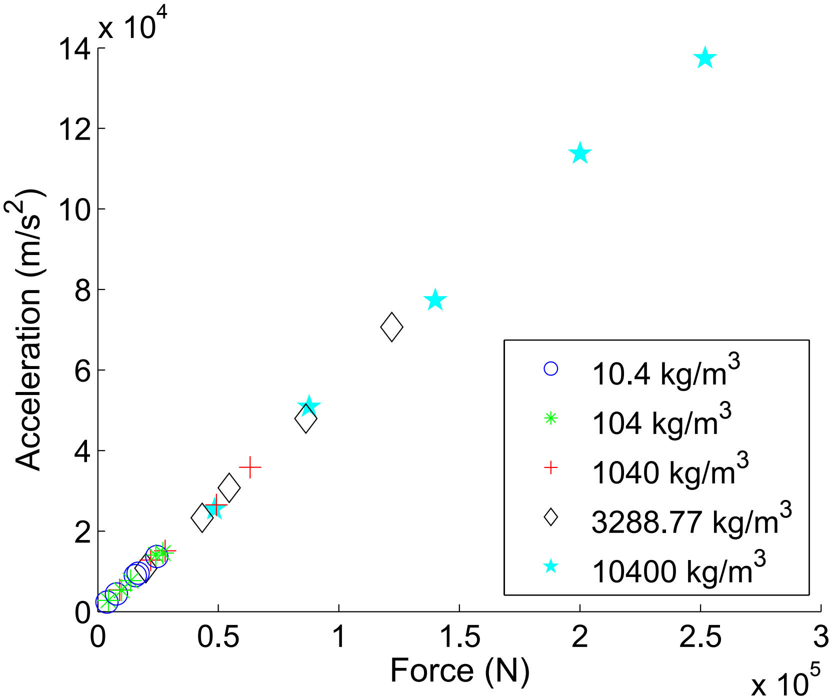


Figure 4: Scatter plot of acceleration at the center of mass versus input force for each simulation in which density was varied. Each symbol denotes a different density value. Acceleration values have been scaled by mass ratios, as previously described.

dynamics. Geometry of the model may also be a factor, and this is a variable that is difficult to quantify.

The points from each simulation corresponding to a certain speed do not necessarily correspond to the same force. This is because the parameters affect the behavior of the sphere upon contact; spheres with low shear modulus, for instance, would spread more and result in a lower peak, but longer force curve.

At higher speeds, low shear modulus, and high density, the shear wave speed became low, according to the relationship, $v_s = \sqrt{\mu/\rho}$. When deformation of impact region became large, a large wave began propagating away from it, causing large deformations and in some cases, termination of analysis due to an excessive amount of time steps. This wave was seen much later than the initial peak of force and acceleration at the center of mass, which was the focus of this study. However, in studying intracranial dynamics, this kind of behavior would be important to capture and model accurately because it would likely contribute to tissue damage. This is where material property realism would become important.

Conclusion

This investigation explored the role of material properties in affecting the acceleration at the center of gravity of a human head model due to impacts mimicking those seen lacrosse. A hyperelastic sphere with a thin, linear elastic shell represented the human head. The density and shear modulus of the inner sphere, or brain, were the parameters under investigation, while the outer shell was given properties characteristic of bone. Plots of acceleration at the center of gravity versus applied force were presented to determine whether changes in the parameters affected that relationship, but this did not appear to be the case. Understanding the role of material properties in acceleration results is important in being able to optimally model lacrosse impacts, and ultimately make predictions about brain injury.

References

[1] P G Young, T B H Beresford-West, S R L Coward, B Notarberardino, B Walker, and A Abdul-Aziz. An efficient approach to converting three-dimensional image data into highly accurate computational models. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 366(1878):3155–3173, September 2008. PMID: 18573757.

[2] Alan M. Nahum, Randall Smith, and Carley C. Ward. Intracranial pressure dynamics during head impact. SAE Technical Paper 770922, SAE International, Warrendale, PA, February 1977.

[3] David F Moore, Antoine Jerusalem, Michelle Nyein, Ludovic Noels, Michael S Jaffee, and Raul A Radovitzky. Computational biology - modeling of primary blast effects on the central nervous system. *NeuroImage*, 47 Suppl 2:T10–20, August 2009. PMID: 19248833.