A new biofidelic backing for the evaluation of the ballistic performance of soft armour and lightweight protective fabrics

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Abstract. The Technical Co-operation Panel (TTCP) Land Group (LND) is a multinational defence science and technology collaboration between the governments of Australia, Canada, New Zealand, United Kingdom and United States. Under the auspices of this organisation, a technical panel was convened to focus on personnel protection and vulnerability. This paper presents the development and validation conducted within TTCP of a new backing that supports armour in a more biofidelic way during ballistic testing, providing protective materials with boundary conditions that likely better represent how armour is worn. The measured ballistic performance of soft body armour and lightweight protective fabrics has been shown to depend on the method of support of the samples during testing. Current support methods such as rigid clamping fixtures and deformable clay backing do not provide representative boundary conditions to armour material during testing. The new backing, mimicking the resistance of the human torso, consists of a multi-layer foam pack made of three well-specified materials respectively representing the epidermis (thin neoprene rubber), the dermis (a soft foam), and soft tissue (a stiffer foam). The local dynamic compliance of the pack was successfully adjusted to match abdominal deflection response. The epidermis and dermis material were chosen with physical properties close to the human skin and demonstrated biofidelic skin perforation thresholds, which enables the use of skin perforation as a criterion for V_{50} and V_{proof} testing of lightweight fragmentation protective materials. In addition, the multi-layer construction offers the capability to estimate projectile residual velocity and absorbed kinetic energy through measurement of depth of penetration in the pack, enabling better prediction of injury outcomes when the armour is defeated. Ballistic data obtained with soft body armour and lightweight ballistic combat clothing on the pack is presented and compared to similar data obtained using other retention methods. The pack is shown to be reliable when used as a backing for measuring ballistic performance of materials and provides additional diagnostics and benefits such as ease of use, procurement, shape adjustment, and conditioning with lower cost than clay backing. Its performance, simplicity and ease of use suggest that a final version could be implemented in ballistic laboratories worldwide.

1. INTRODUCTION

Under the auspices of The Technical Cooperation Program, a study assignment involving five cooperating nations was convened to develop a new biofidelic backing for the evaluation of the ballistic performance of soft armour and lightweight protective fabrics.

The process of penetration of a projectile into an armour material is inherently variable. To quantify the performance of body armour against a given ballistic threat with a high level of confidence, controlled and repeatable test methods are required. Body armour test standards such as the AEP-2920 [1] and the NIJ 0101.06 [2] aim at specifying and bounding a multitude of test parameters in order to augment the reliability and reproducibility of test results within a given test laboratory and across test facilities. A critical test parameter is the armour support or mounting method, as it dictates the lateral and transverse boundary conditions that are applied to the armour sample during the ballistic impacts. The two most widely used support methods for soft armour are the rigid frame, which clamps the armour sample around the four edges with a specified level of clamping force and fabric tension, and the clay backing, in which the armour sample is simply strapped over a block of calibrated deformable clay (Roma Plastilina 1 (RP1)) with no edge constraints. These two support methods offer drastically different lateral and transverse boundary conditions to an armour sample. While it is important to note that the main purpose of such methods is to increase consistency and reproducibility in the test results and not to provide realistic “as-worn” test conditions, it appears that they remain prone to errors if not correctly undertaken. For example, clay backings are susceptible to conditioning/calibration issues [3]. The use of clamping fixtures requires the adjustment of the clamping force and fabric tension to prescribed levels. These levels may vary within a test series if they are not verified and adjusted between firings, introducing variations in the boundary conditions applied to the sample.

The ballistic performance of soft body armours, defined here as the V_{50} for a given ballistic threat, may depend on the method used to support the samples during testing due to differences in how

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the armour is allowed to deform during impact. Therefore, the V_{50} of an armour becomes a measurement of its relative performance compared to other armours tested in a similar fashion, or compared to a benchmark performance defined by a standard using the same test method. Measuring the ballistic performance of an armour using realistic boundary conditions would be of little value if the requirements put on the impact velocity, in particular for Fragment Simulating Projectiles (FSP), were not tied to a specific operational scenario. Many defence departments have a growing desire to align the performance requirements put on fragmentation protection with clearly defined operational scenarios. Alternatively, when working towards maximizing the ballistic performance for a defined armour burden, the ability to reduce the physical burden associated with body armour is also contingent on understanding the true protection level offered by a system. As armed forces are moving towards optimising protection systems, partly through modularity and scalability of the protection level [4], there is a need for a test method that can measure true as-worn performance of soft body armour.

There is also a growing requirement for a support method that can provide additional diagnostic capabilities, useful to the evaluation and optimization of protection systems. For example, defence departments often use modelling tools to perform vulnerability analysis on different body armour designs to support procurement programs or research and development efforts [5]. These modelling tools require experimental data on protective materials that include residual velocity data, which is used to predict potential injury outcome following full perforation of an armour. Unfortunately, current support methods are limited in their ability to measure realistic projectile residual velocity. Finally, current support methods may be difficult to deploy in full-scale explosive trials, which have become more important in the context of testing against threats representative of IEDs [6].

In 2015, Technical Panel 5 of the Land group of The Technical Cooperation Program (TTCP LND TP5) launched a study assignment on a biofidelic test backing for soft body armour. The goal of the study was to scope the development of a backing that would provide representative boundary conditions to soft armour during testing, while offering a set of new capabilities compared to current support methods. The work reported herein was carried out in support of this study. The development and validation work was led by Defence Research and Development Canada (DRDC) with support from Defence Science and Technology Laboratory (Dstl), United Kingdom Ministry of Defence during the validation stage.

2. METHOD

First, a statement of requirements defining and quantifying a list of biofidelity, performance, functional and logistic requirements was established in collaboration with members of TTCP LND TP5. Second, a set of biofidelity metrics were selected as performance targets for the three critical features of the backing (compliance, perforation resistance and penetration resistance). Third, an iterative experimental process was followed to progressively refine the backing design in order to match the performance targets. Finally, the response of the backing was validated across a broader range of conditions.

Table 1 was built in consultation with the technical panel team members, which included representatives of Defence Science and Technology Group (AUS), DRDC, the Defence Technology Agency (NZ), Dstl (UK), and US Army Natick Soldier Systems Center.

To be considered biofidelic, the new backing was required to match the compliance of a selected body region as well as the perforation threshold of human skin. Local compliance will differ across body regions, but the region of the upper torso was prioritized since the backing is primarily meant for testing soft body armours. Matching the perforation of the backing with that of human skin was desirable to enable rapid diagnostics of potential injury outcome during laboratory or full-scale fragmentation trials. When gathering experimental data on the residual velocity of a projectile behind a given armour to feed penetrating injury models, the retardation effect of the skin is important to consider.

The new backing had to be usable for the testing of any protective fabrics or soft armour systems relevant to the defence sector, from a single layer (e.g. low areal density combat clothing, Tier 1 Pelvic Protection (PP) systems) to a multi-layer pack (e.g. fragmentation vest). All the relevant fragmentation threats commonly used in armour testing had to be supported in addition to very light weight projectiles which may be used to represent natural ejecta created in buried IED scenarios (e.g. small spheres made of glass). The estimated relevant threat velocity range spanned from 50 m/s to 1000 m/s because the backing would support testing of very light weight protective fabrics such as combat clothing up to heavy fragmentation vests. One of the additional desirable features of the new backing was the ability to be deployable in full scale explosive tests, which may occur in a range of

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temperatures, to either collect fragment data (act as a witness pack) or evaluate the protective performance of materials in a real environment combining the effects of blast and fragments. Maintaining the integrity of the pack during such explosive tests is important to recover valid fragment data.

Table 1. Performance and logistic requirement for the new biofidelic backing

Biofidelity	Body Region	Thoracic region and/or abdominal region
	Biofidelic characteristics	Local and global compliance; penetration threshold
Protection systems	Type of protection system	Any type of soft armour / lightweight protective fabrics including woven, knitted, felt and uni-directional fabrics
	Protection areal density	0.15 kg/m2 to 4.5 kg/m2
Threat	Threat type	Spheres, RCC, FSP
	Threat material	Metallic (Steel, Aluminum, Magnesium, etc…), Glass, Natural fragments
	Threat mass	2 gr to 130 gr
	Threat velocity	50 m/s to 1000 m/s
Environment	Operating temperature	-10°C to 35°C
Experimental configuration	Type of experiments	Controlled laboratory ballistic experiments and full scale explosive tests
	Sample size	Up to 400 mm by 400 mm flat samples
	Geometry	Possibility to modify the geometry of the backing for fitting PPE in full-scale experiments
	Integrity	Maintains a good level of integrity under blast loadings of relevant severity
	Calibration	Simple and straightforward calibration procedure, if any.
Assessment	Perforation	Rapid and consistent identification of sample and backing perforation/non-perforation
	Striking velocity	Estimation/calculation of projectile striking velocity from DoP measurement for single and multiple simultaneaous impacts
	Residual velocity	Estimation/calculation of projectile residual velocity upon armour perforation
	Projectile recovery	Enable soft recovery of projectiles
Logistics	Procurement	Ease of procurement for Canada, UK, USA, Australia and New Zeland.
	Supply	Ensure security of supply
	Storage	Storage at ambient temperature with no degradation of performance or change in material response
	Cost effectiveness	Reusable or expendable, but remains cost effective compared to other accepted test methods

Based on the shared understanding that the calibration process is often the source of variability in ballistic data generated using RP1 as the backing, it was deemed essential that if there were a calibration procedure for the new backing, it needed to be simple. Likewise, the preparation of the backing needed to be infallible as much as possible. The pack had to enable rapid and consistent assessment of both armour perforation and skin layer perforation, useful to perform V_{50} testing. The criterion on which full perforation of an armour is assessed may be based on armour perforation alone or on pack skin layer perforation, which is analogous to the use of witness materials in the rigid frame method. To support the testing of armour in the overmatch regime or to characterize fragmentation threats, the pack had to enable the estimation of impact velocity from Depth of Penetration (DoP) measurement through DoP vs velocity calibration curves. Such curves may be specific to individual projectile sizes, shapes and densities or be generalized if the pack response allows.

The new pack concept was aimed at providing a long-lasting alternative test method to multiple national departments, so the group agreed on a few logistic requirements. It was deemed important that the base material component for the pack be affordable and easy to procure within the required tolerances. It was important to have a minimum level of resilience and continuity with regards to the supply chain.

2.1 Biofidelity targets

2.1.1 Compliance

Through a review of the open literature, datasets pertaining to the local compliance of the human chest under dynamic loading conditions were identified. Based on a comparison of equivalent mass and impacting velocity [7], two studies in particular used loading conditions comparable to a soft body armour deformation following the ballistic impact of a handgun round. Bir, et al.[8] defined thoracic deflection vs time biofidelity corridors by performing impact tests using long instrumented impactors on Post-Mortem Human Subjects (PMHS). The impactor was 140 g and 38 mm in diameter. Impacts were done at 40 m/s and 60 m/s on the mid-sternum area. The corridors created by Bir were used in

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previous work to tailor the response of a Blunt Trauma Thoracic Rig aimed at assessing the risk of Behind Armour Blunt Trauma [9]. Eck [10] followed a similar approach and defined similar deflection-time corridors based on PMHS tests using a 45 g impactor at 65 m/s. Eck defined corridors for both the epigastric and hypogastric region of the abdomen. Unfortunately, PMHS data for loading conditions closer to those of a small fragment impact on soft armour were not available.

For the development of the new backing, it was decided to prioritize matching the compliance of the abdominal region because the reference data was better reported and it represents a region of the torso that is not covered by hard armour. An average corridor built from the hypogastric and epigastric corridors of Eck was used as the objective performance for the pack. During the iterative design process, backing concepts were tested against the Eck target corridor. However, the final solution was evaluated against the corridors from both Eck and Bir.

2.1.2 Skin perforation

Reviews of published experimental work on the ballistic perforation of skin from various projectile sizes and mass are available from Breeze, *et al.* [11], Jussila, *et al.* [12] and Warlow [13]. With the intent of limiting the amount of ballistic testing in the development stages of the new backing, it was deemed desirable to identify only 3 to 4 relevant datasets against which the response of the skin layer of the backing would be adjusted. These datasets were chosen to cover the whole range of projectile mass identified in the requirement table. All the projectiles in these datasets were non-deforming at the velocities used for the skin perforation assessments. The choice of data type to reproduce was also influenced by the availability of the projectiles and capability to launch them at DRDC.

At one end of the mass spectrum, the experiments from DiMaio, *et al* [14] were selected. DiMaio conducted ballistic experiments on whole PMHS lower limb (thigh region) using 9.12 mm bullet (lead round nose, 113 gr) and observed a perforation threshold at approximately 58 m/s. At the lower end of the mass spectrum, some of the experiments from Missliewetz [15] were selected. Missliewetz reported experiments on complete limb (thigh regions) against small brass spheres of 4 mm and 0.31 g (4.28 gr) as well as small silica glass spheres of 4 mm and 0.086 g (1.34 gr). Obtaining PMHS data for the perforation threshold of the 1.1 g (17 gr) chisel nosed FSP was desirable given that it remains today one of the most used projectiles for the evaluation of body armour. Unfortunately, such data could not be found for human PMHS. The data generated by Breeze, *et al.* [11] on porcine skin specimen was used for this purpose. Breeze conducted experiments on fresh pig limbs, over the thigh region, against the 1.1 g chisel nosed FSP. When upper and lower limits of the threshold were identified in the original study, the upper and lower bounds were used to define the performance target range.

2.1.3 Depth of penetration

Breeze, *et al.* [16] obtained data from ballistic experiments using FSPs of different masses against goat skin and muscle from the thigh. The data related projectile velocity to DoP in soft tissue. Although limited, the data was used to benchmark the pack DoP response during development. The performance target was defined as impact velocity minus threshold velocity as a function of DoP normalised by projectile sectional density. The DoP response of the pack was deemed less critical to match closely to the biological datasets. For the purpose of back calculating impact velocity, a transfer function between recorded DoP in the pack and DoP in soft tissue was acceptable.

2.2 Iterative process

The development of the new pack followed an iterative process. The pack design had to enable recovery of projectiles and easy measurement of DoP, therefore a layered construction was the selected option. The initial design of the new backing, provisionally named the ‘TP5 pack’, was based on the pack construction proposed by James [17], which consisted of a series of 10 mm layers of soft neoprene foams. A skin layer was added to the layered foam concept to fulfil TP5’s requirements.

The process started with the ballistic testing of skin materials. Several silicone and neoprene rubber materials were sourced in multiple hardness (50-80 shore A) and multiple thicknesses (1-3 mm). V_{50} tests were conducted with each skin candidate material, placed over 12 layers of neoprene foam. The four selected projectiles were fired from a small calibre gas gun with interchangeable barrels. All projectiles were fired with their corresponding barrel size (i.e. no sabots required). V_{50} estimates were obtained from a Probit regression of a minimum of 12 shots including a minimum of five perforations and five non-perforations within a maximum range of 20 m/s. Shot spacing was maintained at 50 mm. A perforation was defined as the full perforation of the neoprene rubber material. The best three skin candidates were retained for the next phase.

For the second step of the process, a selection of soft tissue simulant materials was used to construct full packs. Different grades of neoprene foams were sourced, and different layering combinations were created. The local compliance of the various combinations of skin and soft tissue simulants were evaluated by launching a similar 45 g short baton round to the one used in [10], at 60 m/s using a large bore gas gun at DRDC. For each test, the displacement history of the projectile was recorded by tracking the tail of the baton using a high-speed camera placed perpendicularly to the impact direction. Based on the comparison of the compliance response with the target corridor, the best constructions were retained and retested for skin V_{50} and DoP response. DoP tests were conducted with the 1.1 g FSP only, by firing over the range of velocities between the V_{50} and 1.5 x V_{50}, with 25 m/s increments. Once the first round of tests was completed, the process was repeated if further iterations were required.

3 FINAL PACK DESIGN AND VARIANTS

Three iterations of the design process were required to converge to a pack solution that met the biofidelity requirements. There was a significant interaction between the compliance of the first few layers of foam and the skin perforation response. The V_{50} value was influenced by the choice of foam directly underneath the skin layer.

The construction providing the best match to our target values for compliance and skin perforation is shown in Figure 1a. The layering of this first version of the TP5 pack was one layer of a selected neoprene rubber (1.6 mm), one layer of soft neoprene foam (6.35 mm), 12 layers of a harder neoprene foam (6.35 mm each) and 1 layer of isoltop HD sheet (12.7 mm). The first two layers simulate the epidermis and dermis of the skin, while the harder foam is representative of the soft tissues. The pack is 400 mm x 400 mm but can be scaled to any other dimensions to fit within existing target support. Straps may be used to hold the pack together during manipulation but should not affect the pack response. Using straps to hold test samples also enables for a tight fit with minimal constraints, providing more realistic boundary conditions.

a. b. c.

Figure 1, a. TP5 pack b. Pack variants for the conduct of residual velocity tests and c. Pack variant to conduct full-scale explosive tests.

In order to fulfill the requirements with regards to the conduct of residual velocity tests and full scale-explosive tests, two variants of the pack using the same layering scheme were created (Figure 1b and 1c). The first variant was created by adding 15 layers of isoltop HD (12.7 mm), behind the last layer of the original pack to enable characterization of projectile residual velocity over a wide range of impact velocities. Isoltop HD has been used in witness pack applications in the past [18], and a higher density material than the foam was needed to test materials up to a velocity where the energy absorbed by the protective material becomes negligible compared to the residual energy of the projectile. This type of data is important in the context of vulnerability modelling for the generation of empirical models capable of predicting perforation and residual energy.

The second variant of the pack was created to support the characterization of the mass and velocity distribution of natural debris during full-scale explosive testing. It also supports the evaluation of the performance of protective fabrics in the same context. The pack acts as a witness system collecting small natural debris and fragments generated by the detonation of a simulated buried IED. It may not be suitable for capturing metallic fragments directly from ammunitions as the pack materials may not suffice to stop such high energy fragments. The variant in Figure 1c is the same layering scheme, but the dimensions of the pack can be increased to maximize fragment collection and the skin

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layer is completely wrapped around the foam layers to ensure that the pack maintains its integrity during an explosion.

3.1 Validation of the TP5 pack response

3.1.1 Local compliance

The deflection time response of the TP5 pack is shown in Figure 2 for both the 45 g short baton at 60 m/s [10] and the 140 g long baton at 40 m/s [8]. Impacts were performed over the central 300 mm x 300 mm area of the 400 mm x 400 mm front surface of the pack. The local compliance of the pack was successfully demonstrated to fall within the Eck target corridor, lying towards the upper bound and following a similar trend to the original PMHS data. Results were deemed reproducible, with a variability on the maximum displacement of approximately ± 1.5 mm.

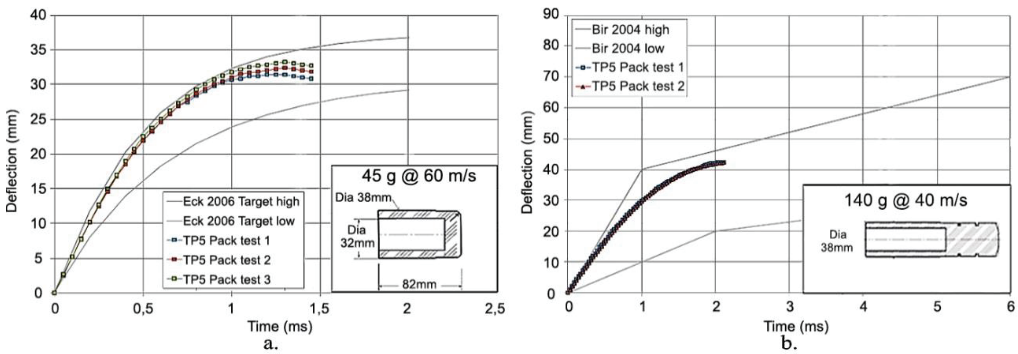


Figure 2, Compliance response of TP5 pack over a. Eck target corridor (n=3) and b. Bir biofidelity corridor (n=2)

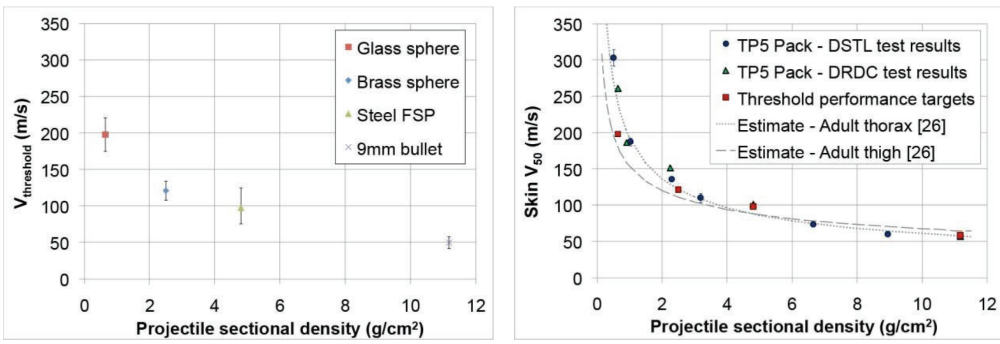
Surprisingly, the local compliance also matched the biofidelity corridor from Bir, *et al.* [8] very well. This indicates that the variability in chest compliance between PMHS is probably greater than the difference in compliance between the abdominal and thoracic regions. By targeting an average abdominal corridor, we obtained a system compliance that also falls within the variability of upper thorax compliance. However, in the case of the Bir corridor, maximum deflection of the pack was reached earlier compared with the reference data. This may be due to the method of retention of the PMHS in the original experiments, where some gross motion of the specimen might have occurred, extending the duration of the whole event. During the impact tests on the pack, the pack is rigidly held at the back, preventing any backward gross motion. The purpose of adjusting the local compliance is to provide the appropriate level of resistance to a deforming armour during the ballistic penetration process, which most likely only involves the local dynamics of the abdomen or thorax. Gross motion of the body is most likely occurring beyond 2 ms, when the penetration process of the projectile is over. If indeed the extended duration observed in the PMHS experiments is due to gross motion, then the match obtained with the TP5 pack is appropriate.

3.1.2 Skin perforation

V_{50} estimates were obtained experimentally for the front layer of the pack. The historical data was used to establish the objective performance were perforation threshold values, which should be expected to be slightly lower than the associated V_{50}. After three iteration cycles, it proved to be challenging to match the target values at both ends of the projectile Sectional Density (SD) range. More specifically, the 9 mm projectile and the 4 glass sphere have very different perforation mechanisms in the skin simulant (punch shear vs stretching) which involve competing material properties in the skin simulant. In the end, the skin material that was chosen for the TP5 pack was thought to be the best compromise over the entire SD range.

Multiple V_{50} validation tests were conducted on the TP5 pack using a range of projectile shapes and sectional densities. In addition to the four projectiles used during the iterative development stage, tests using a custom 2 gr. Rock Simulating Projectile (RSP, [19]) as well as a 2 gr Right Circular Cylinder (RCC) were conducted by DRDC. V_{50} tests using a 3 mm glass sphere, a 6 mm glass sphere, a 4.4 mm steel sphere, a 6 mm steel sphere, a 12.7 mm steel sphere and a 9 mm tungsten sphere were also conducted by Dstl. V_{50} estimates were obtained using a Probit regression on all firings of each projectile. Figure 3a shows the 4 original objective performance values and Figure 3b shows all the obtained V_{50} estimates as a function of projectile sectional density. In order to obtain a more rigorous comparison of the perforation behaviour between the TP5 pack skin and human skin, the empirical model of skin perforation developed by James [17] was plotted over the data of Figure 3b. James proposed region specific empirical fits for the V_{50} of human skin as a function of projectile sectional density, based on a broader study of the data in the literature.

It was found that the TP5 pack response approached the estimate of the V_{50} for the thoracic skin, but may underestimate skin perforation, based on the thigh region. This may be satisfactory, however given that the level of confidence in the thoracic skin estimate is lower [17] and that it would be preferable to not underestimate any injury outcome that the pack aims to be able to predict, a thinner skin layer could be preferable. Following the armour penetration model proposed by Cunniff [20], which drew a correlation between armour V_{50}, armour areal density (i.e number of layers or thickness) and projectile sectional density, it is likely that a small change in the skin material thickness would suffice to bring the V_{50} data in Figure 3b at a more conservative level. It is also likely that the V_{50} for the lower sectional density projectiles will be affected more for a given reduction in skin thickness.



a. b.

Figure 3, a. Threshold velocity for skin perforation for 4 different projectiles based on [11, 14, 15]
b. TP5 pack skin V_{50} as a function of projectile sectional density

3.1.3 Depth of penetration response

Depth of penetration validation tests were conducted by DRDC and Dstl using the first variant of the pack with the same set of projectiles as for the skin perforation tests. When conducting DoP tests with the pack, it was found that the most efficient way to proceed was to complete a series of firings, starting at the measured skin perforation velocity and moving upward by set increments (25 m/s for the 1.1 g FSP) until the complete pack was perforated. The same method was applied to the armour overmatch test, using the armour V_{50} velocity as the start velocity. Once the firings were completed, the pack was disassembled layer by layer, starting from the top, and the DoPs measured individually. Figure 4 shows the DoP reference data from Breeze [16] as well as all of the DoP results from DRDC and Dstl combined. In order to make the comparison with the data from Breeze easier, results from different projectiles are normalized on both axis. The graphs show impact velocity minus threshold velocity as a function of DoP over projectile sectional density. For the current comparison, it is convenient for removing any differences in perforation threshold values in order to focus on the comparison of the DoP trend alone. It appears that the individual DoP datasets from the TP5 pack can be reasonably represented with a linear regression.

The linear fit of the DoP data for the 1.1 g FSP in the TP5 pack has a higher slope than the biological data from Breeze. Through the iterative development, this was found to be very challenging to adjust further without drastically affecting the compliance of the pack. As mentioned previously, it was deemed acceptable that a transfer function or a simple scale factor between Pack DoP and Soft tissue DoP be required. In the current comparison, that scale factor would be approximately 1.5 for the 1.1 g FSP.

The important aspect of the results presented in Figure 4 is that the pack penetration response follows a linear trend for all the tested projectiles. It is also noticed that the slope of the fit is very similar for a given projectile shape and material (e.g steel spheres). By normalizing DoP by SD, it is seen that the results from spheres of a given material may be collapsed on a single fit. This means that by using this specific normalizing scheme, the impact velocity of projectiles of known or estimated mass, shape and material could be estimated with limited DoP calibration data. This is particularly useful when

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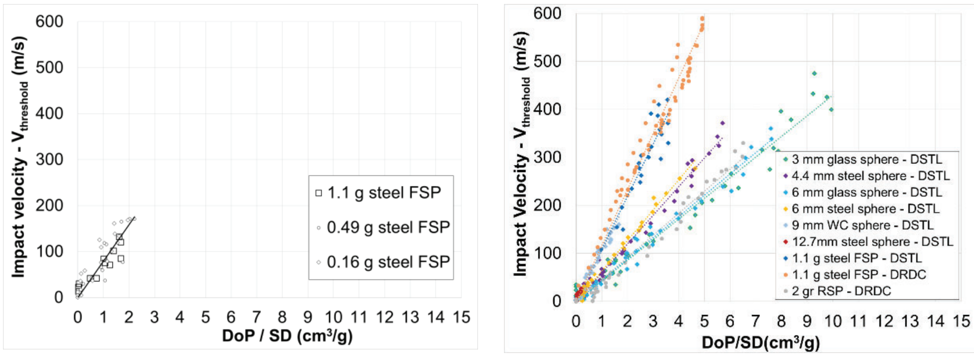
conducting explosive testing and using the pack as a witness system. When fragments are recovered or imaged from the pack, one may use the information on fragment shape and material to estimate sequentially the mass and SD of the fragment, the perforation threshold velocity from the skin V_{50} curve and the impact velocity from the fit in Figure 4. Then, if the data is meant to be used for soft tissue injury prediction, the appropriate scale factor or transfer function may be applied to the DoP value.



a. b.

Figure 4 a. Depth of penetration data from Breeze, *et al.* [16], b. Depth of penetration response of TP5 pack against various projectiles

4. APPLICATIONS

4.1 Testing of Soft body armour

The TP5 pack was used as a backing material for the V_{50} testing of two generic soft armours against the 1.1 g FSP. The soft armours had an areal density of 3.3 kg/m^2.One was made of Ultra-High Molecular Weight Polyethylene (UHMWPE) Unidirectional fabric and the other, a para-aramid plain weave fabric. Figure 5a shows the resulting V_{50} for the 1.1 g FSP along with additional results from V_{50} tests conducted on the same soft armours, but using different test methods. V_{50} data for a third soft armour made of 27 plies of another woven para-aramid fabric was obtained with these other test methods and is included for comparison. The additional methods considered were; Roma Plastilina 1 (RP1), the Blunt Trauma Thoracic Rig (BTTR) [21], the STANAG frame at two different levels of fabric tension and clamping pressure. All V_{50} estimates were obtained from Probit regression over *n* tests, where *n* varied between 25 and 42. Error bars on the graph indicate the 95% confidence interval, which can be seen here as an indication of the amount of variability observed in the data. When the range of velocities leading to a mixed outcome is large, the 95% confidence interval of the regression on the V_{50} is typically higher.

As expected, V_{50} estimates are significantly affected by the test method, with the highest difference between two methods being on the order of 10%. While this may be deemed acceptable, it is concerning that the performance ranking of the fabrics changes from one method to another. Also, it is highly probable that such variability increases when testing protective fabrics at low areal densities. The TP5 pack yields estimates that fall between those obtained with the RP1 and the STANAG frame. The STANAG frame in particular generated significant variability on the woven material, which is likely due to the tension not being uniform across the fabric surface. The TP5 pack generated narrow confidence intervals on both fabrics tested. While this was also the case for the RP1, the calibration process for RP1 is tedious. Conversely, a short series of DoP tests with the TP5 pack could suffice to validate that the materials of the pack behave as expected.

Figure 5b shows an example of results from an overmatch test where the TP5 pack first variant was used to recover the 1.1g FSP after armour perforation and calculate the residual velocity based on the pack calibration curve for that projectile. The graph shows the energy absorbed by the armour as a function of projectile impact energy. This type of response, where the absorbed energy from a soft armour decreases as the impact energy increases has been reported before [20]. The data was very straightforward to obtain with the TP5 pack. The pack has the considerable advantage of maintaining the coupling of the armour with the backing, as opposed to conducting air backed tests to generate similar residual velocity data.

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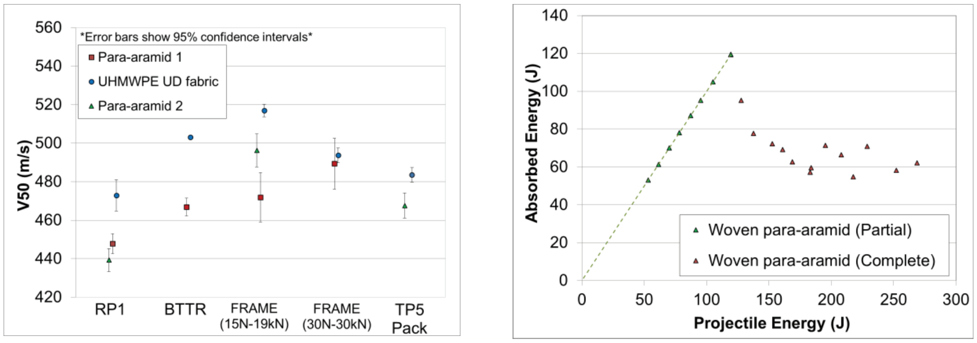


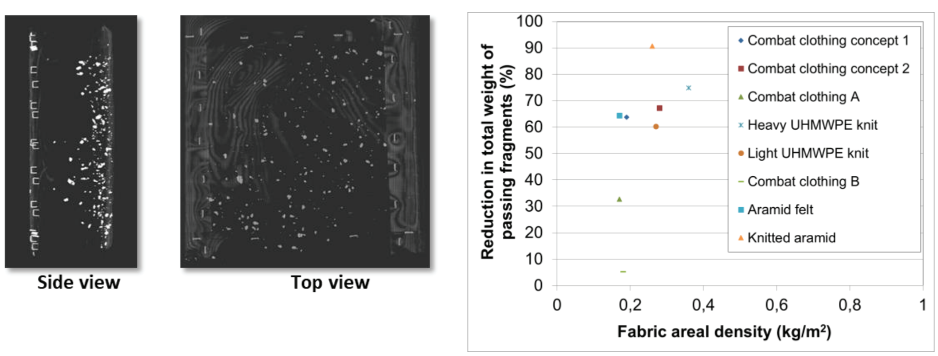
a. b.

Figure 5 a.V_{50} estimates for 3 soft armour against the 1.1 g FSP obtained with different test methods b. Example results from overmatch tests on a woven para-aramid fabric.

4.2 Full-scale explosive trial

The explosive test variant of the pack was used in a series of experiments simulating the detonation of a buried IED. In one trial, over 30 packs were fabricated and deployed at 1.75 m from a charge made of 5 kg of ammonium nitrate-fuel oil explosive, buried at 0.2 m, in order to characterize the generated ejecta distributions as well as to evaluate the protective performance of several very lightweight fabrics. The TP5 pack was found to be resilient to the blast generated, and aside from a few occasions where a large cluster of fragments tore the skin material, the packs held together and allowed for a complete analysis of the captured fragments post-test. To perform such analysis, a semi-automated method using a CT scanner was developed at DRDC [22]. Figure 6a shows an example of side and top views of a scan of one of the packs used during the explosive trial. While the manual extraction and measurement of fragments is always possible, it can be very labour intensive. The CT scanner method enables the semi-automated extraction of the number of fragments, individual fragment location, DoP, size, shape factor and mass (assuming the material of the fragment is known). The characterization of the mass and velocity distribution of an ejecta cloud associated with a threat is very relevant to vulnerability analysis.

Very lightweight protective fabric with relevance for PPE items, such as enhanced combat clothing and Tier 1 Pelvic Protection systems, were tested over the TP5 packs during the same trial. In addition to the qualitative assessment of the resistance of the fabric, the analysis of the pack enabled comparison of the fabrics using quantitative performance metrics. For example, Figure 6b shows a plot of the reduction of total mass of fragments perforating the skin for various fabrics of different areal density. This plot is obtained by comparing the total mass of fragments embedded in a pack from a protected scenario to a benchmark scenario (bare skin or other material covering).



a. b.

Figure 6, a. CT scans of a pack after exposing it to the detonation of a buried explosive charge b. Example of results from full-scale explosive testing of lightweight fabrics using the TP5 pack.

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5. CONCLUSION

Following the launch of a study assignment under The Technical Cooperation Program, a biofidelic test backing, aiming to provide representative boundary conditions for soft body armour during testing, was successfully developed at DRDC. The backing, provisionally called the TP5 pack, exhibits a local dynamic compliance matching abdominal and thoracic deflection responses. The perforation response of the pack skin layer was shown to correlate with skin perforation thresholds over a wide range of projectile SD, which enables the use of skin perforation as a criterion for V50 and Vproof testing. The multi-layer construction was shown to offer the capability to estimate projectile impact velocity, residual velocity or absorbed kinetic energy though measurement of depth of penetration in the pack. While the DoP response of the pack could not directly be tailored to match soft tissue DoP response, the trend of normalized DoP as a function of projectile velocity was similar, which enabled the use of a transfer function for injury prediction. The TP5 pack was shown to be reliable during the testing of soft armours and introduced minimal variability in the testing without necessitating a long calibration process. The pack was also fielded during full scale explosive tests and enabled the ranking of protective materials based on metrics such as reduction of total mass of fragments leading to skin perforation. The pack was deliberately designed using off-the-shelf materials that can be sourced internationally so that it can eventually be readily implemented in any ballistic laboratory worldwide. The final construction is still subject to minor changes.

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