Development and Validation of TSFEM to Blunt Impact Based On Artificial Intelligence and Information Technology

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Abstract. The numerical simulation method is highly repeatable and has a short research cycle, which has been widely popular in predicting blunt ballistic impact to the thorax. A Thorax Simplified Finite Element Model (TSFEM) of projectile-structure interaction was developed by using ABAQUS software. The projectiles made of plastic stick which were used in Bir’s whole body impact testing. The force dynamic response, deflection dynamic response and force - deflection dynamic response were obtained, and validated with the test response corridors of the human body (PMHS) announced by the researchers of Wayne State University, we confirmed the finite element model can be used to predict the ballistic blunt thorax injury risk, in order to provide certain reference to further formulate and assess the design criterion and injury criterion of non-lethal kinetic energy weapons.

Keywords: Non-lethal Kinetic Energy Weapon, Blunt Impact, Thorax Simplified Finite Element Model, Dynamic Response

1. Introduction
Non-lethal kinetic energy weapons are widely used by the military, police and law enforcement agencies of all countries in the world where it is not necessary or suitable to use lethal weapons, such as handling large-scale mass incidents, anti-terrorism or peacekeeping operations to control crowds and avoid escalation. Unlike lethal weapons that can cause very serious or fatal injuries, the principle of non-lethal kinetic energy weapons is to use the terminal kinetic energy of the projectile or projectile fragments to hit living targets, through instantaneous blunt impact, it causes pain and injury, and thus loses resistance or inhibits action, the effect is reversible or non-serious injury. The injury caused by the kinetic energy projectile loaded with the non-lethal kinetic energy weapon was similar to the injury caused by the baseball, which had high kinetic energy and energy density, and still caused irreversible serious injury or even death in the actual combat application. In order to reduce the possibility of serious casualties, the shape design of the kinetic energy projectile had been developed from a cone to a round head or a bag shape, from the early hard plastic projectile, it had developed into a deformable projectile made of less dense and flexible materials. For example, the MP-4-R3 type impact baton in the United States was made of thermosetting plastic, the material of the ALS 4006D REACT type sponge projectile was polyurethane, and the material of the ALS1202 type 12 caliber ‘Rubber Fin
Rocket’ rubber sore block projectile was hard rubber. The material of CTS 2581 Super Sock bean bag was ballistic fiber. The improvement of the projectile material was reflected in its own certain viscoelasticity, which could absorb part of the impact energy through deformable energy, thereby reducing the force during impact and reducing the injury to the target, Reduced the risk of injury to the target, but some literature suggests [1, 2], When a kinetic energy projectile hits the body, It can result in rib fractures, heart or lung contusions, liver injury or fatalities head and neck injuries. All of these were contrary to the design concept and original intention of the use of non-lethal weapons that ‘incapacitate but not kill’ [3].

Therefore, the assessment and prediction of the potential risk of injury and the human terminal effect of non-lethal kinetic energy weapons are obviously the main concerns of designing, manufacturing, decision-making and using. Due to the diversity of kinetic energy projectiles and the complexity of human characteristics, this research was also very challenging. Using the postmortem human specimens (PMHS) and animal experiments as alternatives to obtain resources was difficult and expensive, and requires a multidisciplinary team to complete it. Not only that, the experiment itself was not repeatable and reproducible, also involved ethical and moral issues. In order to overcome the disadvantages of the above experimental methods as much as possible, bionic mechanical surrogates and bionic finite element models were used [4-10]. With the rapid development of numerical calculation methods, the finite element method had gradually become the main method for studying blunt trauma, which has the following advantages:

(1) The finite element method can be flexibly processed and solved when uneven material properties, arbitrary boundary conditions, and complex geometric shapes are mixed together.
(2) Not restricted by ethics, not restricted by experimental venues.
(3) Support more detailed analysis at global and local levels to obtain various physical variables in the material (such as stress, strain, velocity, acceleration, deflection, etc.).
(4) The research cycle is short, repeatable, and cost-effective.

HKS’s ABAQUS software is used as a finite element simulation tool for ballistic blunt impact. The software is good at analyzing complex structural mechanics systems, it can simulate highly non-linear problems, suitable for analyzing short and instantaneous dynamic events, and solving time display integration. In injury assessment, the thorax impact needs to be considered: due to the large surface area of the thorax, it is easy to be one of the main parts of the target to be hit, its low viscosity and low intercostal elastic limit. Mild bruising and laceration, severe rib fracture, broken ribs may puncture the internal organs, resulting in serious thorax injuries, such as pneumothorax, hemothorax, flail thorax, lung contusion, liver puncture, sternal fracture, cardiac contusion, aortic rupture, etc., if not timely treatment will be life-threatening. Researchers at Wayne Neutral University conducted PMHS impact test experiments [11]. the experimental objects were the thorax of 13 cadavers, three ballistic blunt impact tests were conducted respectively, and the corresponding thorax corridors were developed, which is the basic data source for the study of blunt impact of thorax. We intent to development a thorax simplified finite element model (TSFEM) for the assessment of thoracic injury, reproduce the impact test conditions of PMHS, and verify the biomechanical response of TSFEM under the same impact conditions through the thorax response corridors developed by Bir et al. In order to quickly and effectively test the injury risk of a non-lethal kinetic energy projectile, TSFEM was constructed to predict the thorax injury. By reconstructing the impact test conditions of PMHS and the thorax response corridor, the biomechanical response of TSFEM was verified to predict the thorax injury risk of this projectile.

2. Development of TSFEM

2.1. Geometry of the Model
Considering that blunt impact was only related to the local structure of the thorax, a simplified mechanical model ignoring the effects of boundary conditions can be developed. Set a three-layer thoracic model structure (from left to right) : muscles, ribs, and lungs, as shown in Fig. 1. The total
thickness of the model was 130mm, the length was 300mm, and the height was 100mm. Among them, the thickness of muscle layer was 20mm, rib layer was 10mm and lung layer was 100mm.

![Figure 1. TSFEM structure](image)

2.2. Material Properties
Each layer structure was defined as a uniformly distributed deformable solid, and the material properties were shown in Table 1.

|                  | Muscle | Rib   | Lung  |
|------------------|--------|-------|-------|
| $E$ (GPa)        | 2.2    | 7.9   | 7.4x10^{-4} |
| $\nu$            | 0.45   | 0.379 | 0.29  |
| $\rho$ (kg/m3)   | 1050   | 1561  | 600   |

2.3. Interactions
A general contact type (Explicit) was used for the interaction of the model. The contact surface included all outer surfaces and characteristic edges, and the contact property was tangential behavior, friction directionality was isotropic, the friction coeff was 0.15.

2.4. Meshing
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The nodes of each layer were closely connected, the element type of the whole model mesh was C3D8R (an 8-node linear brick, reduced integration, hourglass control.), in which the mesh number of muscle layer was 1356, rib layer 674, and lung layer 6750. The mesh division was shown in Fig. 2.

![Figure 2. Mesh generation of TSFEM](image)

3. Development of Projectile
Bir developed the thoracic response corridor by developing 13 PMHS shock tests, which were a data source for evaluating non-penetrating blunt shocks [11]. The impact test could be repeated in the absence of fractures of the ribs and sternum. The mechanical responses of 13 PMHS breasts under three different impact conditions were determined according to the change of impact force with time, the change of rib deflection with time and the change of impact force with deflection. Different results were given under three different ballistic impact conditions. The BIR corridors were used to verify the biomechanical response of TSFEM under the same conditions. The impactor used in the impact experiment was shown in Fig. 3.
The impactor was an incompressible plastic (PVC) baton projectile of different qualities, a non-lethal weapon for crowd control. The material properties were shown in Table 2. The three impact conditions of the cadaver experiment of the Bir research group were shown in Table 3.

**Table 2. Material properties for the projectile**

|                | Noncompressible PVC baton |
|----------------|---------------------------|
| $E$ (GPa)      | 2.3x10^-3                 |
| $\nu$          | 0.33                      |
| $\rho$ (kg/m³) | 1380                      |

**Table 3 Experimental impact condition**

| Type  | Length (mm) | Diameter (mm) | Mass (g) | Velocity (m/s) |
|-------|-------------|---------------|----------|----------------|
| A     | 100         | 37            | 140      | 20             |
| B     | 100         | 37            | 140      | 40             |
| C     | 28.5        | 37            | 30       | 60             |

The Mesh division of the projectile geometry model was carried out through the Mesh function module of ABAQUS. The approximate unit size is 2mm, the proportion of the minimum size control to the global size is 0.1, and the maximum deviation factor is 0.1. The nodes of the model were closely connected. The element type of the entire model mesh was C3D8R, Type A and Type B of the model mesh number was 19000, Type C 5334 model mesh, the mesh division was shown in Fig. 4.

### 4. Simulation Process

#### 4.1. Main Algorithm and Calculation Process

Transient dynamic analysis technology was used to deal with the collision problem of plastic stick projectile impacting human thrax. Transient dynamic analysis was a technique to determine the response of structures to time-varying loads. The equation of motion used for transient analysis was as follows:

$$
[M][\ddot{u}]+[C][\dot{u}]+[K][u]=[F(t)]
$$

Where, $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $u$ is the node displacement, $\dot{u}$ is the node velocity, $\ddot{u}$ is the node acceleration, and $F(t)$ is the load varying with time.

ABAQUS/Explicit used the central difference method to perform the Explicit time integral on the equation of motion. The dynamic conditions of the previous two incremental steps were used to calculate the dynamic conditions of the next incremental step. At the beginning of the incremental step, the program solved the dynamic equilibrium equation, which was expressed as the node mass $M$
multiplied by the node acceleration $\ddot{u}$ was equal to the reasonable node (the difference between the external force $P$ applied and the internal force $I$ of the unit), namely:

$$M\ddot{u} = p - i$$

(2)

At the beginning of the incremental step (time $t$), calculated the acceleration as

$$\ddot{u}(t) = \left( M \right)^{-1}(P - I)(t)$$

(3)

When calculating the change in velocity, the acceleration was assumed to be constant. The change value of velocity plus the midpoint of the previous incremental step was the velocity to determine the midpoint of the current incremental step:

$$\ddot{u} \left( t, \Delta t \right) = \ddot{u} \left( t, \Delta t \right) + \frac{\Delta t (t + \Delta t)}{2} \dot{u}(t)$$

(4)

The displacement at the end of the incremental step was determined by the integral of the velocity over time plus the displacement at the beginning of the incremental step:

$$u \left( t + \Delta t, \frac{\Delta t}{2} \right) = u \left( t \right) + \Delta t \left[ \ddot{u}(t) \right]$$

(5)

Show the calculation flow of dynamics unit:

1. According to the strain rate $\dot{\varepsilon}$, the element strain increment $d\varepsilon$ is calculated.
2. Calculate the stress $\sigma$ according to the constitutive relation:

$$\sigma \left( t, \Delta t \right) = f(\sigma(t), d\varepsilon)$$

(6)

3. Internal forces of integrated cell nodes $f(t, \omega)$.

4.2. Assembly

After TSFEM and projectile parts were created, Assembly function module was assembled in a unified integral coordinate system to make it a whole. The projectile was positioned by translation and rotation tools, as shown in Fig. 5.

![Figure 5. Model assembly drawing](image)

4.3. Set Analysis Steps and Boundary Conditions

The type of edit and analysis step was dynamic explicit, the time length was set to 4ms, the field output requests step was dynamic explicit, the frequency was evenly spaced time interval (200), the output at approximately time, and the output variables were force and deflection. The interaction mode was selected to general contact (Explicit), The predefined field type was velocity, which were 20m/s, 40m/s, and 60m/s. After completing the above pre-processing steps, the editing job type was complete analysis, and the job is submitted after the data check was correct.

5. Results

In the output of ODB field variables in the post-processing visualization module, deflection values and impact force values of the rib layer were selected respectively to obtain the force - time dynamic response, deflection - time dynamic response, and force - deflection dynamic response, which were compared with the response channels related to the corpse experimental data of the Bir research group, as shown in Fig. 6-8.
The situation where the above individual simulation resulted appears outside the corridors should be considered based on the assumption that the various layers were in direct contact and the materials were uniformly distributed. The body’s tissues, organs, and bones were in partial contact, and considering that the distribution of tissues and blood vessels was complex and non-uniform, there was a cross-border situation with the response corridors of the cadaver experiment. In general, the simulation results were within the corridors of the experiment of Bir’s research group, which can verify the bio-fidelity response of the TSFEM model to ballistic blunt impact.

The most commonly used and widely accepted viscosity standard of thoracic shock at the present stage, \( V_C \), which is defined as the peak value of the product of chest compression \( C(t) \) and compression velocity \( V(t) \), and \( C(t) \) is the amount of compression relative to the standardized chest thickness \( D_0 = 236 \text{mm} \), namely:

\[
V_C = \max[V(t) \cdot C(t)]
\]
Bir used viscosity criteria to predict rib injury risk, which was well correlated with injury assessment by PMHS test. The absence of a rib fracture found on the X-ray was considered AIS 0 (Abbreviated Injury Scale). According to the autopsy results of 13 PMHS, the AIS and VC\textsubscript{max} of different cadavers obtained under three impact conditions were listed, as shown in Fig. 9.

**Figure 9.** Calculated VC\textsubscript{max} values in relation to AIS injury parameter for cadaveric specimens tested VC\textsubscript{max} obtained by TSFEM numerical simulation and VC\textsubscript{max} obtained by Bir cadaver experiment were shown in Table 4.

| Specimen ID | Impact condition | VC\textsubscript{max} | AIS |
|-------------|------------------|------------------------|-----|
| 01          | A                | 0.24                   | 0   |
| 02          | A                | 0.65                   | 0   |
| 03          | B                | 0.14                   | 0   |

It can be seen from Table 4, VC\textsubscript{max} values all fall between the upper and lower limits of VC\textsubscript{max} obtained by Bir experiment. The cadaver data showed that VC\textsubscript{max}=0.8m/s corresponded with a 50% probability of thorax injury (rib fracture) with AIS≥2. According to the damage risk curve of VC\textsubscript{max} of AIS≥2, the injury risks of TSFEM under three impact conditions were obtained by plotting, as shown in Fig. 10.

**Figure 10.** The numerical VC\textsubscript{max} was plotted on the injury risk curve of AIS≥2 to VC\textsubscript{max} (from Bir’s experimental cadaver data.)

It could be seen from Figure 10:
A condition, the probability of AIS≥2 injury risk was 14%,
B condition, the probability of occurrence of AIS≥2 injury risk was 82%,
C condition, the probability of AIS≥2 injury risk was 6.5%.

The injury risks corresponding to the three impact conditions were basically consistent with the data in Fig. 10, in case B, AIS 2 or 3 injury risks occurred.
the diameter was predicted to be 37mm. That is, it was predicted that the threshold velocity when the impact projectile caused a rib fracture (50%) was 25.1 m/s.

6. Conclusion
Using TSFEM as a substitute to verify the impact simulation process of plastic sticks, it could be seen that TSFEM could be used to simulate the human thorax, and the dynamic response of force-time, the dynamic response of deflection-time, the dynamic response of force-deflection were in good agreement with the experimental data of cadaver impact.

The VCmax value was calculated by the viscosity standard, and it was determined that the injury risk probability of thorax AIS≥2 in the case of B impact was 82%, which was very similar to the corpse impact test data, and further verified the biological fidelity of TSFEM. On this basis, the ABAQUS software simulation predicted that the threshold velocity of the impact projectile causing AIS≥2 rib fracture (50%) was 25.1 m/s, that is, if the velocity is lower than this speed, the rib fracture may not be caused, which reduced risk of injury to the human body.

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