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Evaluation of the blunt thoracic trauma due to baseball impacts – Review of the Blunt Criterion

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Abstract: Evaluation of the thoracic injury due to blunt impacts during the contact and collision sports activity is crucial for the development and validation of the chest protectors and safety solid sports for the athletes. In the case of young athletes, proper chest protectors can avoid not only severe chest trauma but also protect them from the sudden death due to commotio-cordis. In order to evaluate the thoracic injury in terms of known engineering parameters (Viscous Criterion), non-linear finite element simulations were carried out by impacting FE model of the thorax surrogate (MTHOTA- Mechanical THOrax for Trauma Assessment) with a synthetic baseball and a synthetic baseball of the same size and weight at the impact speed of 10 – 45 m/s (with an increment of 5 m/s). Synthetic baseball and soft-core baseball produced VC_{max} = 1 m/s at the impact speed of 27.9 m/s and 30.7 m/s respectively. For both sports ball impact cases, Blunt Criterion (which is commonly used as non-lethal munitions design criterion that takes only kinetic energy of the projectile and weight & geometry of the thorax into consideration) was evaluated for all impact cases of two types of baseballs. Results have revealed the projectile specificity of the Blunt Criterion.

Keywords: collision and contact sports, baseball, viscoelasticity, MTHOTA, thoracic injury, viscous criterion, blunt criterion.

Introduction

Injuries to the head, thorax, upper and lower limbs are very common during every sports. In the case of a baseball game, injuries could be due to collision between players, collision with the barricades, due to movements of the body parts and due to the impacts of the solid sports balls and pucks used by the athletes for the sport activity (Bell [1], Elliott *et al* [2], Abrunzo [3], Finch *et al* [4]). Blunt thoracic trauma due to only baseball impacts was considered for the study. Baseball impacts can cause blunt chest trauma ranging from minor sprains and bruises to chest wall injury including rib fractures. The latter depending upon the location and number, may be further complicated by secondary phenomenon like flail chest, pulmonary contusion, hemothorax, pneumothroax, rupture of the aorta, among others.

Blunt chest impacts by solid sports ball, depending upon the location and time of impact with respect to the heart cycle, can also cause fatal injury called commotio-cordis, which is a cardiac arrhythmia caused by the functional re-entry and ventricular fibrillation (Doerer *et al* [5], BLAS *et al* [6], Madias *et al* [7]). From the work of many researchers (Madias *et al* [7], Maron *et al* [8], Link *et al* [9], Link *et al* [10]), it is now established that commotio-cordis is caused by blunt impacts on the cardiac silhouette (para-sternal area). The second pre-condition for commotio-cordis relates to the timing of the impact in relation to the cardiac cycle which must occur during a window in the cardiac cycle when the myocardium is particularly electrically vulnerable for inhomogeneous dispersion of repolarization triggering ventricular fibrillation. This period of the cardiac cycle is during the upslope of the T wave, just before it reaches its peak. Stated simply, such low-frequency impacts, although innocuous in causing structural myocardial damage, lead to commotio-cordis because they happen at the wrong place and wrong time, leading to abnormal cardiac rhythm instead of the normal period of relaxation preceding the next contraction. Due to its peculiarly specific nature, commotio-cordis has to be dealt separately from the structural damage related aspects. Therefore, only structural damage related thoracic injuries caused by the baseball impacts were evaluated and presented. Viscous criterion, which is the product of the chest deformation velocity and chest compression, is the best predictor of the structural damage of the thorax and is used throughout the paper.

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Very limited research has been carried out in the area of evaluation of blunt chest trauma due to solid sports ball impacts. Janda *et al* [11] have impacted thoraces of the child crash test dummy and 5th percentile adult female Hybrid III dummy with baseballs and evaluated viscous responses. However, the dummies used in the experiments were validated and only suitable for the usage as vehicular occupants in the simulated crash tests. Janda *et al* [12] have furthered his own experimental study using the 3-RCS thorax surrogate by impacting it with the soft-core baseballs at 17.9, 22.4 and 26.8 m/s impact speeds. From the study, it was concluded that, soft-core baseballs offer no protection against commotio-cordis in comparison with the standard baseballs. It is critical to note that 3-RCS has got limitations and also not validated for cardiac loads for the evaluation of the commotio-cordis.

Authors have evaluated the viscous injury of the thorax due to baseball impacts with 10 – 45 m/s (with an increment of 5 m/s) speeds. The speed range considered for the present analysis is very realistic as the maximum pitching speeds of the baseball in youth sports (9 – 18 years) could be in the order of 95 mph and above. A fully validated FE model of the thorax surrogate MTHOTA (Thota *et al* [13]) has been employed in the current study. Deflection – time response and viscous injury in terms of VC_{max} obtained from the simulation output were presented in this paper.

Blunt criterion proposed by Clare *et al* [14] has been in use for the design and validation of the non-lethal impact munitions. This criterion is based on the kinetic energy and geometry of the projectile and some parameters of the thorax. Blunt criterion can be evaluated using the following equation.

$$BC = \log_n \left\{ (0.5 \times m \times v^2) \middle| (M^{1/3} \times T \times d) \right\} \quad (1)$$

Where,

BC = blunt criterion

m = mass of the projectile

v = velocity of the projectile

d = diameter of the projectile

M = total mass of the torso

T = thickness of the skin, muscle and fat layers of the torso at the location of the impact.

Due to the size and weight of the both baseballs used in the present study are same (both baseballs differ only in the material and construction), the VC_{max} values were conveniently used for the review of the Blunt Criterion (BC) that has been in use as a design specification for the non-lethal munitions. Review outcome was also presented in this paper.

2. Methodology

FE model thorax surrogate (MTHOTA) was subjected to impacts of the baseball (both synthetic and soft-core) with 8-impact cases (impact speeds from 10 – 45 m/s, with an increment of 5 m/s). From the deflection response of the surrogate, VC_{max} due to baseball impacts were evaluated for all impact cases. Cross section of the FE model surrogate of the thorax - MTHOTA is as shown in the Figure 1.

Using MTHOTA surrogaete, viscous injury in terms of the VC_{max} can be calculated using the following equation.

$$VC_{max} = S\left(\frac{Y_{max}}{D}\right)\left(\frac{Y_{max}}{T}\right) \quad (2)$$

Where,

VC_{max} = Peak viscous injury in m/s

S = scaling factor = 0.366 for MTHOTA

Y_{max}= maximum thorax deflection (sternal deflection) = maximum deflection of the impact plate in case of MTHOTA surrogate in mm

D = dummy constant = 110 mm for MTHOTA surrogate

T = Time at which the deflection is maximum in ms

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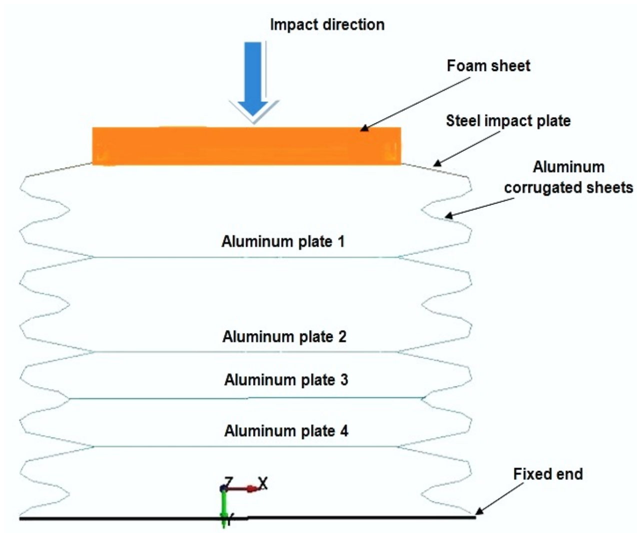

Figure 1: Cross section of the MTHOTA finite element model of the thorax surrogate. Adapted from Thota *et al* [13]

The FE model used for both baseballs in the simulation study presented in the paper is as shown in the Figure 2. Details of the FE model of the baseball were as given in the Table 1. Material data and material model used for the FE model of the baseball were as given in the Table 2.

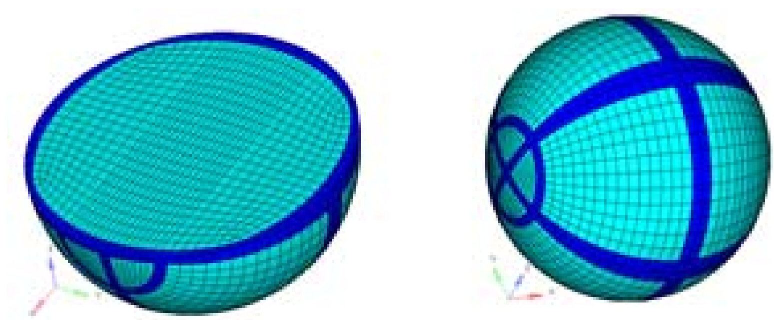

Figure 2: Finite Element model of the baseball

Table 1: FE model details of the baseball

FE entity	comments
Nodes	17589
Elements	Hex8 brick elements – 16360; Penta6 (wedge elements) – 200;
Element size	Smallest 3 mm , longest side 5 mm
Element formulations	ELFORM = 1 and AET = 2 were used
Ball-MTHOTA interface	CONTACT_SURFACE_TO_SURFACE

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Table 2: Material model and material data used for the FE model preparation of the baseball

S.No.	Parameter	Description	Soft-core baseball	Synthetic baseball
1	Material model	Linear Viscoelastic	MAT_006 of LS-DYNA (Hallquist [15])	
2	Shear relaxation behaviour of the baseball material is described by:	$G(t) = G_\infty + (G_0 - G_\infty)\, e^{-\beta t}$	From the published research (Herrmann *et al* [16], Nicholls *et al* [17], Nicholls *et al* [18], Smith [19])	
3	RO	Mass density	6.325×10^{-7} kg/mm^3	
4	BULK	Elastic bulk modulus	0.069 GPa	0.019 GPa
5	G_0	Short-time shear modulus	0.041 GPa	0.002 GPa
6	G_∞	Long-time shear modulus	0.011 GPa	0.001 GPa
7	β	Decay constant	9000 Hz or 9000 s^{-1}	1250 Hz or 1250 s^{-1}
8	Weight of the baseball		140 gram (both soft-core and synthetic)	

3. Results and Discussion

Deflection – time responses were elicited when MTHOTA thorax surrogate subjected to soft-core baseball impacts with speeds of 10 – 45 m/s (with an increment of 5 m/s). Using the dynamic deflection response with respect to duration of the impact and the Equation (2), viscous injury values were evaluated in terms of VC_{max}. Stages of impacting baseball and the MTHOTA FE model thorax surrogate were as shown in the Figure 3.

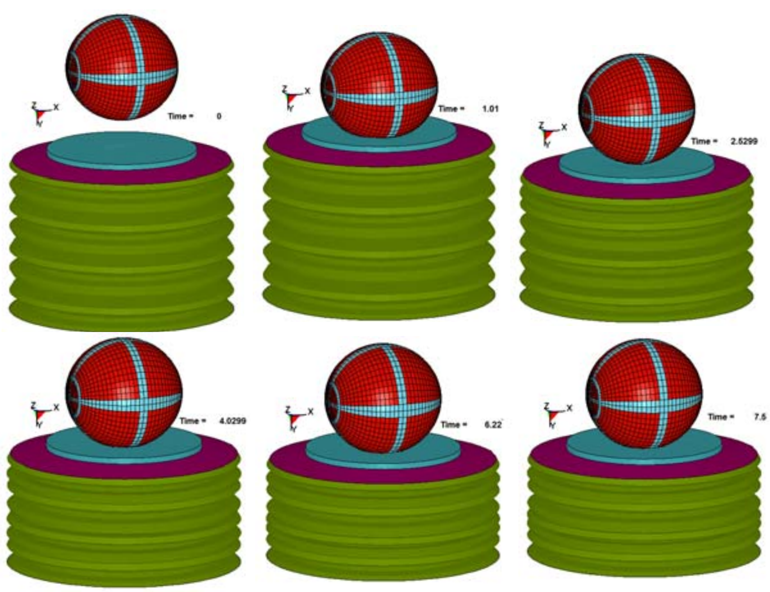

Figure 3: Stages of the MTHOTA FE model surrogate during the soft-core baseball impact with 30.7 m/s impact speed

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Dynamic deflection response of the MTHOTA, which was measured using the time histories of one of the nodes of the impact plate, for all impact cases were as shown in the Figure 4.

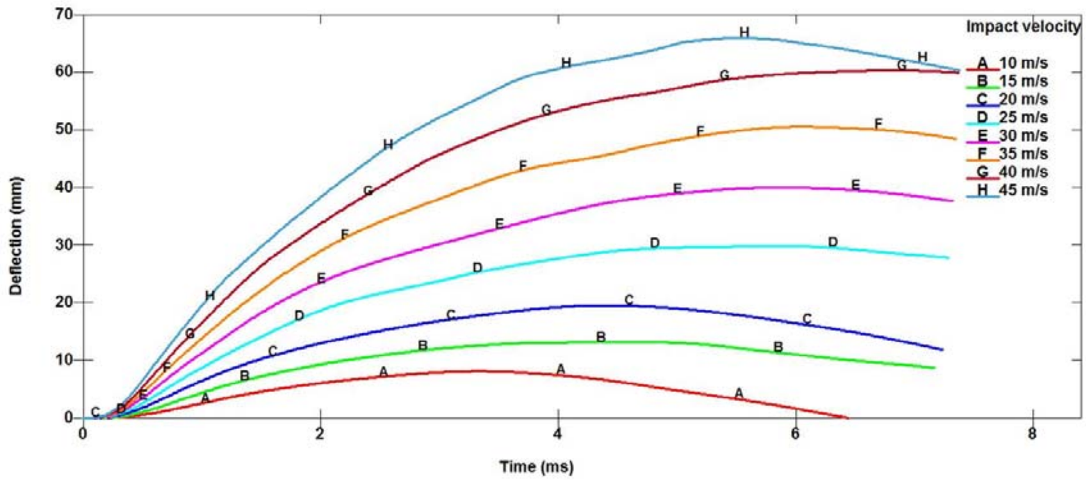

Figure 4: Deflection – time response of the MTHOTA when subjected to impacts of soft core baseball

Similarly, from the dynamic deflection responses as a function of impact duration, VC_{max} values were evaluated for MTHOTA due to synthetic baseball impacts for all impact cases. VC_{max} values evaluated for all impact cases (soft-core baseball and synthetic baseball, 8 cases of impact speed) were shown in the Figure 5.

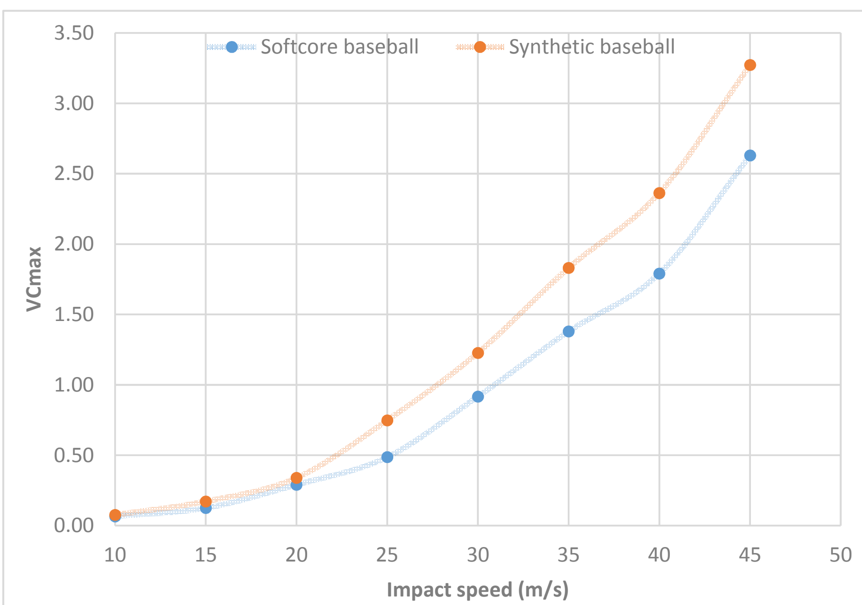

Figure 5: VC_{max} values obtained from the deflection – time responses caused by baseball (both synthetic and soft-core) impacts

Soft-core and synthetic baseballs produced VC_{max} = 1 m/s (i.e., 25 % probability for AIS3+ injuries) at impact speeds 27.9 m/s and 30.7 impact speeds respectively. VC_{max} values clearly show that material

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of the projectile (in this case, baseball) has also got significant effect on the blunt thoracic trauma. As baseballs considered for the study were similar in all aspects except material. From the Figure 5, it is also clear that soft-core baseballs have not shown any significant benefit as the blunt thoracic trauma caused by the impacts is very high at usual pitching speeds.

Blunt impacts involving the projectile mass of 20 – 200 g with the impact speed of 20 – 250 m/s referred to as blunt ballistic impacts (Bir [20]). Therefore, solid sports ball impacts considered for the study come under the category of the blunt ballistic impacts. Blunt criterion (BC) is commonly used specification for the non-lethal impact munitions. Therefore, an attempt was made to discuss the validity of the BC using the VC_{max} values obtained for the impacts of both baseballs.

From the Equation (1), as both soft-core and synthetic baseballs have got the same weight, and same size, blunt criterion for both baseballs would be same. In reality, synthetic baseball produced more VC_{max} than the standard soft-core baseball. For instance, in case of 30 m/s impact speed, VC_{max} values evaluated indicate >25% and $\cong$ 50% probability for AIS3 with soft-core and synthetic baseball respectively. Material of the projectile (in this case baseball) greatly influences the blunt thoracic trauma. Published research pertaining to latest non-lethal munitions also reveals the influence of the projectile material on the thoracic trauma. For instance, plastic baton projectile (37 mm diameter, and weight of 140 g) at 40 m/s impact speed, NS Spartan rubber nose projectile (40 mm diameter, weight of 41.9 g) at 73 m/s impact speed will have almost same values of blunt criterion. However, blunt thoracic trauma caused by these two projectiles greatly differ (VC_{max} values evaluated by Nsiampa *et al* [21] were 0.6 and 1.13 for the PVC baton and NS projectile respectively).

Though equation for BC takes care of the influence of the weight and thickness of the adipose layer of the thorax of the subject into account, influence of the projectile material was not taken into consideration. Therefore, specification in terms of blunt criterion for non-lethal munitions has got no meaning.

4. Conclusions

From the simulation study carried out by impacting the FE model thorax surrogate (MTHOTA) with the soft-core and synthetic baseball with impact speeds 10 – 45 m/s (with an increment of 5 m/s), the following conclusions were drawn.

- Below 20 m/s impact speeds, both baseballs caused almost same amount of blunt thoracic trauma.
- With an increase in the impact speed, synthetic baseball caused higher blunt thoracic trauma when compared to that of soft-core baseball. For instance, soft-core and synthetic baseballs produced VC_{max} = 1 m/s (i.e., 25 % probability for AIS3+ injuries) at impact speeds 27.9 m/s and 30.7 impact speeds respectively.
- Study presented in the paper reveals the influence of the material of the impacting projectile on the blunt thoracic trauma. As Blunt Criterion (BC) doesn't take the material of the projectile into account, BC may not be useful as a specification for non-lethal impact munitions.
- The study presented highlights the efficacy of MTHOTA FE model surrogate for thoracic trauma evaluation due to blunt ballistic impacts.

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References

1. P. Bell, 1992,"Spondylolysis in fast bowlers: principles of prevention and a survey of awareness among cricket coaches," *British Journal of Sports Medicine,* vol. 26, no. 4, pp. 273-275.
2. B. Elliott, A. Burnett, N. Stockill, and R. Bartlett, 1995,"The fast bowler in cricket: A sports medicine perspective," *Sports Exercise and Injury,* vol. 1, no. 4, pp. 201-206.

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3. T. J. Abrunzo, 1991,“Commotio cordis: The single, most common cause of traumatic death in youth baseball,” *American Journal of Diseases of Children,* vol. 145, no. 11, pp. 1279-1282.
4. C. F. Finch, P. White, R. Dennis, D. Twomey, and A. Hayen, 2010,“Fielders and batters are injured too: A prospective cohort study of injuries in junior club cricket,” *Journal of Science and Medicine in Sport,* vol. 13, no. 5, pp. 489-495.
5. J. J. Doerer, T. S. Haas, N. A. M. Estes Iii, M. S. Link, and B. J. Maron, 2007,“Evaluation of Chest Barriers for Protection Against Sudden Death Due to Commotio Cordis,” *The American Journal of Cardiology,* vol. 99, no. 6, pp. 857-859.
6. C. A. BLAS, and F. M. CAUSSADE, 2011,“Commotio cordis as a cause of sudden cardiac death,” *Emergencias,* vol. 23, pp. 471-478.
7. C. Madias, B. J. Maron, J. Weinstock, N. Estes, and M. S. Link, 2007,“Commotio cordis—sudden cardiac death with chest wall impact,” *Journal of cardiovascular electrophysiology,* vol. 18, no. 1, pp. 115-122.
8. B. J. Maron, T. E. Gohman, S. B. Kyle, I. N. Estes, and M. S. Link, 2002,“CLinical profile and spectrum of commotio cordis,” *JAMA,* vol. 287, no. 9, pp. 1142-1146.
9. M. S. Link, P. J. Wang, B. A. VanderBrink, E. Avelar, N. G. Pandian, B. J. Maron, and N. A. M. Estes, 1999,“Selective Activation of the K+ATP Channel Is a Mechanism by Which Sudden Death Is Produced by Low-Energy Chest-Wall Impact (Commotio Cordis),” *Circulation,* vol. 100, no. 4, pp. 413-418.
10. M. S. Link, P. J. Wang, N. G. Pandian, S. Bharati, J. E. Udelson, M.-Y. Lee, M. A. Vecchiotti, B. A. VanderBrink, G. Mirra, B. J. Maron, and N. A. M. Estes, 1998,“An Experimental Model of Sudden Death Due to Low-Energy Chest-Wall Impact (Commotio Cordis),” *New England Journal of Medicine,* vol. 338, no. 25, pp. 1805-1811.
11. D. H. Janda, D. C. Viano, D. V. Andrzejak, and R. N. Hensinger, 1992,“An Analysis of Preventive Methods for Baseball-Induced, Chest Impact Injuries,” *Clinical Journal of Sport Medicine,* vol. 2, no. 3, pp. 172-179.
12. D. H. Janda, C. A. Bir, D. C. Viano, and S. J. Cassatta, 1998,“Blunt chest impacts: assessing the relative risk of fatal cardiac injury from various baseballs,” *J Trauma,* vol. 44, no. 2, pp. 298-303.
13. N. Thota, J. Epaarachchi, and K. T. Lau, 2014,“Development and validation of a thorax surrogate FE model for assessment of trauma due to high speed blunt impacts,” *Journal of Biomechanical Science and Engineering,* vol. 9, no. 1, pp. JBSE0008-JBSE0008.
14. V. R. Clare, J. H. Lewis, A. P. Mickiewicz, and L. M. Sturdivan, 1975 "*Blunt trauma data correlation"*, DTIC Document.
15. J. O. Hallquist, 2007 "*LS-DYNA Keyword User's Manual, Volume II"*, Livermore Software Technology Corporation, USA. .
16. L. Herrmann, and F. Peterson, "A numerical procedure for viscoelastic stress analysis." pp. 60-69.
17. R. L. Nicholls, B. C. Elliott, K. Miller, and M. Koh, 2003,“Bat Kinematics in Baseball: Implications for Ball Exit Velocity and Player Safety,” *Journal of Applied Biomechanics,* vol. 19, no. 4
18. R. L. Nicholls, K. Miller, and B. C. Elliott, 2006,“Numerical analysis of maximal bat performance in baseball,” *Journal of biomechanics,* vol. 39, no. 6, pp. 1001-1009.
19. L. Smith, 2001,“Evaluating baseball bat performance,” *Sports Engineering,* vol. 4, no. 4, pp. 205-214.
20. C. A. Bir, 2000 “The evaluation of blunt ballistic impacts of the thorax,” Biomedical Engineering, Wayne State University, Detroit, Michigan, USA.
21. N. Nsiampa, C. Robbe, A. Oukara, and A. Papy, "Comparison of less lethal 40 mm sponge projectile and the 37 mm projectile for injury assessment on human thorax." p. 03002.