Research on Modeling and Simulation of Head Injury Assessment Based on LSDYNA Software Technology

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Abstract. In the anti-terrorism and anti-riot missions, there have been many kinds of excessive injury caused by the use of kinetic energy projectiles as a non-lethal weapon, so it is urgent to predict its wounding effect scientifically in order to assess the safety in actual combat. In order to study the injury power of SIR-X sponge grenade (SIR-X for short) impacting the head, LSDYNA software was used to simulate the process of SIR-X vertically impacting the temporal region of the head of the fourth generation THUMS 50 percentile standing virtual human AM50 model (AM50 for short). Taking the maximum effective range of the SIR-X as a reference, the maximum TICP and contact force at the corresponding impact velocity of 86m/s were calculated to be 178.25kPa and 9.516kN, respectively. Both results are bigger than the brain injury thresholds for the human maximum transient intracranial pressure inside the cisterna magna and the maximum force on the human head, severe skull fractures were likely to occur.

1. Introduction

Blunt ballistic impact trauma is a hot issue in current research [1]. Its growing importance is mainly due to the widespread use of non-lethal kinetic energy weapons in anti-terrorism and riot control missions, which are used to incapacitate dangerous personnel or control rioting crowds to prevent violent, suspicious or dangerous behavior. The first use of non-lethal kinetic energy projectiles was during labor riots in Hong Kong in the 1950s, when wooden baton materials were converted into wooden projectiles and fired by ‘RUC riot gun’ and ‘Verey Pistol’ [2]. The potential for excessive injury due to design defects or improper use is irreversible, which leads to numerous reports of disability and death caused by kinetic energy projectiles, especially head impact [3-7]. Therefore, there is a need for further scientific assessment of the risk of head impact injury so that non-lethal kinetic energy projectiles can be used more safely.

In order to better protect the head and minimize the injury caused by blunt ballistic impact, it is necessary to study its tolerance. Researchers around the world have carried out studies on the impact of cadaver heads, animal heads, and solid head models. These experiments were accompanied by the development of computing technology, and finite element (FE) models of the head were constantly being developed for more in-depth biomechanical research. This research used the THUMS 50 percentile standing posture virtual human model AM50 (AM50 for short) developed by Toyota Motor Corporation and Toyota CENRAL R&D Laboratory. The AM50 simulates the internal structure of the human body based on human anatomy, which can accurately assess the impacting injury of various parts of the human body. The cranial model of the AM50 includes: scalp, skull, brain, brainstem, meninges, etc. The meninges include pia mater, dura mater, and arachnoid; the model uses solid units
to simulate bones, shell units simulate thin films and 1D units simulate thin Muscle tissue, as shown in figure 1.

**Figure 1. AM50 head model**

2. **Assessment criteria for head injury**

The head injury assessment of the NATO standard framework AEP-103 [8] indicates that the areas causing head injuries are the frontal, temporal and apical regions, as shown in figure 2.

**Figure 2. Anatomical positions of the frontal, temporal, parietal, and cisterna magna**

Two criteria predict the severity of brain injuries due to the impact of a non-lethal projectile. The first criterion is the maximal value of the Transient Intracranial Pressure, TICP (threshold measured during Post-Mortem Human Subject, PMHS, and animal tests). The second criterion is the maximal contact force (threshold calculated by a numerical model based on the intracranial pressure data). Table 1 presents different severities of injuries to the brain correlated with the maximum TICP, measured inside the magna cisterna, or correlated with the contact force.

| Injury severity | Maximal value of the Transient Intracranial Pressure in the cisterna magna [kPa] | Maximum force on the human head [kN] |
|-----------------|---------------------------------|----------------------------------|
| Minimum risk of loss of consciousness | value < 25 | value < 2.2 |
| Risk of loss of consciousness (< 30 min) | 25 ≤ value < 45 | 2.2 ≤ value < 3.6 |
| Risk of intracranial hematoma and coma | 45 ≤ value < 150 | 3.6 ≤ value < 7.4 |
| Significant risk of fracture | 150 ≤ value | 7.4 ≤ value |
3. Impact modeling

3.1. Modeling of SIR-X
The reference projectile for the NATO standard framework AEP-103 used to perform model validation and calibration is the 40mm B&T SIR-X sponge grenade (SIR-X for short), as shown in figure 3. The projectile is 62.2mm long, with a diameter of 40mm, a total weight of 32g, a deformable nose of 6.6g and a plastic body of 25.2g. In LSDYNA, the deformable nose material is No. 181 simplified rubber, and the plastic body is No. 1 elastic material (polyurethane sponge material). The material properties are shown in Table 2.

![Figure 3. B&T SIR-X sponge grenade](image)

| Parts | Density (kg/m³) | Bulk modulus (MPa) | Poisson’s ratio | HU | SHAPE |
|-------|----------------|--------------------|----------------|----|-------|
| Nose  | 231            | 3000               | 0.2            | 0.2| 15    |
| Sabot | 1354           | 2300               | 0.387          | —  | —     |

In AEP 103, in order to verify the numerical model of SIR-X, forward vertical impacting simulations were required on a completely rigid wall at 29m/s and 61m/s respectively. The axial displacement curves corresponding to the impact direction of SIR-X nose at the two velocities should be within the response boundary (as shown in Table 3), which were used to verify the validity of the SIR-X numerical model.

| Time corridor min [ms] | Displacement corridor min [mm] | Time corridor max [ms] | Displacement corridor max [mm] |
|------------------------|--------------------------------|------------------------|--------------------------------|
| 0                      | 0                              | 0                      | 0                              |
| 0.1                    | 2                              | 0.1                    | 6                              |
| 0.7                    | 16                             | 0.3                    | 19                             |
| 0.9                    | 17                             | 1                      | 21                             |
| 1.5                    | 12                             | 1.5                    | 15                             |

| Time corridor min [ms] | Displacement corridor min [mm] | Time corridor max [ms] | Displacement corridor max [mm] |
|------------------------|--------------------------------|------------------------|--------------------------------|
| 0                      | 0                              | 0                      | 0                              |
| 0.1                    | 2                              | 0.1                    | 6                              |
| 0.7                    | 16                             | 0.3                    | 19                             |
| 0.9                    | 17                             | 1                      | 21                             |
| 1.5                    | 12                             | 1.5                    | 15                             |

Through LSDYNA simulation, figure 4 shew the axial displacement corresponding to the impact direction of SIR-X at two velocities respectively. Since the curves were basically in the corridor, it could be considered that the finite element model of SIR-X could be verified.
3.2. Validation of AM50

The SIR-X impacted the temporal region of the AM50 head, as shown in figure 5.

According to LSDYNA simulation, figure 6 showed the TICP and contact force of SIR-X vertically impacting on the head temporal region of AM50 model at three velocities, and their maximum values were respectively within the response range of AEP-103 (Table 4). It could be considered that the AM50 model based on SIR-X impacting could be verified.

| Velocity (m/s) | Max TICP (kPa) | Max Contact Force (kN) |
|---------------|----------------|------------------------|
| 48.8          | 24.4≤value≤57.7 | 47.85                  |
| 59.2          | 46.2≤value≤101.1 | 73.58                  |
| 79.5          | 150.9≤value≤342.3 | 165.23                 |
4. Result and discussion

Based on the above validation of SIR-X and AM50 models, we further assessed the injury risk of SIR-X impacting the head in practical applications. In the assessment process, the impact condition (especially the impact velocity and impact angle) and the impact position of the projectile are the most important, which are mainly used for risk injury assessment. These depend on the initial velocity of the projectile, the external environmental conditions, the ballistic characteristics of the projectile and the distance of the projectile launch. The relationship between the projectile velocity and the engagement distance was given by the hysteresis function (Equation 1), which was determined by experimental fitting [10].

\[ V = V_0 e^{-\lambda s} \quad \text{with} \quad \lambda = \frac{\pi d^2 \rho_{\text{air}} CD_0}{8m} \quad (1) \]

In Equation 1, \( V_0 \), \( V \), \( d \), \( m \), \( \rho_{\text{air}} \) and \( CD_0 \) represent the initial velocity of the projectile, the projectile velocity corresponding to the engagement distance, the diameter of the projectile, the air density (1.206 kg/m\(^3\)) and the drag coefficient (0.2) respectively. The closer the engagement, the higher the corresponding velocity, and the higher the risk of serious injury to the target.

The maximum effective range of SIR-X is about 40m, and the corresponding impact velocity is calculated as 86m/s according to Equation 1. The maximum injury is taken the position of the projectile impacting the temporal region of the head vertically in the forward direction, and the falling distance of the projectile in the flight process is not considered, the maximum TICP was 178.25kPa and the maximum contact force was 9.516kN through LSDYNA simulation. Both results were bigger than the injury threshold shown in Table 1. The target was likely to have a severe skull fracture and on-site coma.

In actual combat applications, the use of non-lethal kinetic energy weapons is strictly prohibited to target the head and neck of the human body, because these two parts contain many important organs, tissues and nerves of the human body, and they are usually exposed to the external environment, which causes vulnerable to serious injury. However, due to the complex and chaotic environment of the battlefield, it is inevitable that the operator may accidentally injure the target in the head, so we did a risk assessment of the temporal region of the head here, and concluded that the target is likely to be very dangerous.

5. Conclusion

In order to scientifically assess the injury power of SIR-X impacting the head, the effectiveness of SIR-X and AM50 models were verified according to NATO standard framework AEP-103. Taking the maximum effective range of the SIR-X as a reference, the maximum TICP and contact force at the corresponding impact velocity of 86m/s were calculated to be 178.25kPa and 9.516kN, respectively. Both results are bigger than brain injury thresholds for the human maximum transient intracranial pressure inside the cisterna magna and the maximum force on the human head, the most serious injury would occurred, it is likely to have a severe skull fracture and accompanied by a coma. It is suggested that aiming at the head of the human body is strictly prohibited. In the following research of head impact injury, the injury assessment of the parietal region and frontal region can be added, and the yaw angle of the projectile impact can be adjusted at the same time, from which the injury rule of the projectile impact on the head can be explored under the impact of different regions and different yaw angles.

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