An Alternative to Plastilina for Evaluating the Performance of Body Armours

Benoît Anctil[1], Tim Bayne[1], Daniel Bourget[2], Gilles Pageau[2], Jean-Sébastien Binette[2],
Kirk Rice[3], and Amanda Toman[4]

[1] Biokinetics and Associates Ltd.
[2] Defence R&D Canada - Valcartier (DRDC Valcartier)
[3] National Institute of Standards and Technology (NIST)
[4] Technical Support Working Group (TSWG)

Abstract

A different approach to evaluate body armours was developed to address the problems typically associated with ballistic testing using clay backing. The new system was designed to reproduce the biomechanical response of the thorax under defeated ballistic impact conditions. The prototype was evaluated experimentally and the results showed that the test device has adequate biofidelity while meeting the constraints of a test standard methodology. Future work will entail the definition of suitable injury thresholds and performance criteria.

Introduction

The most established evaluation method for body armour protective performance employs a residual deformation limit (crater depth) into Plastilina (oil based clay) [1, 2]. This approach, however, has been criticized for its limited scientific basis for many years by various groups of specialists [3] because a detailed correlation between injury severity and the simple measurement of the crater depth in clay has not been established [3]. The typical use of Plastilina, modelling materials for sculptors, does not require a stringent control of its properties. This is a potential problem in an application as demanding as a performance evaluation standard by introducing undesirable sources of test variability. From a practical point of view, use of clay for ballistic testing is less than ideal. Packing and repairing the clay after testing is a labour intensive and dirty process, requiring extra personnel and set-up time for each and every test series. The clay must also be conditioned at high temperatures to achieve the proper compliance thereby limiting the available testing time outside the conditioning environment.

Given these limitations, an alternative approach to evaluate body armours was sought with the objective of developing a device that is both functionally simple, more biofidelic, and suitable for future implementation into a test standard methodology. It was decided early on to build on the experience acquired through previous work conducted in this area [4] by improving the flexible membrane concept that mimics the biomechanical response of the thorax. Since it would be critical to eliminate any chance of penetrating the membrane and damaging costly instrumentation, the proposed body armour evaluation procedure was divided into two phases. The first phase evaluates the penetration performance of the armour on a human shaped form, identified as the "penetration rig" (Figure 1), while the second phase assesses the risk of blunt trauma from non-penetrating ballistic impacts with an instrumented thoracic membrane, identified as the “trauma rig” (Figure 2).

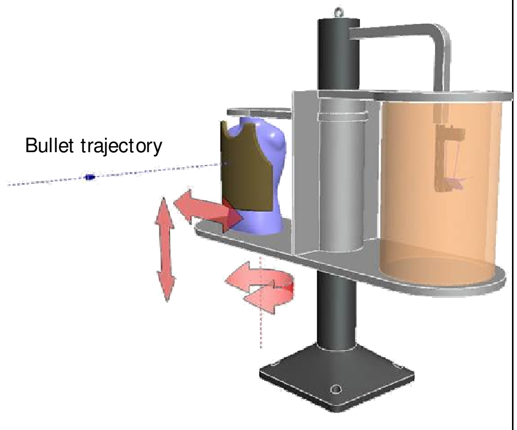

Figure 1: Penetration rig.

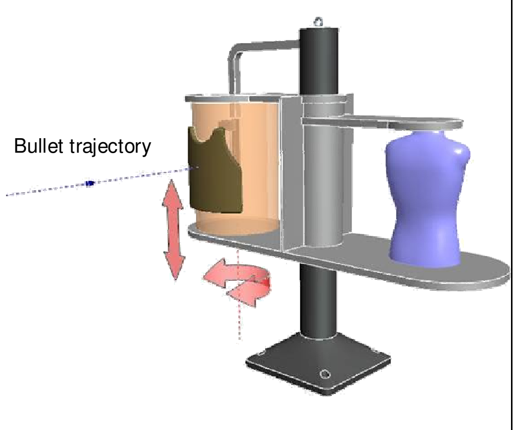

Figure 2: Trauma rig.

A review of the latest research studies [5, 6, 7, 8] was conducted initially to provide the necessary background for defining preliminary concepts and design objectives.

There are two general approaches to evaluate the risk of blunt trauma from non-penetrating ballistic impacts. The first method is based on the measurement of the chest kinematics (deflection, velocity, acceleration) and the second uses the applied force to quantify the severity of impact. While a recent study [8] indicates that impact force is better correlated with the risk of sternal fracture, a dynamic deflection measurement system was preferred for the trauma rig. The rational for selecting this approach was essentially based on the hypothesis that body armours must be evaluated under the most representative conditions, i.e. against a flexible structure that deforms like a human chest under impact, unlike the force measurement method. This aspect was also perceived to be more relevant for soft body armour. Regrettably, it was not found feasible to measure accurately the impact force on a deformable structure using a simple measurement system that would meet the constraints of a test standard methodology.

Therefore, as a key design requirement, the trauma rig response would have to reproduce the dynamic deflection characteristics of the human thorax under non-penetrating ballistic impacts. Ideally, a range of behind armour reaction data, including chest deflection as a function of time, for various combinations of handgun and rifle bullets against an assortment of body armour designs tested with Post Mortem Human Subjects (PMHS) or large animal test subjects would be used to define the trauma rig response. Unfortunately, very limited published information was available on this topic. The biofidelity corridor proposed by Bir [9] (Figure 3) was considered the most suitable reference to quantify the dynamic behaviour of the trauma rig even though it was originally developed for impacts associated with kinetic energy non-lethal weapons (KENLW). The corridor shown in Figure 3 was established based on an experiment conducted with PMHS impacted at mid-sternum level with a PVC baton (140 g, 37 mm diameter) at 40 m/s.

The momentum conservation principle was utilized to verify if the impact conditions used to define the selected biofidelity corridor was applicable to non-penetrating ballistic impacts. Momentum (i.e. the mass of the object multiplied by its velocity) is conserved in any collision if the effect of any external forces present is negligible relative to the effect of the collision. In this case, kinetic energy may be dissipated by heat, sound, etcetera, but the objects' momentum before and after the collision remains constant. According to Walker [10], Newtonian physics dictate that momentum is conserved when a person is hit by a moving object, meaning that the momentum before impact and the momentum transferred to the person through the armour should be the same. Table 1 presents a set of representative input conditions and associated behind armour reactions calculated using the momentum conservation principle. These input conditions were defined based on current body armour performance requirements [1] or published experimental data [11]. The estimated behind armour reactions were found similar to the KENLW impact conditions used by Bir [9] as shown in Figure 4. The calculated behind armour impact conditions were also in agreement with the proposed region of blunt ballistic impact [9]. These results suggest that it would be reasonable to base the design of the trauma rig on the dynamic properties described by the selected biofidelity corridor.

Table 1: Input parameters for typical ballistic impacts and estimated behind armour reactions.

	Projectile			**Armour**	**Behind armour reactions**		
Caliber	**Mass**	**Velocity**	**Momentum**	**Areal Density**	**Effective Area**	**Effective Mass**	**Velocity**
	(g)	**(m/s)**	**(kg - m/s)**	**(kg/m^2)**	**(cm^2)**	**(g)**	**(m/s)**
9x19mm FMJ RN	8.0	367	2.9	5.1	181	93	32
0.357 Magnum JSP	10.2	436	4.5	5.1	181	93	48
9x19mm FMJ RN	8.0	436	3.5	6.5	181	118	30
44 Mag JHP	15.6	436	6.8	6.5	181	118	57
7.62 mm NATO FMJ	9.6	809	7.8	21.7	104	227	34

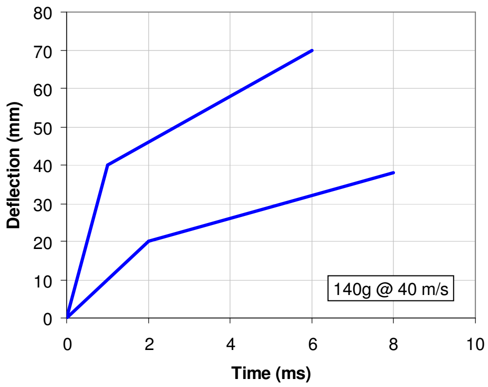

Figure 3: Biofidelity corridor.

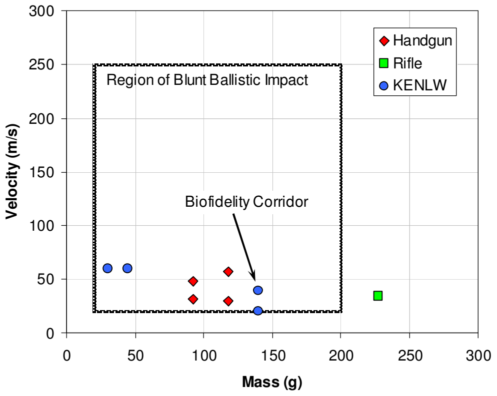

Figure 4: Ballistic blunt impact conditions.

Description

Trauma Rig

For the trauma rig, the general design objectives were established as follows:

- must accommodate both male and female vests and its size should allow adequate fit for the smallest to the largest body armour;
- arbitrary and multiple target locations within a specified boundary should be possible;
- the biomechanical response would be the same everywhere to match the selected biofidelity corridor since no relevant data was found for side or abdominal impacts;
- a proposed life expectancy of six months or 5000 impacts, which ever comes first, should be considered (this estimate is based on 40 shots/day x 5 days/week x 25 weeks)
- ease of use and a reasonable cost are essential requirements considering future application in performance standard evaluation.

A cylindrical shape was adopted for the membrane to ensure a more uniform response by reducing edge effects. This shape also provides a usable area of 360^{o}. Only normal shot impacts were considered with the trauma rig. Oblique impacts would be assessed on the penetration rig, if required. The polymer membrane was selected to represent a simplified physical model of the human thorax based on earlier concepts proposed by Tam [12] and Bourget [4].

After a review of current instrumentation technologies, a triangulating laser displacement measuring gauge was found to be the most desirable option to measure the dynamic deflection of the trauma rig membrane. The system is non-contact and the resulting signal can easily be differentiated to determine velocity. A commercially available laser displacement transducer was integrated to the structure to measure the dynamic deflection (D) of the membrane behind the point of impact as shown in Figure 5. Data post-processing techniques were reviewed to identify a suitable algorithm for calculating the membrane velocity (V) as a function of time (t), a parameter required for blunt trauma risk assessment. To keep integrity of the signal response, the following equation developed to calculate chest velocities of crash test dummies was found to provide satisfactory results.

$$V(t) = \frac{8\times[D(t+\delta t)-D(t-\delta t)]-[D(t+2\delta t)-D(t-2\delta t)]}{12\times\delta t}$$

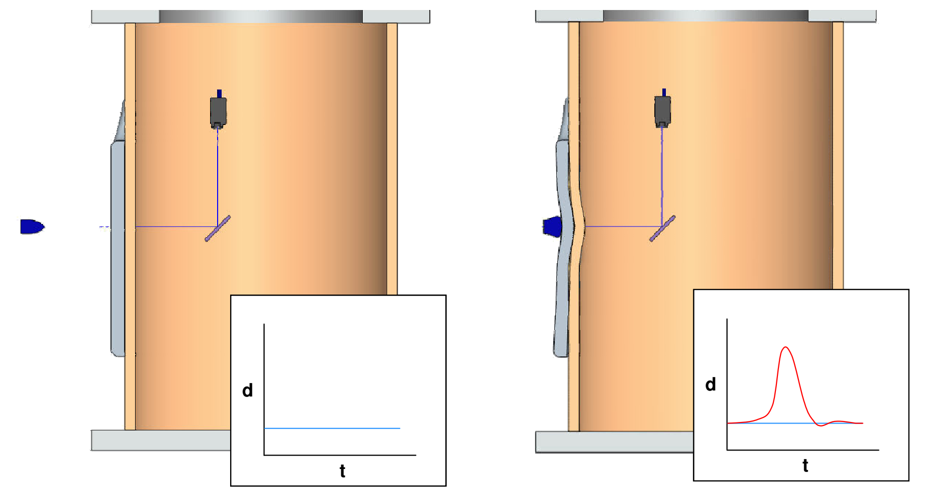

Figure 5: Schematic side cross-section view of the trauma rig before and after impact.

A first prototype was built and air cannon trials were conducted to compare the response of the torso membrane to the biofidelity corridors (Figure 6) and to evaluate the effect of impact location on the measurements (Figure 7). In summary, the results of the air cannon trials have demonstrated that:

- the membrane design (material, thickness, and shape) meets the selected biofidelity corridor;
- impact location does not affect peak deflection within the designed area of impact;
- impact location affects the unloading phase.

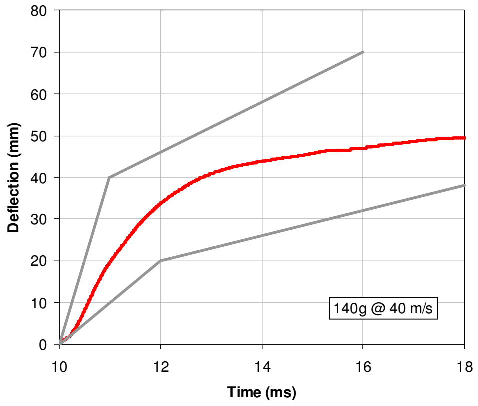

Figure 6: Trauma rig response vs. biofidelity corridor.

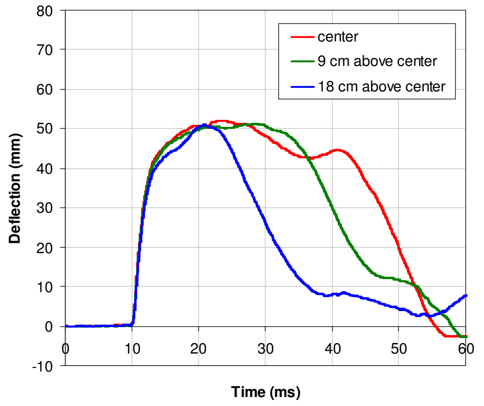

Figure 7: Trauma rig response as a function of impact location.

Ballistic trials were then conducted to evaluate the response of the membrane against different combinations of threats and body armour materials. Three different handgun bullets (9 mm FMJ, 0.357 Magnum JSP, and 44 Magnum JHP) were fired at two types of soft armour materials, Kevlar® 129 840 denier and Zylon® 500 denier, weighing 3.5 and 3.6 kg/m^2, respectively. Impact velocities corresponded to approximately 80% of the ballistic limit (V_{50}) to avoid penetration. Results are shown in Figure 8 and Figure 9. In these figures, a typical response associated with the biofidelity corridor impact condition is added for comparison. The dynamic back face deflection of the thoracic membrane measured with a non-contact laser transducer was able to discriminate the effect of various projectiles on the same type of body armour panel. The membrane was also found to exhibit different deformation patterns for different armour materials as shown in high-speed video images (Figure 10). In summary, the results of the ballistic trials have demonstrated that:

- the trauma membrane response for KENLW impacts and behind armour reactions (handgun bullets) are similar,
- the deflection measurements varied for the different armour / bullet configurations;
- the loading areas varied for the different armour / bullet configurations;
- the impact conditions of the biofidelity corridor are representative of non-penetrating ballistic impacts (soft body armour).

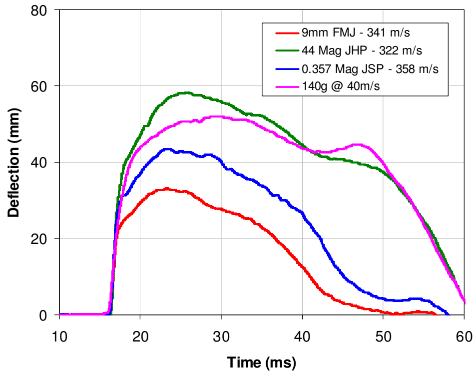

Figure 8: Trauma rig response with Kevlar® armour material.

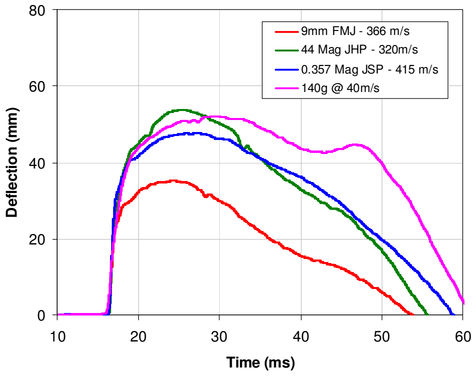

Figure 9: Trauma rig response with Zylon® armour material.

Kevlar 129 / 3.5 kg/m^2
44 Mag JHP (322 m/s)

Zylon / 3.6 kg/m^2
44 Mag JHP (320 m/s)

Figure 10: Deformation pattern for 2 types of armour material (interior chest wall view).

Penetration Rig

The penetration rig was designed to be more anthropomorphic and to accommodate male and female armour shapes. The intent was to evaluate complete body armour systems as a worn by law enforcement or military personnel. Five sizes of penetration rigs would eventually be required to accommodate the five armour sizes NIJ has been considering for future revision of the standard. Initially, only one penetration rig size, corresponding to the 50th percentile male, was considered during the development of the prototype. The proposed shape is illustrated Figure 11.

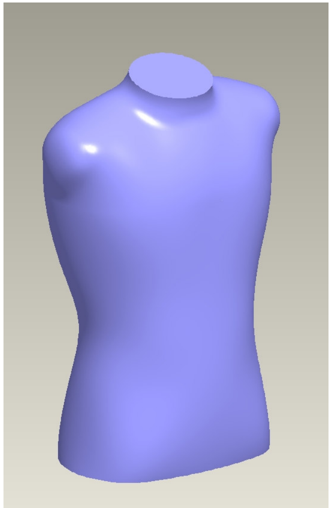

Figure 11: Penetration rig.

The material used to build the human shaped form was selected based on its performance to assess the ballistic limit (V_{50}) using the approach and initial findings of Bosik et al. [13] where the effect of the backing material on the ballistic limit was evaluated. Figure 12 shows the results of the tests conducted with body armour samples (17 layers of Kevlar 129 - 840 denier), 9 mm FMJ (124 gr), and various backing materials. In this figure the red bars indicate the results obtained by Bosik et al. [13] and the results of the current evaluation are represented with the blue bars. The overall ballistic limit variability was found to be less than 6% with an average value of 433.8 (-11.5/+12.2) m/s. The difference between the tested backing materials to evaluate ballistic limit was not found to be significant, therefore the most cost effective and long-lasting option, a low density flexible polyurethane foam, was selected. The ballistic limit results obtained with human shaped penetration rig made out of the selected polyurethane foam were found to be similar to other backing materials, 449.5 (-12.5/+14.5) m/s (indicated by the green bar in Figure 12).

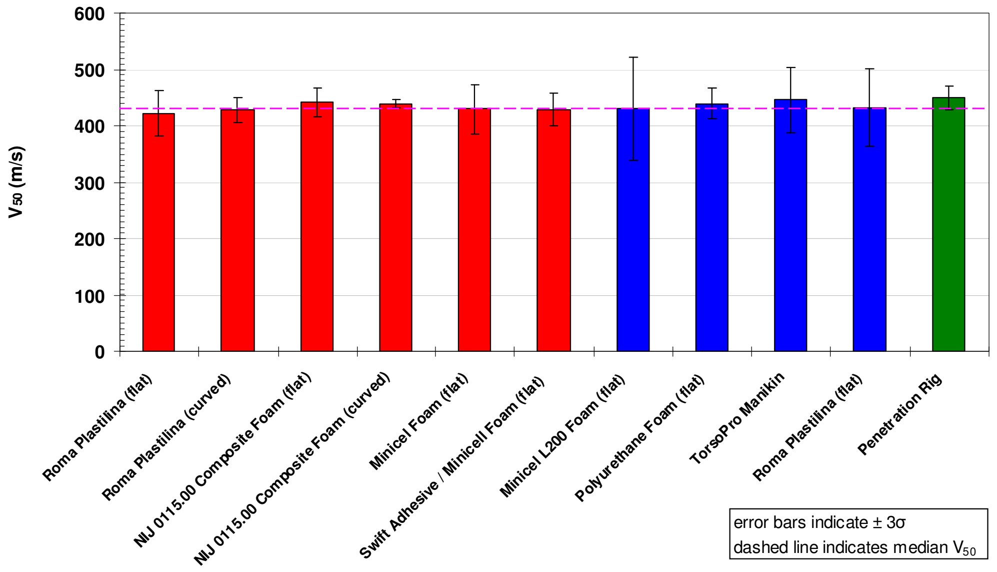

Figure 12: Ballistic limit test results.

Future Work

Experimental trials conducted with the trauma and penetration rigs showed promising results. Preparation of a detailed test methodology is on-going along with the development of data processing methods and calibration procedures required for a future implementation in a test standard.

While the work described previously led to a more biofidelic test device for evaluating body armours, no valid performance criteria has been identified at the time of writing. To develop such criteria, the proposed approach consists of reproducing a series of reported incidents with the trauma rig where the projectile, impact velocity, body armour characteristics, and injury outcomes are known. It is expected that a combination of parameters would be required to discriminate between injurious and non-injurious impacts. Peak deflection alone is most likely not sufficient to assess body armour performance while the viscous criterion has been identified as a suitable injury risk predictor for KENLW impacts [5, 14]. Further investigation will be conducted in this area before recommending an appropriate thorax injury criteria and associated threshold. In concert with the definition of performance criteria, a series of tests will be conducted by different laboratories to assess the repeatability and accuracy of the system.

Conclusions

An alternative to Plastilina for evaluating the performance of body armours has been demonstrated. Evaluation of the test device prototype showed that the general design objectives were met. The trauma rig, used to evaluate the risk of non-penetrating ballistic trauma, was able to reproduce the dynamic deflection of a human chest.

Further testing conducted with body armours and handgun bullets demonstrated the ability of the system to quantify behind armour reactions and to discriminate between the various combinations of ballistic materials, bullets, and impact velocities. Additional work will establish suitable performance criteria. The penetration rig, designed to evaluate the penetration resistance of armours, is a much simpler test device. It provides a human shaped support to body armour during ballistic penetration tests (V_{proof} and V_{50}).

Remaining work includes additional ballistic trials to define injury criteria and thresholds and to finalize the proposed approach. At the project completion, a validated test device and associated methodology will be available to evaluate body armours that would be more practical and more biofidelic than current methods.

Acknowledgement

The work presented here was supported by the International Counter Terrorism Research and Development Program Agreement between the Government of the United States of America and the Government of Canada, Defence Research & Development Canada (DRDC) Valcartier and the U.S. Office of Law Enforcement Standards and the National Institute of Justice (NIJ). The authors are also thankful to Mr. Doug Baines and Mr. Michael Pees of Biokinetics for their support during the experimental trials.

Reference List

1. NIJ (2001). Ballistic Resistance of Personal Body Armor. US Department of Justice. Washington DC. NIJ 0101.04 Revision A.
2. Croft, J. and Longhurst, D. (2007). HOSDB Body Armour Standards for UK Police (2007) Part 2: Ballistic Resistance. Home Office Scientific Development Branch. Washington DC. 39/07/B.
3. Tobin, L. (2004). Feeling Depressed. Personal Armour Systems Symposium, The Hague, The Netherlands.
4. Bourget, D., Anctil, B., Doman, D. and Cronin, D. (2002). Development of a Surrogate Thorax for BABT Studies. Personal Armour Systems Symposium, The Hague, The Netherlands.
5. Bir, C. A. and Viano, D. C. (2004). Design and Injury Assessment Criteria for Blunt Ballistic Impacts. The Journal of Trauma Injury, Infection, and Critical Care 57(6): 1218-1224.
6. Bir, C. A. and Eck, J. (2005). Preliminary Analysis of Blunt Ballistic Impacts to The Abdomen. IUTAM: Impact Biomechanics: From Fundamental Insights to Applications, Dublin, Ireland.
7. Shen, W., Niu, Y. and Stuhmiller, J. H. (2005). Biomechanically Based Criteria for Rib Fractures Induced by High-Speed Impact. Journal of Trauma Injury Infection and Critical Care 58(3): 538-545.
8. Bass, C., Salzar, R., Lucas, S., Davis, M., Donnellan, L., Folk, B., Sanderson, E. and Waclawik, S. M. (2006). Injury Risk in Behind Armor Blunt Thoracic

Trauma. International Journal of Occupational Safety and Ergonomics 12(4): 429-442.

9. Bir, C. A., Viano, D. C. and King, A. (2004). Development of Biomechanical Response Corridors of the Thorax to Blunt Ballistic Impacts. Journal of Biomechanics 37(1): 73-79.
10. Walker, J. D. (1998). Turning Bullets into Baseballs. Technology Today, Southwest Research Institute.
11. Sarron, M. P. and Destombe, V. B. C. (1999). Lesions Thoraciques Fermees par Balle de Guerre. Direction Generale pour l'Armement.
12. Tam, W., Dorn, M. R. and Gotts, P. L. (2000). A New Method for Quantifying Behind Armour Blunt Trauma. Personal Armour Systems Symposium, Colchester (UK).
13. Bosik, A., Hedge, C., Lightsey, S. and Pageau, G. (2002). Initial Findings on the Development of Test Procedures for Multi-Hit Testing Body Armour. Personal Armour Systems Symposium, The Hague, The Netherlands, TNO Prins Maurits Laboratory.
14. Sturdivan, L., Viano, D. C. and Champion, H. R. (2004). Analysis of Injury Criteria to Assess Chest and Abdominal Injury Risks in Blunt and Ballistic Impacts. The Journal of Trauma Injury, Infection, and Critical Care 56(3): 651-663.