Title: A Novel Test Methodology to Assess the Performance Ballistic Helmets

Authors: B. Anctil[1], M. Keown[1], D. Bourget[2], and G. Pageau[2]

[1]Biokinetics and Associates Ltd., 2470 Don Reid Drive, Ottawa, Ontario, K1H 1E1, Canada
[2]Defence R&D Canada – Valcartier, 2459, blvd. PIE-XI north, Val-Bélair, Québec, G3J 1X5, Canada

Enhanced ballistic helmets using novel lightweight armour materials are now capable of defeating soft-core bullets and heavier fragments from exploding munitions. However, the reduction in weight and lower inherent stiffness of these helmets often result into larger helmet back-face deformation from non-penetrating ballistic impacts resulting into higher loading to the head capable of causing serious skull and/or brain injuries. Until recently, no validated and biofidelic evaluation procedure was available to assess the level of blunt trauma protection offered by ballistic helmets against non-penetrating impacts. To overcome this deficiency, a novel headform allowing measurement of impact force was developed. Various helmets models were evaluated. Rather large discrepancies were observed in the measurement of the peak impact force even though all helmets prevented penetration.

INTRODUCTION

Ballistic helmets were introduced several years ago to protect military and law enforcement personnel against penetrating injuries caused by impact with shrapnels from fragmenting munitions and, since more recently, small caliber ammunition (handgun and rifle bullets) [1]. Such impact usually results in critical (AIS=5) to unsurvivable (AIS=6) injuries as categorized by the Abbreviated Injury Scale (AIS) system [2]. The benefits of ballistic helmets in stopping high-velocity projectiles are incontestable. Although, even if the projectile is stopped, the helmet shell indentation formed during impact may apply sufficient force to cause head injury from blunt impact. This is an important and immediate concern especially since the introduction of novel lightweight composite materials for ballistic protection that are lighter and thus more compliant under impact.

Methods to assess penetration performance of ballistic helmets are relatively straightforward. They are defined in several test standards [3, 4, 5, 6, 7] and the results obtained are recognized for ranking helmet performance. For non-penetrating ballistic impact, there is currently no widely accepted test method to evaluate the performance of helmets. However, recent work at DRDC Valcartier [8, 9] and at the University of Virginia for the U.S Army Natick Soldier Center and Medical Research & Materiel Command [10, 11] led to two major outcomes: a) a validated procedure for measuring the load to the head applied by the backface deformation of helmet and,

b) an human injury tolerance threshold. In this research program, the physical response of a helmeted surrogate head (modified Hybrid III headform) was characterized for a series of ballistic impacts. Experimental setup and test conditions were reproduced with Post Mortem Human Subjects (PMHS) to identify the most suitable biomechanical parameter for predicting the risk of injury. The results showed that the dynamic peak force measured at the surface of the skull correlates well with the occurrence of skull fracture [12]. The outcomes of this work were used to develop a transfer function to transpose the injury risk curve from PMHS to the head surrogate.

Building upon this research work, following activities consisted of adapting the method into a standard test procedure for performance evaluation of ballistic helmets. Force transducer technologies were evaluated to identify the most suitable candidate and test setup and procedure were developed.

IMPACT FORCE MEASUREMENT HEADFORM

For the development of injury models, the dynamic force on surrogate head and PMHS skulls was measured with PVDF (polyvinylidine fluoride) film sensors. They have good dynamic sensing characteristics and do not affect the mechanical properties of the structures (e.g. bone) on which they are mounted. These transducers were identified as the best option to characterize the localized load applied by the backface deformation of helmet at the surface of the human skull.

Current concerns with PVDF film sensors are the calibration, ease of use, and degradation of the gauges for potential use in helmet performance evaluation in the context of standard testing. Alternatives for measuring dynamic force applied by the helmet backface deformation are limited. The main issues are the response time and space requirements of the transducers. To evaluate the differente options, two different PVDF force sensors and a miniature load cell were selected as potential candidates [13].

The first PVDF force transducer model selected was the PVF11-.25-EK manufactured by Dynasen Inc., Goleta, CA. It was similar to the unit used during the development of the helmet backface force measurement technique mentioned above. This gauge is a superimposed piezoelectric/strain gauge arrangement combining one biaxially-stretched stress gauge to a bi-directional strain gauge. Since PVDF force sensors are sensitive to bending, concurrent strain measurement allow to correct the output signal of the PVDF gauge to keep only the normal force component. While essential for measurements on the PMHS skulls, the strain gauges were not used in this work because theses sensors were mounted on a rigid surface where no bending occurred. This sensor can measure force greater than 1000 N and it has as an active sensing area of 40 mm^2.

The second PVDF sensor model was a Piezotech PVDF M25-25-PL (Ktech Corp., Albuquerque, NM) and can measure transient pressures from 1 KPa to 40 GPa with an active sensing area of 25 mm^2. It is thin (less than 25 µm) and adaptable to complex contours. This gauge is manufactured from 26-µm thick biaxially-stretched film and poled using the Bauer method.

A miniature piezoelectric load cell SlimLine Sensor Model 9131B (Kistler Instrument Corp., Amherst, NY) was proposed as an alternative to the PVDF film sensors. This quartz dynamic transducer was selected because of its small size and its suitability to dynamic impacts. It has the ability to measure load up to 2500 N with a sensing area of 18 mm^2.

A series of tests was conducted to evaluate these transducers. Preliminary work showed that backface deformation of ballistic helmet may introduce substantial variability in the load applied to an instrumented headform. To provide a more repeatable input to the measurement systems being evaluated, ballistic helmets were not used in this study. Instead, the backface loading conditions were estimated and reproduced with an instrumented impactor launched from an air cannon.

The impactor striking velocity was estimated from the backface deformation of a composite plate impacted with a 9 mm FMJ bullet 124 grains at 350 m/s. The composite plate was made of a woven aramid laminate used typically for ballistic helmets. The deformation profile was obtained from high speed video (provided by the Délégation Générale pour l'Armement, France) and derived to obtain the velocity as a function of time. The mass of the impactor was assessed using the momentum conservation principle which states that the momentum (the mass of an object multiplied by its velocity) is the same before and after the impact. Thus, if $m_1v_1=m_2v_2$, then $m_2=$ (8.0 g x 350 m/s) / 30 m/s = 93 g. The convex impact surface shape of the impactor was determined from the permanent deformation of ballistic helmets after defeating 9 mm FMJ bullets. The impactor diameter was set to 37 mm to match the internal diameter of the air cannon barrel. An accelerometer (PCB Model 350A03) was installed on the rear end of the impactor's aluminium head. A foam body provided protection to the accelerometer and strain-relief for the wire. It also stabilizes the impactor during flight.

Figure 1 shows the relationships between the peak force applied (impactor) and the peak pressure (force transducer) measured. Peak pressure values, calculated by dividing peak force by the sensing area, are used to compare the results obtained from one force transducer to another. Least squares fitting to the original data are illustrated with trend lines. Results obtained with the load cell are consistent over the entire range. A good correlation is observed for the Dynasen film sensor at lower input force but the correlation is rather poor at higher input force. The Ktech sensor has a large variability over the entire range of input force with no indication of a linear trend.

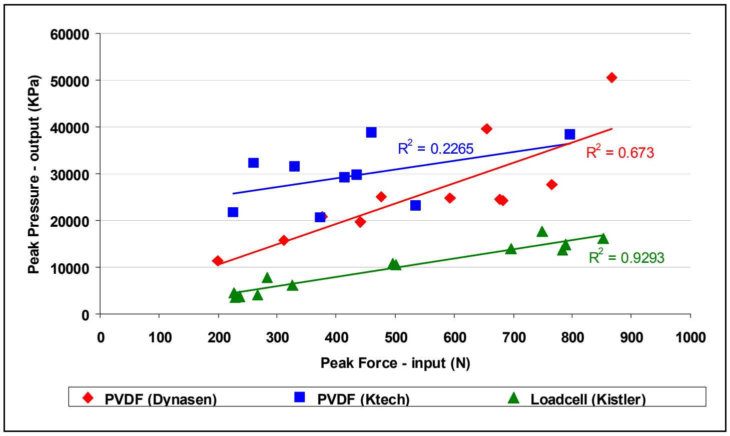

Figure 1. Output peak pressure vs. input peak force.

Considering the advantages of the miniature load cell for helmet performance evaluation in the context of standard testing, additional work was conducted to integrate a series of these sensors into a surrogate head. The shape of the Hybrid III mannequin headform and the sensor pattern were similar to previous research studies [10]. Five load cells (Model 9212 Kistler Instrument Corp., Amherst, NY) were mounted on a rigid module which can be installed on either side of the headform. Several design iterations were required to avoid signal noise caused by the excitation of impact pads located over the miniature load cells. The final design of the load cell module is presented in Figure 2. The surface area of the centre and lateral impact pads are 210 and 270 mm^2, respectively. A piece of Hybrid III synthetic skin (vinyl plastisol, 12 mm thick, First Technology Safety Systems) recovers the entire module. The headform assembly is mounted on a flexible Hybrid III neck. A sheet of pressure sensitive film (Pressurex, Sensor Products Inc.) is placed directly over the top surface of the load cell module to verify impact location (Figure 3).

BALLISTIC HELMET PERFORMANCE EVALUATION

Three models of current combat helmets were used for evaluation. The objective of the experimental trials was to assess the capabilities of the impact force headform to measure the dynamic loads under various conditions. Trials were conducted using 9 mm FMJ Ball round (124 gr). Impact velocities ranged between 364 and 432 m/s without exceeding the ballistic penetration limits of helmets. The dynamic force response of each load cell was recorded and the peak force value of the five signals was used to quantify the load applied by the helmet backface deformation.

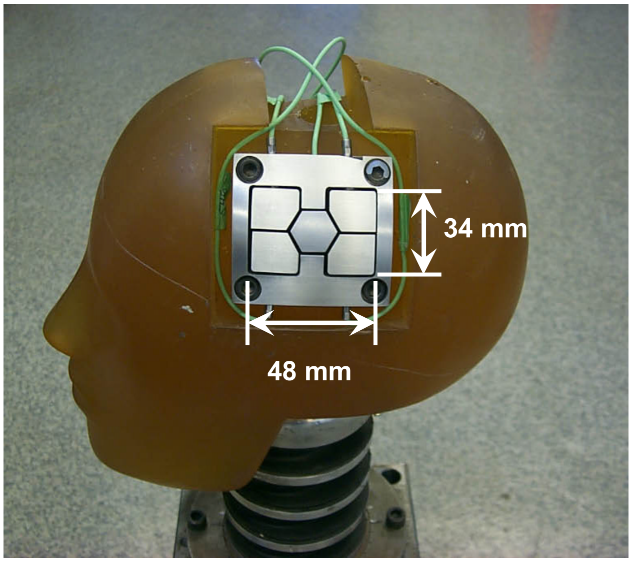

Figure 2. Headform instrumented with load cell module.

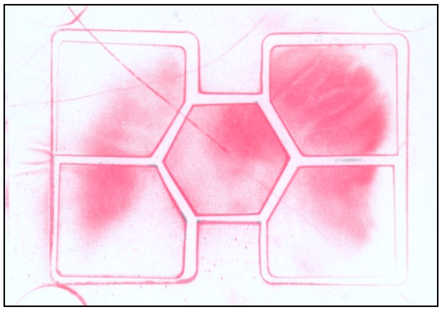

Figure 3. Typical load distribution recorded with pressure sensitive film.

A summary of peak impact force results are presented in Figure 4. The relationship between projectile velocity and impact force is different for each helmet model. Higher peak force values were measured with Helmet B. The lowest peak force values were observed with Helmet C and the force increase as a function of impact velocity was also smaller for this model. Helmet C has energy absorbing material to distribute the load over a larger area on the skull. As demonstrated in Figure 5 and Figure 6, the forces measured by each load cell on helmet C are distributed over a longer period of time.

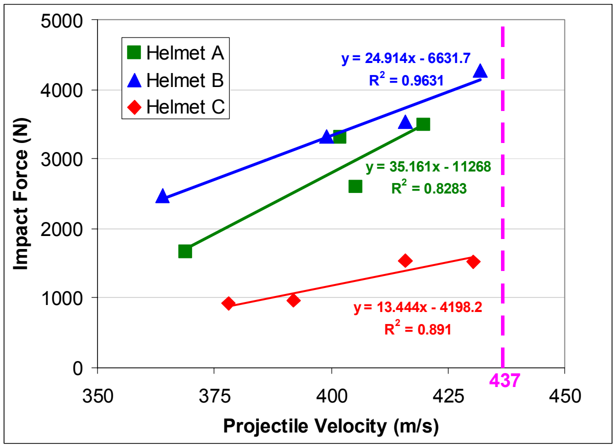

Figure 4. Peak impact force of individual load cells as a function of projectile velocity.

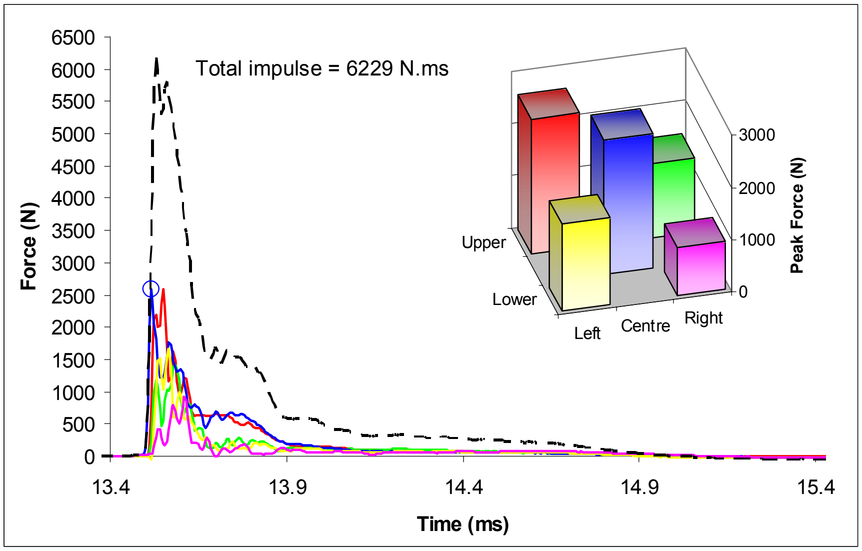

Figure 5. Impact force measurement for Helmet A (9 mm FMJ at 405 m/s). The dashed line corresponds to the sum of the five load cell signals.

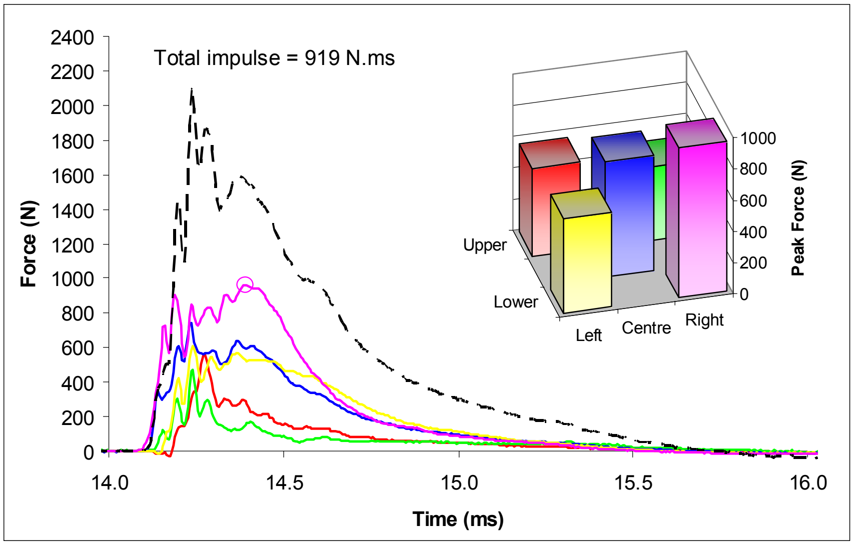

Figure 6. Impact force measurement for Helmet C (9 mm FMJ at 392 m/s). The dashed line corresponds to the sum of the five load cell signals.

Good correlation is observed between projectile impact velocity and the measured force on the headform for different helmet models. These results demonstrate the capability of the instrumentation to measure the loads caused by the backface deformation of ballistic helmets. The next step is to establish a data analysis scheme that will allow injury prediction for a given ballistic impact.

ANALYSIS OF HEADFORM RESPONSE

Figure 7 (right) shows the injury function proposed for the headform instrumented with the load cell module. It was obtained by combining the injury function developed by Bass et al. [11] (Figure 7, left) with the relationship between impact velocity and peak impact force (helmet model B, Figure 4). A 50% risk of skull fracture correspond to a value of 4256 N measured on the headform. Note that these functions are valid for concentrated loads and assume that the maximum force is recorded by one of the transducers. Experimental evaluation with pressure sensitive film showed however that contact region between the backface helmet deformation and the headform is not always limited to the measurement area. Different helmet models and various impact conditions results sometime in loading outside the five impact pads. A simple measure to avoid incorrect injury assessment is to verify with pressure sensitive film (Figure 3) that the peak load is within the sensing area otherwise the results are not valid and the test must be repeated.

A more elaborate analysis method can also be used to account for the load distribution. Using image processing techniques, it is possible to evaluate the exact loading area covering only the five impact pads, termed effective area (A_e). Then, using the following equation, it is possible to obtain a more accurate assessment of the average peak pressure (P_e) over this area:

$$P_e = \frac{\sum_{i=1}^{5} F_i(t)}{A_e}$$

where $F_i(t)$ corresponds to the signal recorded by load cell *i*.

CONCLUSION

Evaluation of force transducers identifies the miniature load cell as a suitable alternative for measuring the dynamic load from the helmet backface deformation. The prototype headform equipped with these transducers was able to quantify the performance of different helmet models under typical ballistic impacts.

In a simple way, the headform response indicates the probability of sustaining skull fracture for a person wearing the helmet under similar conditions. This is true only for concentrated loads in the vicinity of the mid-coronal plane on the parietal bones of the skull. Injury outcomes will more likely be different if the forces are more distributed (e.g. helmet C) or, for rigid helmets, if no deformation occurs but the impact energy is sufficient to induce significant head acceleration. Further considerations for these other types of injury and review of associated injury models are therefore required [14, 15, 16]. Other measurements (e.g. head acceleration) or data analysis procedure may have to be added in the helmet evaluation procedure. Future work should consider additional impact locations (e.g. front, rear), a calibration procedure, and laboratory re-enactments of injurious cases presented in the literature where skull fracture was observed.

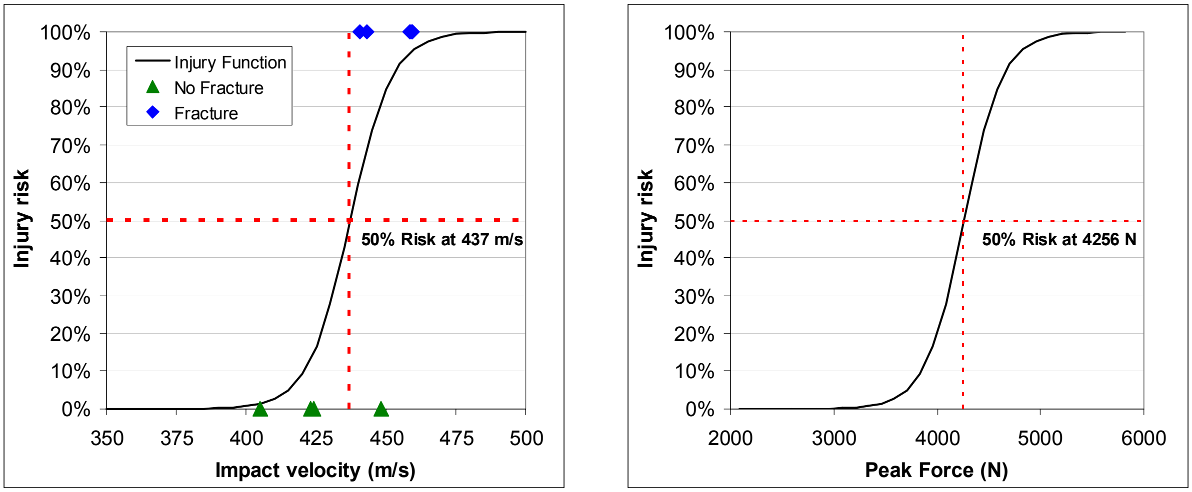

Figure 7. Skull fracture injury function. Left: function developed for helmet model B with PMHS (from [11]). Right: same function adapted for the instrumented headform using equation provided in Figure 4.

ACKNOWLEDGEMENT

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