Modeling and Evaluation of the Human Torso

Joint Services Small Arms Systems Annual Symposium, Exhibition & Firing Demonstration May 7-10, 2007

Andrew C. Merkle\textsuperscript{1} and Jack C. Roberts\textsuperscript{1,2}

\textsuperscript{1} The Johns Hopkins University, Applied Physics Laboratory
Laurel, Maryland 20723-6099

\textsuperscript{2} The Johns Hopkins University, Department of Mechanical Engineering
Baltimore, Maryland 21218-2686
Soft armor vests are an essential component of personnel protection
  - Prevent penetration of tissue piercing ballistics into the thoracic region

The use of strong, deformable materials provide ballistic resistance
  - Allows backface deformation; augmented by higher energy threat conditions
  - Potential for Behind Armor Blunt Trauma (BABT)

Need to understand the relationship between the mechanical insult and the risk of internal injury
Recognized need for evaluating soft armor vests and investigating BABT

- NIJ Standard 0101.04 – ballistic resistance
- Ballistic gelatin – energy transfer
- Animal models – physiological response of living tissue
  - Liden (1988); Baosong (1996); Yen (1998)
- Post Mortem Human Subjects (PMHS) – develop injury criterion
- Computational Models
- Physical Surrogate Models
Motivation

- Investigate the ability of the torso models to
  - Detect the transfer of impact energy to the thoracic tissues
  - Measure potential injury risk predictors
  - Evaluate influence of factors including
    - Impact location
    - Surrounding local environment
    - Remote tissue response

- Compare the torso model response trends with the clay deformation observed from similar impact conditions
Goal

Understand human thorax response to blunt ballistic impact

Establish Injury Criteria based on BABT injury risk

Assess incapacitation from resulting injuries; contribute to the development of optimal engagement equipment
Approach

- Create both a computational and physical human torso model
  - Human Torso Finite Element Model (HTFEM)
  - Human Surrogate Torso Model (HSTM)
- Current models complete with:
  - Skeletal Structure (ribs, sternum, cartilage and vertebral column)
  - Organs (lungs, liver, heart, and stomach)
  - Soft tissue (muscle, skin, viscera)
Approach (cont.)

- Simulate ballistic impacts on HTFEM
  - Obtain deformations, organ pressures and acceleration of sternum
- Conduct ballistic experiments on HSTM
  - Obtain organ pressures and sternal acceleration
- Validate model response
- Employ models in understanding torso response under various threat conditions
  - Flexibility of computational or experimental evaluation
Model Development

- Human Geometry
- Rapid Prototype/Physical Model
- Rendered Digital Model
- Finite Element Model
- High-rate Tissue Testing

Biosimulant Tissues

- Shear Strain
- Shear Stress

Shear Strain

- 0.0
- 0.2
- 0.4
- 0.6
- 0.8
- 1

Shear Stress

- 0
- 0.01
- 0.02
- 0.03

Double-Lap Shear Fixture
Human Torso Finite Element Model (HTFEM)

5th Percentile HTFEM

50th Percentile HTFEM

9 mm; 425 m/s; Sternal shot location

T = 0.0 ms .20 ms .25 ms .30 ms .35 ms .40 ms .50 ms

T = 0.75 ms 1.00 ms 1.25 ms 1.50 ms 1.75 ms 2.00 ms 5.00 ms
Human Surrogate Torso Model (HSTM)

- Fabricated from biosimulant materials
  - Organ material properties evaluated under high strain-rate materials testing
  - Bone simulant material

- HSTM instrumented with sensors
  - Pressure sensors in organs
  - Accelerometer on sternum
  - Load cell in vertebral column
A Look Inside the HSTM

Intestinal cavity  Liver  Heart  Lungs
Ballistic Impact Conditions

- **Shot Locations**
  - Sternum: 1 in. superior to the vertical level of T6
  - Stomach: 1 in. lateral to mid-line and slightly superior of stomach

- **Threat conditions**
  - NIJ Standard 0101.04 test conditions
  - Soft armor only

<table>
<thead>
<tr>
<th>Vest Type</th>
<th>Caliber</th>
<th>Ammo Mass (grains)</th>
<th>Impact Velocity (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>.22</td>
<td>40</td>
<td>1079</td>
</tr>
<tr>
<td>IIa</td>
<td>9-mm</td>
<td>124</td>
<td>1119</td>
</tr>
<tr>
<td>II</td>
<td>9-mm</td>
<td>124</td>
<td>1204</td>
</tr>
<tr>
<td>IIIa</td>
<td>9-mm</td>
<td>124</td>
<td>1430</td>
</tr>
</tbody>
</table>
Experimental Methods

Impact over the Sternum

Level II vest; 9 mm bullet; $IV = 1180$ ft/s
Experimental Results

Sternum Impact Location
(Heart sensor response)

<table>
<thead>
<tr>
<th>Level</th>
<th>Thickness (mm)</th>
<th>Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIIa</td>
<td>10.82</td>
<td>732</td>
</tr>
<tr>
<td>II</td>
<td>9.50</td>
<td>526</td>
</tr>
<tr>
<td>IIa</td>
<td>7.88</td>
<td>453</td>
</tr>
<tr>
<td>I</td>
<td>4.87</td>
<td>148</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Level</th>
<th>Pressure (kPa)</th>
<th>dP/dt (kPa/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>181</td>
<td>10170</td>
</tr>
<tr>
<td>II</td>
<td>359</td>
<td>18360</td>
</tr>
<tr>
<td>IIIa*</td>
<td>841</td>
<td>32260</td>
</tr>
</tbody>
</table>

* Impact location approximately 1” low
Experimental Results

Stomach Impact Location
(Stomach pressure response)

<table>
<thead>
<tr>
<th>Level</th>
<th>Thickness (mm)</th>
<th>Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIIa</td>
<td>10.82</td>
<td>732</td>
</tr>
<tr>
<td>II</td>
<td>9.50</td>
<td>526</td>
</tr>
<tr>
<td>IIa</td>
<td>7.88</td>
<td>453</td>
</tr>
<tr>
<td>I</td>
<td>4.87</td>
<td>148</td>
</tr>
</tbody>
</table>
**Experimental Results**

### Stomach Impact Location

*(Stomach and Liver response)*

<table>
<thead>
<tr>
<th>Test Level</th>
<th>Pressure (kPa)</th>
<th>dP/dt (kPa/ms)</th>
<th>Pressure (kPa)</th>
<th>dP/dt (kPa/ms)</th>
<th>Pressure (kPa)</th>
<th>dP/dt (kPa/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>517</td>
<td>25500</td>
<td>310</td>
<td>17700</td>
<td>69</td>
<td>4000</td>
</tr>
<tr>
<td>IIa</td>
<td>779</td>
<td>39400</td>
<td>469</td>
<td>33200</td>
<td>145</td>
<td>13500</td>
</tr>
<tr>
<td>II</td>
<td>1241</td>
<td>69200</td>
<td>979</td>
<td>65500</td>
<td>269</td>
<td>22300</td>
</tr>
<tr>
<td>IIIa</td>
<td>1682</td>
<td>98900</td>
<td>1406</td>
<td>69030</td>
<td>496</td>
<td>27800</td>
</tr>
</tbody>
</table>
Repeatability

9 mm Bullet at 1410 ft/s
Level IIIa Soft Armor Vest

- Stomach
- Left Lobe of the Liver
HSTM vs. HTFEM

(Left Lobe of the Liver)

9 mm bullet at 1090 ft/s
Level II soft armor vest

![Graph showing pressure vs. time for HSTM and FEM simulations](image)
Increasing severity of impact conditions produced rising initial peak pressures:

- Heart: $P_{\text{IIIa}} = 4.5 \times P_{\text{I}}$
- Stomach: $P_{\text{IIIa}} = 3.25 \times P_{\text{I}}$
- Vest thickness increase does not completely counteract impact energy increase

Pressures from sternal impacts less than those from stomach impacts:

- Bony structure dissipates energy
- Produces triple pressure spike

Peak pressure reduced in liver versus stomach
Increasing severity of impact conditions produced increasing rates of pressure change (dP/dt) follows trends similar to pressure peaks.
Clay/vest FEM validated for Level II impact
- Model adapted to produce Level I, IIa, and IIIa clay displacements due to vest Backface Signature (BFS)
- All vests “passed” since 44 mm BFS level not exceeded

Normalized values based on Level I results
- Pressure increases at a much steeper rate with each change in test condition
- Clay deformation change decreases with increased test conditions

<table>
<thead>
<tr>
<th>Test Level</th>
<th>Clay Deformation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>14.5</td>
</tr>
<tr>
<td>IIa</td>
<td>33.4</td>
</tr>
<tr>
<td>II</td>
<td>33.8</td>
</tr>
<tr>
<td>IIIa</td>
<td>36.4</td>
</tr>
</tbody>
</table>
Conclusions

- Surrogate torso models have been evaluated under NIJ-Standard 0101.04 impact conditions
  - Provides dynamic measurement of impact response
  - Differentiates between the severity of impact conditions
  - Demonstrates sensitivity to impact location

- Greater impact energy results in disproportionately greater increase in organ pressure versus clay deformation

- Torso models may provide additional information in assessing incapacitation from resulting injuries
  - Contribute to the development of optimal engagement equipment

- Future work:
  - Understand ceramic plates
  - Transfer function between PMHS injury and torso model response
  - Further development of biosimulant materials to improve model biofidelity
The authors would like to acknowledge the Office of Naval Research (ONR) for supporting this research under contract awards N00014-03-PD-2-0010 and N00014-04-PD-2-0279(1).