MAE: 259B: Mechanics of Slender Structures and Soft Robots Midterm Report

Team 6: Chris Campbell, Lily Clay, Ryan Fadell

Abstract— **The model developed effectively simulates a neck/spine, skull, brainstem and brain impacting a wall. Further detail will be added using a more complex brain model that incorporates spring and damper effects. Additionally, the code will be improved by adding realistic material properties.**

I. INTRODUCTION AND PROJECT OBJECTIVES

The primary objective of this project is to develop a 2D model of the brain, surrounding cerebrospinal fluid, and skull that can quickly simulate impacts. This model can be used to estimate stresses and strains within brain tissue, identify where a concussion might have locally occurred, and optimize safety devices such as helmets designed to reduce rapid acceleration of the brain. Protective foams, shells, and fluids may be integrated into the model as time permits to simulate the effect of existing or proposed safety products and determine their effectiveness at preventing concussions. The simulation was generated using beam elements for each body part connected by individual nodes. The head experienced acceleration until it contacted a perfectly rigid wall and rebounded. Simultaneously, the movement and deformation of the neck, brainstem, brain and skull was calculated using Newton's method. For each simulation, the model tracks the velocity and acceleration of the brain and will be further expanded to include force. As of the semester midterm, the simulation function has been developed and debugged, but realistic material parameters still need to be added. In the final weeks, additional detail of the brain will be also added and the simulation will be matched to results found in previous concussion studies. This will allow the simulation to model the actual mechanics of a head impact [1,2,4].

II. MODELING APPROACH

This model simulated concussions by modeling a 2D skull as a rigid body shell, the brain as a series of interconnected elastic nodes, and the brainstem and neck using discrete elastic beams. Each segment will be improved using existing studies and datasets to incorporate accurate material and dimensional properties [1,2,4]. The brain may also be modified to include additional nodes and spring/damper interactions in order to better approximate its shape and deformation during impact. Accelerations consistent with previous concussion studies will then be applied to this model and the stress/strain on the brain will be compared with previously obtained results. Angular accelerations have been shown to be particularly concerning for concussions so these are also applied in the simulation [2]. The studies can be compared to each other using the following metrics on the brain: peak linear and angular accelerations, peak linear and angular velocities, brain strain and force. The goal for these comparisons is to better understand concussion impact mechanics and which aspects can be modified to reduce head trauma.

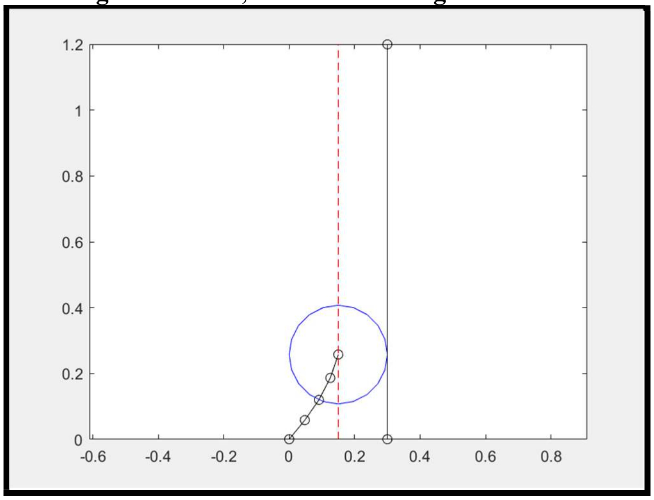
III. MODEL PROGRESS

The model containing the neck/spine, brainstem, and simplified brain sufficiently simulates the mechanics of a head hitting a rigid wall. The following sections detail how each body part was modeled. Now that the simulation is working, accurate material and dimensional properties will be added to make a realistic model. Additionally, elastic collision equations will be added to calculate the rebounding forces which will then be applied using Newton's method. A more complex brain model containing springs and dampers was also developed, but needs to be swapped into the simulation in place of the simplified brain.

A. Neck/Spine

The neck has been modeled as a 2D discrete elastic beam with an adjustable number of nodes. Acceleration or forcing functions were applied at the beginning of the simulation to every node along the neck in order to initiate movement. The model has been designed with virtual limits or "walls", which rebound the motion of the beam in the x-direction. The rebound is calculated using the Newton-Raphson method on any node that passed beyond the "wall." The node's x coordinate index is switched to fixed, and that x value is set to the x value of the "wall." The simulation continues running. Once the x value of that node is evaluated to be to the correct side of the wall, the fixed index switches back to free and the simulation can continue. This way, the beam can effectively bounce off the barrier while only considering its innate discrete elastic parameters. Figure 1 shows the initial collision model containing only a neck and skull impacting a wall.

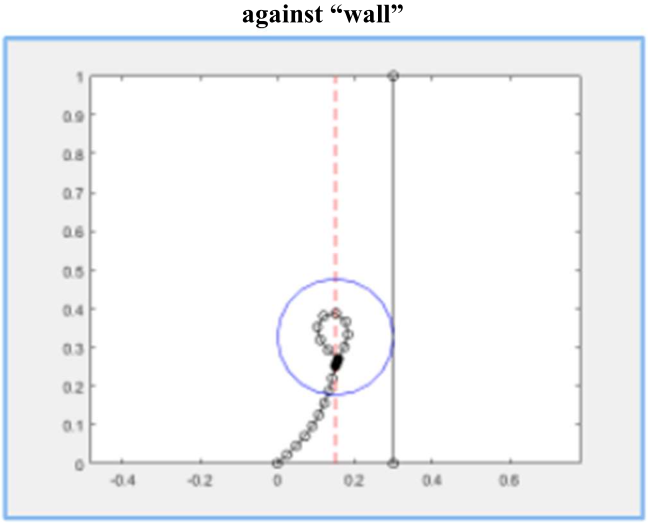
Figure 1: Neck, Skull collision against "wall"



B. Connections

The neck/spine, brainstem and brain are all connected by fixing the final node on each body part. This keeps each body part connected, but allows forces to transfer along the kinetic chain. The "fixing" is accomplished by calculating the x-y offset of the matched points after each iteration of Newton's method. The offset is then applied to ensure that the points remain together. For interacting components such as the brain contacting the edge of the skull, the locations of each node are analyzed using for loops until contact is detected. Once the nodes intersect, a basic elastic calculation is performed and the forces for the current loop are updated. The simulation currently contains fully defined models of the spine and brainstem, but only a simplified brain model used to develop the brain's interactions while the more detailed brain model was developed simultaneously. Now that the simulation is functioning, the more complex brain can be added by merging a single node with the neck. Figure 2 shows the collision model continuing the neck/spine, skull, brainstem and simplified brain.

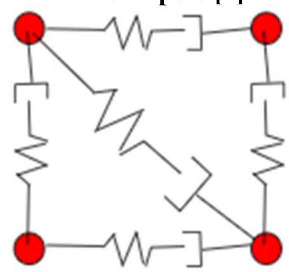
Figure 2: Neck, skull, brainstem and brain collision against "wall"



C. Brain

The brain is currently modeled as four nodes in a square, connected by springs and dampers. In its current state, the script has the brain traveling through viscous fluid with an external force on one node. The brain deforms while the force is active. When the force stops the brain returns to its original shape and ceases moving [4]. Now that this model has been developed, it will be added to the main model as a next step. Figure 3 shows this updated brain model [4].

Figure 3: Brian model incorporating a series of springs and dampers [4]



IV. Data Capture

The simulation captures the brain's velocity and acceleration as shown in Figure 4 and Figure 5 which can be easily converted into force values. This force capture will be implemented in the final portion of the project. Currently the simulation doesn't have realistic material properties, dimensions, etc. Once these realistic properties have been added, the influence of each parameter on the overall force can be examined. Furthermore, elasticity values for the skull can be altered to simulate the deformation of a helmet and study head safety devices.

Figure 4: Brain velocity vs time captured in the simulation

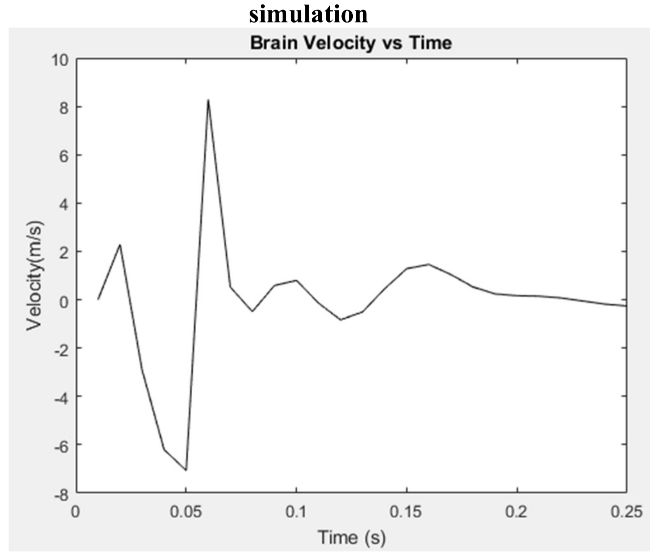
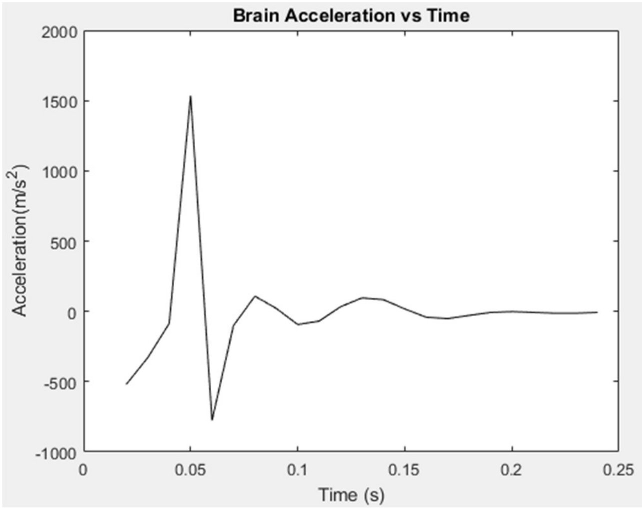


Figure 5: Brain velocity vs time captured in the simulation



V. Future Work

The most immediate changes to be made are to clean up all existing code and ensure the modifiable simulation parameters are easy to access and change. Afterwards, the current code will be reevaluated just to ensure the basic simulation behavior is still working as intended. Connection points may be altered to better resemble actual human biology and additional nodes and connection points may be added to ensure forces are being transferred effectively between simulation elements. The more accurate brain model will also be added. Next, the elastic and discrete parameters will be iteratively altered to match the specific outputs and behaviors detailed in studies. The biomechanical characteristics of the brain are laid out in multiple referenced papers, and will be used to fine tune the simulation to a satisfactory state [1,2,4]. Once the model has been tuned, various forces, impacts, and protective devices can be simulated, and data can be used to determine the risk of concussion and the effectiveness of safety technologies.

VI. Evaluating Technology

The easiest way to evaluate head safety equipment such as helmets will be to adjust the material properties of the skull. The Physics collision equations will then capture the change in force experienced by the brain. This is the most realistic material property that would be modified in reality since most properties such as the neck modulus of elasticity are defined by the human body. This is further supported by testing and examining the parameters of a head impact that could be altered to improve the brain's impact and outcome.

VII. Conclusion

The simplified 2D model is functioning as of the midterm report, but needs to be built upon and validated in order to accurately simulate the mechanical forces on a brain during a collision. This simulation will allow rapid iteration and better understanding of the kinematics and variables involved in a collision. The study will primarily focus, as time allows, on helmets and aim to identify key parameters that can reduce head trauma. However, the primary objective will first be to make the model as realistic and accurate as possible so that it can deliver useful results.

[1] W. Decker, A. Baker, Y. Xin, et al., "Development and Multi-Scale Validation of a Finite Element Football Helmet Model," *Annals of Biomedical Engineering,* no. 48, pp. 258-270, 2020.

[2] E. D. Anderson, T. Wu, M. B. Panzer, et al., "Predicting Concussion Outcome by Integrating Finite Element Modeling and Network Analysis," *Frontiers in Bioengineering and Biotechnology,* vol. 8, p. 309, 2020.

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[4] L. J. Ng, V. Volman, M. M. Gibbons, et al., "A Mechanistic End-to-End Concussion Model That Translates Head Kinematics to Neurologic Injury," *Frontiers in Neurology,* 2017.

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[6] S. P. Broglio, A. Lapointe, K. L. O'Connor, et al., "Head Impact Density: A Model To Explain The Elusive Concussion Threshold," *Journal of Neurotrauma,* vol. 34, no. 19, 2017.

[7] Bicycle Helmet Safety Institute, "Researcher's Resource Page," 2022. [Online]. Available: https://helmets.org/research.htm.