Validation of Human Finite Element Model for Non-Lethal Blunt Ballistic Impact Damage Assessment

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Abstract. To validate digital human thorax targets suitable for blunt ballistic impact damage assessment, based on the NATO STANDARD AEP-99 THORAX INJURY RISK ASSESSMENT OF NON-LETHAL PROJECTILES numerical validation method, The L5 digital model of a non-lethal kinetic energy projectile is constructed by finite element method and the digital target of Hybrid III 50th% Dummy is hit. The data is processed and verified by Bir biomechanical corridor and viscosity standard. The results show that Hybrid III 50th% Dummy digital target can be used for assessment of blunt ballistic impact damage of non-lethal kinetic energy projectile on human thorax, providing a reference for simulation setting of blunt impact study of non-lethal kinetic energy projectile on human thorax. It can lay a theoretical foundation for constructing and verifying the Chinese 50 percentile human thorax digital target for blunt ballistic impact damage assessment.

Keywords: Thorax digital target; Biomechanical corridor; Viscosity criteria; Passive ballistic impact; Endpoint effect

1 Introduction

Non-fatal kinetic energy impact damage is blunt ballistic damage [1]. Impact to the thorax is a major consideration when assessing the power of blunt ballistic damage, since it is one of the most commonly impacted areas, and since the thorax includes vital human organs, a non-lethal kinetic energy projectile can cause serious injury or even death by impacting the area. Foreign researchers often use Finite Element models of Human body or bionic human thorax to simulate experimental working conditions. Nsiampa[2] constructed and verified the Surrogate Human Thorax For Impact Model (SHTIM), a finite element model for thorax damage assessment, and conducted a comparative study on impact damage assessment of six kinds of non-lethal kinetic energy projectile based on viscosity criteria. Bracq et al. [3] used a non-lethal kinetic energy projectile Flash-Ball finite element model to impact the thorax of HUByx finite element model to identify model-related numerical indicators for predicting blunt trauma to the lung and heart. Compared with foreign countries, non-lethal blunt ballistic impact damage assessment started late in China and is in the stage of tracking simulation. By constructing and verifying the 18.4mm rubber bullet finite element model and impacting the improved thorax blunt impact damage assessment model MTHOTA-I, Wang Song [4] et al gave suggestions on the safe use of 18.4mm rubber bullets at different shooting distances by using the viscosity standard. LU Haitao[5] et al. built and verified a finite element model of human torso with relatively complete anatomical features based on the Chinese visual human body dataset, analyzed the damage to human tissues and organs caused by non-lethal kinetic energy projectile impacting the thorax, and put forward suggestions on its effectiveness and safety.

Although the domestic results maintain a good consistency with the foreign research results, the specific details of the existing studies are rarely disclosed, which makes it difficult to provide referable simulation samples of non-lethal blunt ballistic impact experimental conditions. In this paper, a non-lethal kinetic energy missile L5 finite element model and a blunt impact Hybrid III 50th% finite element model are constructed, and data processing is performed according to the NATO STANDARD AEP-99 THORAX INJURY RISK ASSESSMENT OF NON-LETHAL PROJECTILES (AEP-99). By comparing and analyzing the data of Bir biomechanical corridor and viscosity standard, it is verified that Hybrid III 50th% finite element model is suitable for the assessment of blunt ballistic impact damage of non-lethal kinetic energy projectile on human thorax. It can provide a reference for the simulation setting of the endpoint effect of different types of non-lethal kinetic energy projectiles on the human body, and then lay a theoretical foundation for the construction and verification of Chinese 50th% human thorax physical and digital targets for the assessment of blunt ballistic impact damage of non-lethal kinetic energy projectiles.

2 Hybrid III 50th% Finite Element Model

Hybrid III 50th% finite element model (Hereinafter referred to as dummy) is a digital model developed by Livermore Software Technology Corporation based on the anthropomorphic test device Hybrid III 50th% solid sitting dummy. It contains 279,203 nodes, 256 beam units, 238,052 shell units, 227,632 solid units, using the mm-ms-kg-kN unit system. Compared with the human thorax, the dummy model has a simplified thorax design, lacking organs and soft tissue fillings. Qi Wei et al. [6] verified the feasibility of using dummies for the assessment of human thorax damage caused by impact of most non-lethal kinetic energy weapons through blunt impact tests. Zhao Fadong and Chen Chaoming et al. [7, 8]carried out a study on verification and damage assessment of the finite element model of non-lethal kinetic energy projectile impact Hybrid III. Its appearance is shown in Figure 1, and its main parameters are shown in Table 1.

(a) Front view (b) Side view (c) Top view

Fig. 1. Hybrid III finite element model.

Table 1. Hybrid III finite element model parameters.

Part	Material	Density /(kg/m^3)	Young modulus /Pa	PR
Jacket	Viscoelastic	794	/	/
Chestpad	Viscous foam	450	/	0.05
SternumAssembly	Elastic	3200	7E+10	0.3
ClavicleLink Assembly	Elastic	2700	7E+10	0.3
RibsSteel	Elastic	7890	2.1E+11	0.3

According to the requirements of Bir impact on cadaver experiment conditions [9], the projectile was selected to impact the thorax of the dummy in a positive direction, and the impact position was the center of the third rib of the dummy directly to the skin surface node. The impact point is shown in the Figure 2.

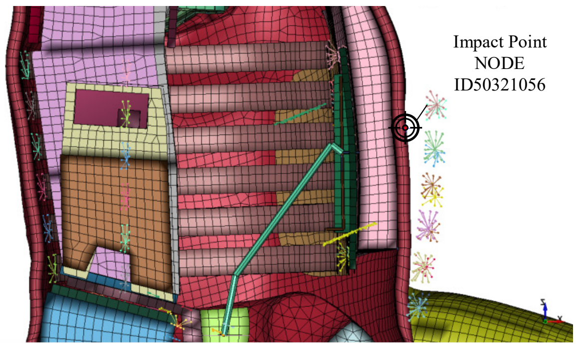


Fig. 2. Hybrid III finite element model impact position.

3 Construction of L5 Projectile Finite Element Model

The L5 cylindrical projectile, made of incompressible polyvinyl chloride (PVC) material, comes in two types, long and short, with a diameter of 37 mm and a mass of 140 g and 30 g respectively. These projectiles, which are generally considered rigid projectiles, are used to define biomechanical corridors in Bir impact cadaver experiments [1]. The L5 projectiles are made of *MAT-001 ELASTIC[10], and its physical diagram and grid division diagram are shown in Figure 3. their physical and grid drawings are shown in Figure 3.

(a) Projectile physical diagram (b) Projectile meshing model diagram

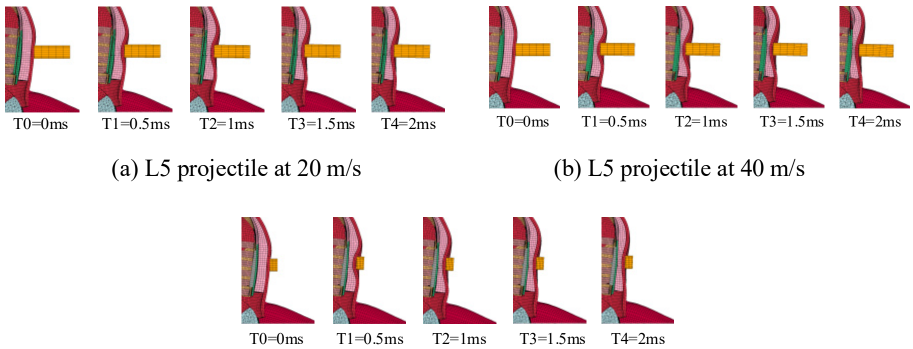
Fig. 3. L5 projectile.

4 Verification Method and Simulation Setting of Human Thorax Digital Model

AEP-99[10,11] specifies the verification method of human thorax model. Take the L5 long projectile to the vertical impact reference point of 20 m/s and 40 m/s, and the L5 short projectile to the vertical impact reference point of 60 m/s, and measure the displacement signal output as a function of time, and calculate VCmax according to the viscosity standard. The finite element model of human thorax suitable for non-fatal blunt ballistic impact damage assessment was successfully validated when it met the corridor interval defined by AEP-99.

Lagrange algorithm is used to characterize the precise change of impact process. At the same time, several materials of the dummy are bio-soft materials with low elastic modulus and large calculation step size, which is defined as *CONTACT_TIMESTEP TSSFAC and assigned a value of 0.67. Execute the *SET_PART_LIST command to participate in the entire impact simulation as a whole. For contact, use *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. To consider the volume cell calculations during simulation, execute the *CONTROL_SOLID command. Enter the termination command with the experimental data, and run the *CONTROL_TERMINATION command. Set ENDTIME to 4. Run *INTIAL_VELOCITY to add the initial speed. The simulation of impact test conditions is shown in Figure 4.

The L5 projectile, as a rigid body, has no obvious deformation during the whole impact process, and the impact site of the dummy has two stages: compression (loading) and rebound (unloading). In the compression (loading) stage, the thorax is continuously compressed in the direction of projectile velocity by projectile impact. The L5 projectile with an initial velocity of 20 m/s reaches the maximum compression displacement peak after T4, and the L5 projectile with an initial velocity of 40 m/s reaches the maximum compression displacement peak between T1 and T2. The L5 projectile with an initial velocity of 60 m/s reaches the peak compression displacement after T4. After the rebound (unloading) stage, the compression of chest displacement decreased, but did not show significant recovery at 5ms.



(a) L5 projectile at 20 m/s

(b) L5 projectile at 40 m/s

(c) L5 projectile at 60 m/s

Fig. 4. Sectional impact sequence of L5 projectiles at different velocity.

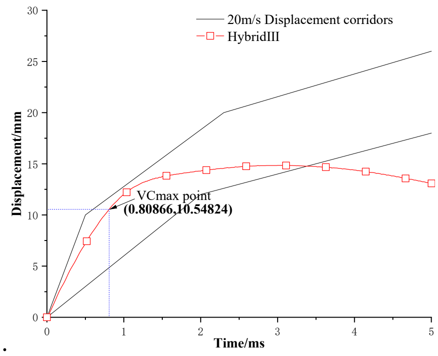
5 Digital Model Data Processing and Result Analysis

The finite element model of the human thorax for non-lethal blunt ballistic impact damage assessment was validated by Bir biomechanical corridor and viscosity criteria. The viscosity criterion, is based on the dynamic deflection of the rib cage and is determined by the viscous response, which is the product of the rib cage deflection (compression) and the rib cage deflection rate normalized by the thickness of the thorax wall. The viscosity criterion VCmax is defined as the maximum viscous response of the thoracic cavity. Bir et al. [10] showed that VCmax could be used to assess the risk of non-lethal blunt ballistic impact damage. Its formula is shown in equation (1) and (2).

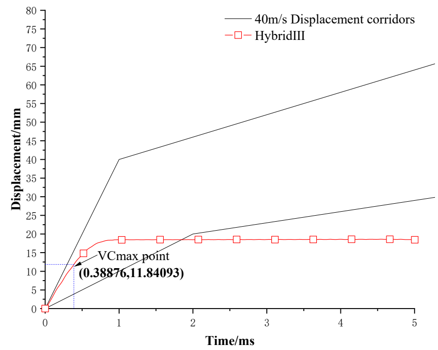
$$Visous\ reponse = (v(t) \times C(t)) \tag{1}$$

$$VC_{\max} = (v(t) \times C(t))_{\max} \tag{2}$$

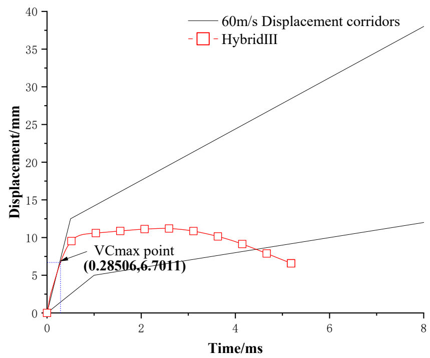
Where, the mean compression *C(t)* is expressed as the ratio between the displacement *d(t)* measured at the impact point and the length d_0=0.236m. *V(t)* is the velocity of the impact point. According to the AEP-99, test results need to be filtered and normalized by CFC1000. The digital filtering process adopts ISO 648:2015, SAEJ211, using a four-order Butterworth low-pass filter (CFC). Displacement-time curves under three experimental conditions of 20 m/s, 40 m/s, 60 m/s and VC-time curves are shown in Figure 5 and Table 2.



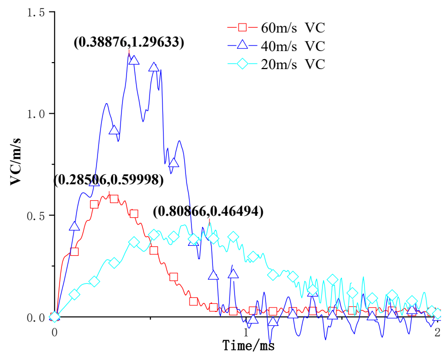
(a)20 m/s data



(b)40 m/s data



(c)60 m/s data



(d)VC data

Fig. 5. L5 projectile data at 20, 40, 60 m/s

The thorax compression of the dummy under three experimental conditions of 20 m/s, 40 m/s and 60 m/s presents an upward trend of first fast, then slow and then decline. In the early stage of impact (t= 1.22ms under 20 m/s, t= 0.80ms under 40 m/s, and t= 0.67ms under 60 m/s), the thorax compression growth rate of the dummy is fast and close to the upper limit of displacement corridor. In the middle stage of impact (t= 3.37ms under 20 m/s, t= 1.84ms under 40 m/s, and t= 4.40ms under 60 m/s), the thorax compression growth rate of the dummy is slow, and the thorax compression peaks are generated, whose peak points are (3.01188, 14.84333) (1.51889, 18.49585) (2.48309, 11.21813), and then a downward trend, close to the lower limit of the displacement corridor; At the later stage of impact, the thorax compression of the dummy is lower than the lower limit of displacement corridor and tends to zero. From the whole impact process, it is found that the thorax compression displacement-time of the dummy is not completely in the corridor. On the one hand, because the dummy is a certain rigid response. On the other hand, according to the cadaveric experiment, the cadaveric bodies used in the experiment lack physiological characteristics, and most of them are over 70 years old, and the skin and tissue aging lack tolerance, so the displacement range continues to rise.

The point coordinates (0.80866, 10.54824), (0.38876, 11.84093) and (0.28506, 6.7011) correspond to the point coordinates of VCmax in its working condition, and the point coordinates and the previous displacement-time curves are all in the corridor. As shown in Table 2, VCmax values under the three working conditions all meet the defined interval, indicating that the dummy can be used to evaluate non-fatal blunt ballistic impact human thorax injury.

Table 2. Impact case and VCmax comparing with PMHS.

Case	Projectile	Velocity /(m/s)	*VC*max corridor /(m/s)	Simulated Result	
				*VC*max/(m/s)	$t_{VC\max}$/(ms)
1	140g L5	20	(0.24，0.51)	0.464 94	0.808 66
2	140g L5	40	(0.65，2.35)	1.296 33	0.388 76
3	30g L5	60	(0.14，0.60)	0.599 98	0.285 06

6 Conclusion

In this paper, the AEP-99 method is adopted to construct the finite element model of L5 projectile and conduct the experimental simulation of the thorax blunt impact of the dummy. Through the Bir biomechanical corridor and the viscosity criterion comparison, the effectiveness of the dummy for evaluating the thorax injury of non-lethal blunt ballistic impact is verified. The next step can be to develop a digital target for Chinese human thorax combined with Chinese human body characteristics, so as to promote the establishment of a standardized document suitable for the assessment of human thorax injury by blunt impact of non-lethal kinetic energy projectiles in China.

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