Finite Element Analysis of Head Impacts in Contact Sports

Eyal Bar-Kochba¹, Mark Guttag¹, Subham Sett², Jennifer A. Franck¹, Kyle McNamara¹, Joseph J. Crisco³, Janet Blume¹, and Christian Franck¹

¹School of Engineering, Brown University; ²Dassault Systemes Simulia Corp; ³The Warren Alpert Medical School of Brown University and Rhode Island Hospital
TBI and Sports

- TBI is a leading cause of death and disability in the US (Selassie et al., 2011)
  - It accounts for 30% of all injury related deaths

- The rate of concussions per athletic exposure has double over the last two decades in 15 NCAA sports (Hootman, 2007)

- Many sports have implemented new rules to protect players from injury including (Crisco, 2011):
  - Regulations for protective equipment and
  - Against certain types of hits
Current Technology
(Courtesy: Dr. Crisco, Rhode Island Hospital)

- The Head Impact Telemetry system (HITs) created by Simbex is currently being used by several NCAA schools:
  - Brown
  - Dartmouth and
  - Virginia Tech

- The system collects real time impact data and relays the information to the sideline
Multiscale Approach to Develop Injury Criteria

- 1. Run experiments and gather impact data
- 2. Run Finite Element simulations to determine the stresses and strains in the brain
- 3. Apply the results from the Finite Element simulations to actual neurons

Goal: To determine an injury criteria for TBI due to impact
The Mesh

- The mesh was created from an MRI of a male head (Simpleware Ltd.)

- The mesh of the head is made up of 12 different sections
Constitutive Model

- Constitutive Model:
  - Neo-Hookean hyperelastic model for soft tissue
  - Linear elastic model for bone
    - $E = 6.50 \times 10^9$ Pa
    - $\rho = 1,412$ kg/m$^3$
    - $v = 0.22$

\[
U = \frac{\mu}{2} (I_1 - 3) + \frac{K}{2} (J^{el} - 1)^2
\]

<table>
<thead>
<tr>
<th>Section</th>
<th>Density (kg/m$^3$)</th>
<th>$K$ (Pa)</th>
<th>$\mu$ (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>1,040</td>
<td>$2.19 \times 10^9$</td>
<td>$2.253 \times 10^4$</td>
</tr>
<tr>
<td>Ventricles</td>
<td>1,040</td>
<td>$2.19 \times 10^9$</td>
<td>$2.225 \times 10^4$</td>
</tr>
<tr>
<td>Skin</td>
<td>1,040</td>
<td>$3.47 \times 10^7$</td>
<td>$5.880 \times 10^6$</td>
</tr>
</tbody>
</table>

Neo-Hookean Material Values (Moore et al.)
Boundary and Loading Conditions

- A rigid cylinder was given a mass of 80kg and an initial velocity of 8m/s.

- There is a rigidly fixed boundary condition at:
  - The base
  - The shoulders
  - The base of the CSF, Cervical Vertebrae, and Brain Stem

- Two distinct boundary conditions between the skull and brain were examined:
  - Free
  - Bonded
Modeling Considerations: Free Model

- Initially all adjacent sections of the mesh shared nodes with one another
  - The case for the bonded model

- The free model was created by making the skull a separate part from the rest of the model

- A Tie Constraint between the outside of the skull and the inside of the skin was created

- General Contact was defined between the brain and the skull
Total Contact Time of Impact

**Simulation:** ~2 ms.

Reconstruction of real hit data: ~15 ms

Laboratory data: ~2.5 ms

ASTM M size test headform equipped with Head Impact Telemetry (HIT) system (Simbex).

(Viano et al., 2007)
Head Motion Dynamics

- The kinematics of the model are consistent with the phenomenon of whiplash

**Bonded Model**

- $t_0$: Time when wave reaches anterior
- $t^*$: Time when wave reaches posterior
- $\Delta t = t^* - t_0 \approx 1.2$ ms
- $c = 125$ m/s

**Free Model**

Image/Animation compiled by Eyal Bar-Kochba
Pressure Wave Propagation

- The pressure is on the order of $10^5$ times larger than the shear stress.
Current Work: Loading Conditions

- Two more models are being developed using the free boundary condition:
  - Acceleration Loading
  - Force Loading

- **Acceleration Loading Model:**
  - The skull is a rigid body with linear accelerations applied to the center of mass of the skull

- **Force Loading Model:**
  - A force is applied directly to the surface of the head

![Graphs showing acceleration and force over time]
Current Work: Head Motion Dynamics

- Acceleration Loading Model runs 2x the rate of the Force Loading Model
- Both models demonstrate whiplash
Current Work: Pressure Wave Propagation

- **Acceleration Loading Model** runs 2x the rate of the Force Loading Model

- Both models demonstrate a pressure wave propagating through the brain
Summary and Future Work

Summary

- Two boundary conditions between the CSF and skull were examined using a cylinder impact model
- The kinematics of the model are consistent with the phenomenon of whiplash
- A pressure wave is observed propagating through the brain
- The boundary conditions greatly affect the results

Future Work

- Increase the accuracy of the acceleration loading model by including rotational acceleration
- Apply more sophisticated material models
- Include active neck stiffening
Acknowledgments

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THANK YOU
Supplemental Slide: Acceleration Loading Velocity (Lower Scale)