Comparative Study on Numerical Simulation of Thorax Blunt Impact Based on LS-DYNA Software Technology

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Abstract. In order to better predict the risk of blunt impact on human thorax, the LS-DYNA software was used to reproduce the launch conditions of the postmortem human specimens (PMHS) experiment of the Wayne State University research group. Numerical simulations of thorax blunt impact were carried out in combination with the human body model AM50 and Hybrid III 50th Dummy model. The projectiles of impact test were respectively 37mm in diameter, 100mm in length, 140g in mass, with an impact velocity of 20m/s and 40m/s, and 37mm in diameter, 28.5mm in length, 30g in weight, with an impact velocity of 60m/s. The numerical response of thoracic compression was obtained by simulation experiment, which was verified by comparison with the experimental data of PMHS. The displacement curves of the thoracic compression of the two models were both in the response corridors of PMHS by the simulation experiment, and the differences between two displacement curves were analyzed. The viscous standard of Dummy under three launch conditions was calculated to be within the boundary of VC max in PMHS experiment, which provided a certain theoretical reference for Dummy as a subsequent experimental research object.

1. Introduction

With the rapid development of computer and numerical simulation technology, the exploitation of finite element models has been widely used in evaluating the problem of blunt impact on the human body [1]. In various parts of the human body, the impact injury of the thorax needs to be considered: one is because the thorax has a large surface area, which is easy to be hit as one of the main parts of the target. the other is the complex structure of the thorax, adjacent to the head and neck, underneath the abdomen, and overlying the thorax cage, with the heart, lung and important blood vessels and nerves inside. Excessive blunt impact on this area may cause serious injury or even death. The exploitation of the finite element model based on the human anatomy structure and the dummy model specially designed with reference to the physiological characteristics of the actual human body has the advantages of economy, safety and reproducibility, which can provide an effective approach for the evaluation of blunt trauma to the human thorax.

The finite element model of human thorax was first created in 1970 and established by Roberts [2], all bones were made of linear elastic materials, ignoring surrounding soft tissues and only using static loading in this model. Roth et al. [3] established a combined finite element model of thoracic and abdominal cavity, they used dynamic and static loading methods in the experiment to reconstruct all the major organs, what was different from the past was that the thoracic and abdominal organs and organ spaces were endowed with fluid elements. Thota et al. [4] also pointed out that researchers had
begun to develop digital human (finite element) models as alternatives to cadavers in virtual test environments due to limitations such as the scarcity of cadavers, the absence of internal organs in simulated human body model, and the error ratio from animal experiments to human body model. Ndompetelo et al. [5] established a thorax finite element model different from the exact anatomical structure based on LS-DYNA software, in which the ribs were modeled as continuous entities with a constant elliptical cross section. Nsiampa et al. [6] pointed out that cadaver experiments were not repeatable and reproducible, and also had moral problems, and the use of biomimetic mechanical substitutes and biomimetic virtual substitutes (numerical models) became the main research means. Jonsson et al. [7] designed a anthropometric dummy specifically for explosion, blunt impact and projectile testing. Qi Wei et al. [8] used Hybrid III 50th percentile international standard dummy to carry out the thorax blunt impact experiment, which could effectively obtain the acceleration, displacement, kinetic energy and other data for evaluating the mechanical response of the dummy thorax, making it possible to quantitatively describe the injury of the human body subjected to kinetic impact. The above research showed that academics had chosen to varying degrees the thorax finite element model that approximates the structure of the human body for blunt impact injury evaluation, but seldom used a complete finite element model containing human tissues and organs. Therefore, the average size male (50th percentile) finite element model (AM50) developed by Toyota Motor Corporation and Toyota CENRAL development Laboratory in January 2021 and the Hybrid III 50th Dummy model developed by Hunan University were selected in this paper, as shown in Figure 1. This was validated by reconstructing the Wayne State Team’s PMHS (cadaveric) data to evaluate the risk of blunt impact trauma to the thorax.

Figure 1. AM50 and Hybrid III 50th Dummy models.

2. Model verification
The process of blunt impact on human body is reflected by the propagation of pressure wave, which usually manifested as large displacements and large strains, structural failure or damage[9]. In order to better understand these phenomena and the different injury mechanisms involved, numerical simulation LS-DYNA software has become mainstream. LS-DYNA was developed by Livermore Software Technologies (LSTC), it is the world’s most famous general-purpose explicit dynamic analysis program, capable of simulating a wide range of complex real-world problems. It is particularly suited to solving nonlinear dynamic impact problems such as high-velocity collisions, explosions, and metal forming of a variety of three-dimensional nonlinear structures.

2.1. Description of AM50
AM50 model has the anatomical structure of the human body, including 1285 parts, 1527480 solid elements, 442273 shell elements, 204 beam elements and 772172 nodes. The design of each component is based on the 50th percentile of a real person’s size, from the outside to the inside are skin, muscle, bone and organs. Since most human tissues are non-uniform and anisotropic, in order to facilitate the simulation, the materials of the AM50 are considered to be uniform and isotropic. The material properties of the different thoracic organs were shown in table 1.
Table 1. AM50 thorax tissue material properties

| Part        | Density [T/mm³] | Young modulus [Mpa] | Bulk modulus [Mpa] | Poisson’s ratio |
|-------------|-----------------|---------------------|--------------------|-----------------|
| Ribs        | 8.62E-10        | 40                  | -                  | 0.45            |
| Sternum     | 8.62E-10        | 40                  | -                  | 0.45            |
| Skin        | 1.1E-9          | 11                  | -                  | 0.4             |
| Spon        | 1.0E-9          | 40                  | -                  | 0.45            |
| Pleura      | 1.0E-9          | 0.55                | -                  | 0.45            |
| Diaphragm   | 1.0E-9          | 0.122               | -                  | 0.45            |
| Sternum     | 8.62E-10        | 40                  | -                  | 0.45            |
| Costal cartilage | 1.0E-9   | 29              | -                  | 0.4             |
| Heart       | 1.0E-9          | -                   | 100                | -               |
| Lung        | 1.29E-12        | -                   | 1.4                | -               |

2.2. Description of Dummy

The dimensions, mass distribution, joint movement and other features of the Hybrid III 50th percentile dummy are specially designed with reference to the physiological characteristics of the actual human body, including 367 parts, 225602 solid elements, 225910 shell elements, 256 beam elements and 276025 nodes. In terms of biomechanical properties, the head, neck, chest, lumbar vertebrae, upper limbs, buttocks, thighs, calves and feet of the dummy’s body parts are designed on the basis of data referenced to a series of cadaver experiments and volunteer experiment data and a large number of anatomy, which learned from the advantages of previous multi-generation dummies. Dummy’s materials are uniform and isotropic, and the material properties of the main parts of its chest are shown in table 2.

Table 2. AM50 thorax tissue material properties

| Part          | Density [T/mm³] | Young modulus [Mpa] | Poisson’s ratio |
|---------------|-----------------|---------------------|----------------|
| Chest Pad     | 1.0E-9          | 0.023               | 0.3            |
| Bib Assembly Doubler | 1.14E-9    | 500                 | 0.3            |
| Front End Stiffener Plate  | 7.89E-9   | 210000              | 0.3            |
| Ribs Steel    | 7.89E-9        | 210000              | 0.3            |
| Sternum Assembly | 3.2E-9      | 70000               | 0.3            |
| Chest Pad     | 1.0E-9         | 0.023               | 0.3            |

2.3. Reproduction of launch conditions

According to the NATO standard AEP-99[10], the verification of the thorax numerical model requires reference to the baseline data of the PMHS experiment at Wayne State University. The L5 projectile used in the PMHS experiment is made of incompressible polyvinyl chloride (PVC) material. The material properties are shown in table 3. We draw the model through UG10.0, and then used HyperMesh 2019 to divide the mesh as shown in figure 2.
Table 3. L5 material characteristics

| Condition | Density [T/mm³] | Young modulus [Mpa] | Poisson’s ratio | Number of elements |
|-----------|----------------|----------------------|----------------|--------------------|
| A         | 1.38E-9        | 2300                 | 0.33           | 6732               |
| B         | 1.38E-9        | 2300                 | 0.33           | 6732               |
| C         | 1.38E-9        | 2300                 | 0.33           | 2040               |

In conditions A and B of PMHS experiment, L5 projectile with length of 100mm and mass of 140g impacted the body at the velocity of 20m/s and 40m/s respectively. In condition C, the L5 projectile with a length of 28.5mm and a mass of 30g impacts the body at a velocity of 60m/s. Reproduced the above three situations, the impact of L5 with AM50 and Dummy should be normal to the thoracic surface with a 0° yaw angle, as shown in figure 3.

3. Result and discussion

In order to verify the model, according to the PMHS experimental results of Wayne State University [11], combined with the biomechanical response corridor determined by three impact conditions, the forward impact AM50 of L5 projectile and the thorax of dummy model under three same conditions were respectively reproduced, and the thoracic compression curves of the two models were calculated, as shown in figure 4 and figure 5.
Compression curves are lower than the lower boundary of the response corridor in the rear section. This is because the objects of PMHS test were the elderly (the average life span is 73 years). As the age increases, the changes in the biological structure of the human body reduce the tolerance of thorax injury [12], therefore, the thoracic compression curve of PMHS experiment basically shows an upward trend, while AM50 and dummy model materials are evenly distributed and isotropic, there is a certain degree of tolerance to the impact of L5 projectile, so some curve segments are not in the corridors.

Under the same launch conditions, it is found that the dummy responds faster to the impact of the L5 projectile, the time to reach the maximum thoracic compression are shorter than AM50, and the maximum displacements are smaller than AM50. This is because the dummy models are mostly made of steel or aluminum compared with the rubber and foam materials of AM50, the material of Dummy have stronger resistance and stronger ability to resist deformation.

In order to further evaluate the risk of injury to the thorax of Dummy, the widely used viscous standard of thorax impact \( (VC_{\text{max}}) \) [13] was adopted. It is defined as the peak value of the product of thoracic compression \( C(t) \) and compression speed \( V(t) \), and \( C(t) \) is the amount of compression relative to the standardized thoracic thickness \( D_0 = 236 \text{mm} \), namely:

\[
VC_{\text{max}} = V(t) \cdot C(t) = \frac{dD(t)}{dt} \cdot \frac{D(t)}{D_0}
\]

Thoracic compression (initial thickness 270mm) of Dummy was processed by MATBLE, and the curves \( VC_{\text{max}} \) obtained were shown in figure 6. Table 4 showed the results of \( VC_{\text{max}} \) under three launch conditions, all of which were within the PMHS experimental boundary. Therefore, Dummy had been verified to be used to simulate blunt impact experiments on the human thorax.

**Table 4. \( VC_{\text{max}} \) obtained by numerical simulation and PMHS**

| Condition | Min | Max  | Numerical simulation |
|-----------|-----|------|----------------------|
| A         | 0.24| 0.51 | 0.255                |
| B         | 0.65| 2.35 | 1.095                |
| C         | 0.14| 0.60 | 0.574                |

**4. Conclusion**

By reconstructing the launch conditions of PMHS experiment in Wayne State University, L5 plastic stick projectile was used to simulate the thorax of AM50 and Hybrid III 50th Dummy respectively. It was calculated that the thoracic compressions were basically within the PMHS viscous response corridors. The similarities and differences of thoracic compression curves of the two models were found and analyzed. Finally, the viscous standard of Dummy under three launch conditions were calculated to be within the boundary of \( VC_{\text{max}} \) in PMHS experiment. Therefore, the Dummy model was verified, which provided a certain theoretical reference for the dummy as a subsequent experimental research object.
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