PERFORMANCE EVALUATION OF SOLDIER'S PROTECTION SYSTEMS

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Abstract

Today's soldiers are facing an evolving range of threats from blunt trauma to ballistics, explosive devices and blast weapons. Characterization of the threats they face and accurately predicting the level of injury mitigation is essential to the design of effective personal protection systems. Timely evolution of the equipment standards and evaluation methodologies is also required to reflect the current understanding of injury risks and to provide personnel protection at the highest possible level of confidence.

Current efforts on blunt impact, ballistic, and blast protection evaluation systems are presented. A new test procedure is being proposed to assess blunt trauma protection capabilities of crowd management equipment. To assist helmet designers with preventing skull fracture and brain injuries resulting from backface deformation of the ballistic helmet shell during impact, a novel test headform was developed. A similar approach for measuring behind armour effects is used to characterize the performance of body armour against the defeated bullet. Another series of tools and test methods is being developed to evaluate personal protection systems against explosive devices and blast weapons.

1. Introduction

Evaluating the effectiveness of the personal protective equipment first requires a thorough understanding of the threat environment surrounding the soldier. With today's political and operating environments, we are in the midst of a dynamic environment where changes to the threat type, severity and incidence are occurring. With these changes comes a poorer understanding of the threats themselves and their affect on human life. The manner in which we respond to these changes will also influence the eventual threat exposure to the soldier. For example, changes to the roles and responsibilities of the soldier are occurring on an ongoing basis while forces adapt to new situations. When combined with short and long term improvements to the forces' capabilities, it becomes apparent that the manner in which protective systems are assessed also need to be dynamic and reflect the current threat environment and state of knowledge.

The approach used for evaluation of soldier's protection systems involves the following sequence:

- threat definition
- test method
- surrogates
- performance requirements
- protective system evaluation

The threat environment can consist of penetrating, impact and blast type loading conditions resulting from small arms fire, fragmentation from explosives, over pressure from blasts, impact as the soldier is thrown against a rigid object or even personal assault from others in crowd management situations. The threats addressed in the paper will focus on behind armour blunt trauma to the torso and head from a defeated projectile, overpressure loading from explosive devices and finally on blunt impact experienced in crowd management type situations.

Development of a test method to assess performance of soldier's protective systems requires knowledge of the threat and the types of injuries to be mitigated. The test conditions and measurement of the physical response can then be defined to realistically rank system effectiveness or predict injury risk. An effective way to accomplish the evaluation is through the use of physical surrogates.

Physical surrogates have a number of desirable characteristics in that they can be tuned to respond in a human-like manner to impact, they can be donned with the protective equipment as they are intended to be used, and physical surrogates are highly repeatable, durable and accessible to researchers, regulators, purchasers and end users.

Protective systems are evaluated relative to a performance requirement expressed as some form of threshold. Various approaches can be taken to define the value of the threshold. It is common that the metric used for the performance threshold has some defined relationship to injury potential. However, due to limitations in the human-like response of the surrogate used, protective capacity of current technology and the need to maintain the soldier's operational capabilities, the performance requirements often reflect the protective capacity of current and developmental systems.

Finally, one must evaluate the protective system to ensure that the intended level of performance is satisfied. Issues dealing with sampling requirements, environmental conditioning, certification needs and even performance throughout the service life of the equipment must be dealt with.

The current paper centers on various test surrogates that have been developed in response to current and emerging threats as well as in response to recent knowledge on injury causation and prevention.

2. Ballistic Protection

2.1 Body Armour

With the increasing need for higher levels of ballistic protection by military and law enforcement personnel comes an associated need for meaningful and practical armour testing procedures. The most established evaluation method for penetration and blunt trauma performance of body armour employs a residual deformation limit (crater depth) into an oil based modelling clay (Figure 1). In fact, the body armour compliance program of the National Institute of Justice (NIJ) is the oldest of NIJ's commercial testing programs and has successfully resulted in controlled performance of body armour for over three decades [Rice and Lightsey 2000]. This method, however, has been criticized for its limited scientific basis for more than 10 years by various groups of specialists [Tobin 2004]. The reason is simple. The direct correlation between injury severity and the simple measurement of the crater depth in clay has never been established [Sendowski, Martin et al. 1994].

Figure 1: Body armour mounted onto a clay block for ballistics performance evaluation.

Nevertheless, the clay method is used routinely worldwide and is also referenced by many national test standards. From a practical point of view, use of the clay in the test methodology 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 elevated temperatures to achieve the proper compliance thereby limiting the available testing time outside the conditioning environment. Further, pre-test and post-test verification of the clay's compliance is required.

Given the limitations of using a clay box as support for the body armour, an alternative torso surrogate which is both functionally simpler, and more biofidelic would be advantageous. One existing method, the Thoracic Impact Membrane (TIM), has been developed by Biokinetics in conjunction with Defence Research & Development Canada - Valcartier to assess blunt trauma resulting from behind armour effects for ballistic loading (Figure 3). The TIM consists of a polymer membrane with a dedicated support structure. It is a simplified physical model of the human thorax designed to assess the risk of injury caused by the behind armour reactions under non-penetrating ballistic impact [Bourget, Anctil et al. 2002]. The TIM is based on an earlier concept proposed by the Defence Science and Technology Laboratory [Tam, Dorn et al. 2000] but was enhanced to mimic the visco-elastic biomechanical response of the human thorax under ballistic loading conditions [Bir 2000]. The device has demonstrated an ability to differentiate body armour performance and to assess blunt trauma injury risk. Further validation and development are currently on-going to ensure its suitability for use under a wide range of impact conditions.

Figure 3: Body armour over the Thoracic Impact Membrane for blunt trauma assessment.

Integral to the function of any torso surrogate is the instrumentation required to measure the physical response. On the current Thoracic Impact Membrane, back face displacement and acceleration are measured quantities from which parameters such as velocity can be derived for assessment of injury risk. It is important that the instrumentation has as little influence on the event as possible, and to this end, non-contact displacement measurement has been the chosen approach. A Laser Displacement Transducer (LDT), which uses a vertical sheet of laser light, is the method currently being used to measure the back face deformation of the TIM (Figure 2).

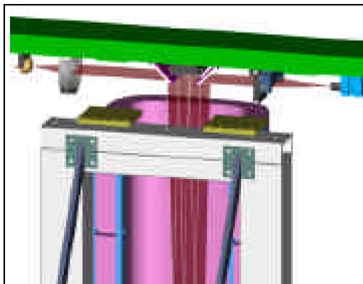

Figure 2: Laser Displacement Transducer for measuring behind armour effects.

2.2 Helmet

Current ballistic helmet evaluation procedures [NIJ 1981; MIL-H-44099A 1986; H.P White Laboratory 1995; NATO 1996; MIL-STD-662F 1997] address penetration resistance but lack behind armour blunt trauma (BABT) injury risk evaluation for non-penetrating ballistic impacts. The latter aspect is of immediate concerns because of the increasing availability of lighter ballistic helmet shells on the market. Lighter helmets typically have less structural resistance which often results in larger deformation under ballistic impact and thus larger BABT effects are expected.

Figure 4: Ballistic helmet test with the instrumented headform.

The findings of several years of research work [Bolduc 1998; Bolduc and Tylko 1998; Waclawik, Bolduc et al. 2002; Bass, Boggess et al. 2003; Anctil, Bourget et al. 2004; Anctil, Keown et al. 2005] have lead to the development of a test method for evaluating the level of BABT protection offered by ballistic helmets. It uses a headform with an instrumented skull surface to measure the dynamic load applied by the inward deformation of the ballistic helmet shell (Figure 5). The risk of blunt trauma is assessed by comparing the peak measured force to the human injury tolerance threshold for skull fracture proposed by Bass et al. [Bass, Boggess et al. 2003].

The method for measuring behind armour impact forces combined with penetration resistance assessment of the shell can provide a more accurate evaluation of the overall ballistic helmet performance. This approach is currently considered in the development of a new ballistic helmet test standard CSA Z613 by the Canadian Standards Association.

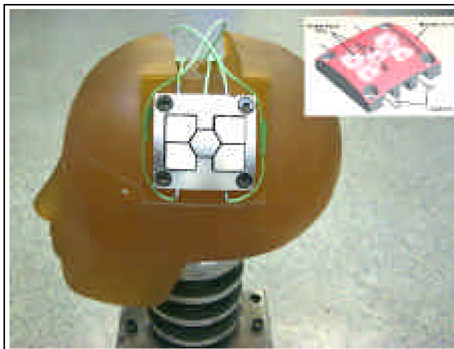

Figure 5: Instrumented headform (2nd generation) and load cell module to assess behind armour blunt trauma.

3. Blast Protection

The development of a mannequin for blast incapacitation and lethality (MABIL) was initiated by DRDC Valcartier to improve the survivability of dismounted soldier against blast weapons by providing a tool, i.e. the mannequin, to allow personal protection systems to be quantitatively evaluated in terms of injury potential [Anctil, Keown et al. 2004; Jetté, Dionne et al. 2004]. During the definition phase, the types of injury to be mitigated were identified along with the associated biomechanical parameters. The results suggest that the injury assessment capabilities should be divided in two distinct categories. The first category includes injuries caused by global body acceleration and impact. Assessment of these injuries requires the reproduction of body kinematics. Thus, a device replicating primary human body characteristics such as shape, dimensions, inertia and weight is mandatory. The capability to withstand impact and high acceleration is also required. The second category encompasses primary blast injuries, *i.e.* injuries caused by the direct interaction of the blast wave (overpressure) with the body. Global body motion is not required and should be avoided to reduce the risk of damaging the surrogate and its instrumentation. The proposed MABIL concept was the defined as one system with two possible configurations:

1. The first configuration is a complete mannequin representing the main characteristics of a human body. It is based on the technology of Anthropomorphic Test Devices (ATD) commonly used to evaluate the performance of protection systems in automotive safety research (Figure 6).
2. The second configuration consists of a simplified physical model of the head and torso with the measurement systems required to assess the risk of blast injuries. This model is mounted on a rigid structure to maintain its position and orientation during testing (Figure 7).

Table 1 presents the type of injuries that are considered for MABIL. The current challenges are to develop appropriate measurement methods and associated instrumentation that are associated with injury prediction. Nevertheless, the latest surrogate design has shown promises by being able to differentiate between various types of protection systems.

Figure 6: Hybrid III ATD.

Figure 7: MABIL.

Table 1: MABIL's injury assessment capabilities.

Injury Type
Head injuries caused by global body acceleration and impact
Torso injuries caused by global body acceleration and impact
Middle ear injuries caused by blast overpressure
Lungs injuries caused by blast overpressure
Thermal burns affecting head and torso regions
Eye injuries caused by flash Head and torso injuries caused by secondary fragmentation, eye injuries caused by flying debris
Airways and bowel injuries caused by blast overpressure.
Injuries caused by chemical products (e.g. burns and intoxication)

4. Blunt Impact

As the soldier's role changes to peacekeeping and rebuilding responsibilities, there exists the threat of blunt impact during crowd control operations or confrontation with people. The types of threats encountered can comprise airborne objects thrown from a distance, handheld objects such as pipes and sticks, personal assault or even being thrown against rigid structures. The body regions exposed to the threats are numerous including the head, neck, torso, abdomen, groin, spine and extremities (arms, legs).

Injuries related to blunt trauma are not uncommon but few test standards exist to evaluate the performance of protective systems. Many of the more pertinent standards do not reflect the types of threats encountered, the body regions injured or do not assess the types of injuries expected. Existing standards include:

CSA Z617-06	Personal protective equipment (PPE) for blunt trauma.
BSI 7971-2:2003	Protective clothing and equipment for use in violent situations and in training.
CAN/CSA Z611-02	Riot helmets and faceshield protection.
EN1621-1:1998	Motorcyclists' protective clothing against mechanical impact.

The most recent standard, CSA Z617, has been developed to address many of the aforementioned shortcomings for application to law enforcement and correctional services personnel [CSA-Z617 2006]. The anticipated threats include both focal and diffuse loading encountered from thrown bricks, swung pipes and being kicked, to name a few. These are classified into several categories which were then greatly simplified for the test protocol to capture the scope of threats (i.e. diffuse/focal loading, low and high energy). The level of insult was initially selected to be consistent with the capacity of well designed body armour intended for these applications. However, the maximum level of threat can be considerably higher than that afforded by current product offerings (*e.g.* maximum of 240 J vs. 75 J required). The test protocol of CSA Z617-06 requires the measurement of transmitted force through the protective equipment when impacted with a focal load (90° edge anvil) and distributed load (49 mm radius sphere). Transmitted force has been shown to correlate well for skeletal fracturers and provides a reasonable ranking metric.

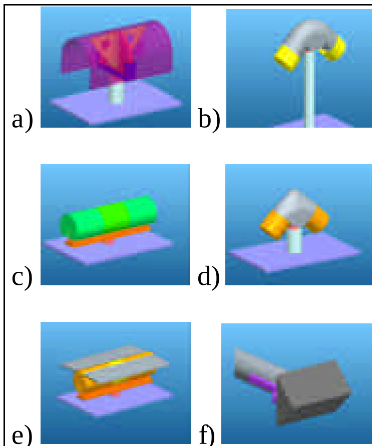

Figure 8: Test surrogates and anvil (a) hip/thigh/groin (b) shoulder (c) lower leg (d) elbow (e) spine, arm (f) edge anvil.

The protective equipment is supported by a number of support surrogates representing different body regions (Figure 8). The surrogates are rigid in nature to ensure repeatability and therefore provides a relative assessment of injury risk. One additional surrogate is required for assessing blunt trauma to the torso. The torso impact membrane shown in Figure 9 provides a human-like compliance allowing for the prediction of injury risk based on deformation of the chest wall interior. Injury risk functions based on chest compression and velocity can be used with the measurements.

Figure 9: Torso impact membrane being used for blunt trauma assessment from impact.

Assessment of blunt trauma for defence applications can likely use the same test methodology and performance limits as described in CSA Z617.

Summary

A need has been identified for assessing the performance of soldier's protective systems in the current operational environment. The emergence of new and old threats has changed both the incidence and type of injuries experienced in the field necessitating changes to the level of protection offered by current equipment. Many of the past evaluation methods were limited in their ability to represent the threats and injury mechanisms. In response to the need for evaluating blunt impact, behind armour blunt trauma and blast type loading, a number of new surrogates have been developed. A torso impact membrane (TIM) to assess thoracic injuries from defeated ballistic impacts, a load sensing headform to assess closed head injuries from direct contact with the interior of ballistic helmets, a mannequin for assessing blast incapacitation and lethality (MABIL) with conventional and enhanced blast weapons, and finally a series of surrogates intended to assess blunt impact trauma in crowd management and confrontation situations. It is anticipated that with additional experience and refinement of the surrogates that effective protective systems can be developed for the soldier of today and tomorrow.

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