Are the sensor based BABT test methods suitable for helmet and body armour certification?

B. Anctil[1], M.M.G.M. Philippens[2] and N. Shewchenko[1]

[1]Biokinetics and Associates Ltd., 2470 Don Reid Dr., Ottawa, Ontario, K1H 1E1, Canada, anctil@biokinetics.com
[2]TNO Defence Security and Safety, P.O. Box 45, 2280 AA, The Netherlands

Abstract. The ability of a helmet and body armour to attenuate blunt ballistic impact is currently assessed by clay backing indentation used to estimate impact severity and, presumably, trauma. Even though clay has guided the safety of body armour over the years, it has limited relationship with human bodily response and Behind Armour Blunt Trauma (BABT) injury. While new test methods have been developed to have a more human-like response and capability to evaluate BABT injury risk, it is unknown if their measurement accuracy is adequate for regulating protective equipment in performance standards. To address this concern, experimental investigations were carried out with new and established BABT test methods. An initial test series was conducted with a rigid impactor (37 mm dia., 93 g, 25-35 m/s) simulating BABT conditions. For the head, five impact locations were selected on the clay filled and the load sensing headforms. Similar impact conditions were used for the torso using clay backing fixtures and the instrumented torso surrogate. After 600 headform shots, the average standard deviations (SD_{avg}) were 7% for clay indentation compared to 2% for peak total force measured with the load sensing headform. For the torso, the average SD was 11% for clay indentation compared to 5% for the chest velocity-compression parameter (VC) of the instrumented torso surrogate. A second test series was performed using 18 body armour samples (53 shots total) and 9 mm FMJ bullets (350 m/s). For the clay indentation, the SD was 6% compared to 7% for the VC values obtained with the instrumented torso surrogate. The results showed that the new BABT test method variability is comparable to established methods while possessing better biofidelity and lower test effort. Future work will focus at reducing further BABT test method variability which, in combination with better biofidelity, would lead to better optimization and future innovations of helmets and body armour.

1. INTRODUCTION

Test standards and product specifications have been relying on clay backing indentation to evaluate the ballistic blunt impact attenuation capability of personal armour systems. This approach has been used to certify helmet and body armour even if the clay material has limited relationship with the dynamic response of the human body [1, 2] and does not address the injury mechanism which is driven by the motion of the body wall [3].

Other alternatives are now being considered to evaluate Behind Armour Blunt Trauma (BABT). The Ballistic Load Sensing Headform (BLSH) [4] and the Blunt Trauma Torso Rig (BTTR) [5] are biofidelic (i.e. reproduce human bodily response) test devices amongst others [6-8] and have the capability to evaluate BABT injury risk [9, 10] with the added benefits of requiring less manual handling and operating in a cleaner working environment in comparison with the established clay methods. The application of these new methods to performance standards remains, however, uncertain without assessing measurement accuracy

The BLSH is a magnesium, ISO shaped headform equipped with up to 2 arrays of seven miniature load cells to measure the dynamic loads imparted to the skull. A polymer skin cover is used over the load cell array to better simulate normal skull load distribution response. The load sensing headforms are mounted on a flexible neck from the Hybrid III anthropomorphic test device to reproduce head kinematics (Figure 1).

The BTTR is similar to the BABT test rig developed by Dstl [11] which uses a flexible membrane to reproduce the biomechanical response of the human chest. A triangulating laser displacement measuring gauge and a mirror located inside the cylindrical membrane is used to measure the dynamic deflection of the chest wall behind the impact point (Figure 1).

To compare the various test methods, the clay block, clay headform, the BLSH and the BTTR were impacted directly by a rigid projectile simulating BABT loading conditions [12]. The use of a rigid impactor provides representative input conditions without the inherent variability of bullets and body armour. In a second test series, armour samples were introduced allowing the performance test methodologies to be evaluated with actual products.

BLSH BTTR (cross-section)

Figure 1. Instrumented Head and Torso Surrogates

The test program was developed with the recommendations from the National Research Council [13, 14] in mind where testing related variability was controlled by limiting error sources introduced by the operator, measurement methods and tools, projectile construction, sample conditioning, targeting and impact speed, to the extent possible.

2. MATERIALS AND METHODS

2.1 Direct Impact Tests

An air canon equipped with a smooth bore barrel was used to launch a rigid plastic (Delrin®) baton (37 mm dia., 94 g) shown in Figure 2 on the clay blocks, clay headforms, BLSH and BTTR at two test velocities. The first velocity (25 m/s) was established from helmet backface deformation data [12]. The second test velocity (35 m/s) was selected to represent approximately twice the energy of the first condition (29 J vs. 58 J). The targets were positioned at approximately 75 mm from the muzzle (Figure 3) to maintain the projectile in the barrel during impact to control the angle of incidence.

Figure 2. Rigid Baton

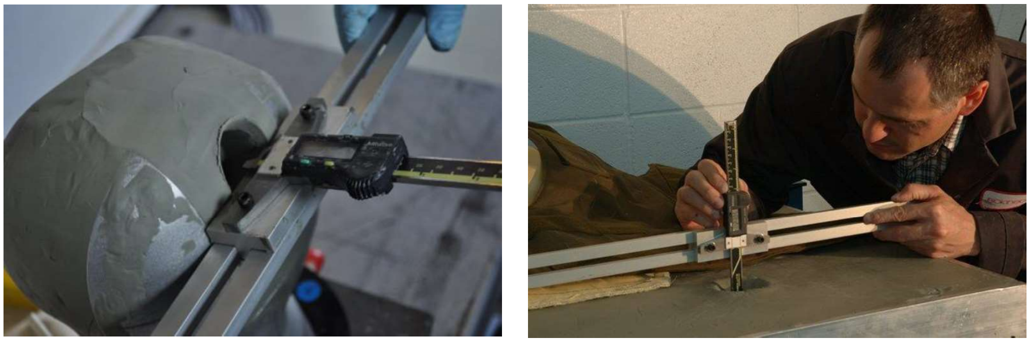
Clay Headform BLSH BTTR

Figure 3. Test Surrogates

For head impacts, the clay indentation was evaluated using the procedure described in the "Helmet, Advanced Combat Helmet Performance Specification" [15] with NIJ 0106.01 [16] clay headform modified to have slots in both directions. Five clay headforms were used in this test series.

They were filled with clay from the same production lot. The clay headforms and the BLSH were tested at five impact locations as indicated in the test matrix (Table 1).

The NIJ 0101.06 [17] methodology was used to prepare, validate, and measure clay indentations associated with torso impact (Figure 4). Two clay backing fixtures (610 mm x 610 mm x 100 mm depth) were used for each test series (15 shots / clay block).



Clay Headform

Clay Block

Figure 4. Clay Indentation Measurements

Signals from the BLSH's load cells (Kistler Model No. 9712B5000) were conditioned with Kistler PiezoSmart Power Supply Coupler (Type 5134B) having built-in 10 kHz (-3 dB) lowpass anti-alias filtering (4-pole Butterworth). Analog-to-digital conversion and data recording was conducted with a data acquisition unit (National Instruments' cDaq Model No. 9172 and 9215). The sampling frequency corresponded to 100 kHz. The recorded force signals were filtered using a 4-pole Butterworth zero-phase forward and reverse digital lowpass filter (4.5 kHz at 3 dB) prior to calculating the total dynamic force applied on the load cell array using Equation (1).

$$Total\ Force\ (t) = \sum_{k=1}^{7} F\ (t,k) \tag{1}$$

where: *k* corresponds to the load cell number

The signal of the BTTR's laser displacement transducer (Micro-Epsilon model no. optoNCDT 1627-200) was sampled at 10 kHz and recorded with a National Instruments' data acquisition unit (model no. USB-6009) connected to a personal computer. The BTTR membrane deflection signal was filtered using a 4-pole Butterworth zero-phase forward and reverse digital lowpass filter (1 kHz at 3 dB) before evaluating the deflection rate (V) – Equation (2) and viscous criterion (VC) – Equation (3). BTTR impacts were located at the centre of the membrane.

$$V(t) = \frac{8\left[C(t+\delta t) - C(t-\delta t)\right] - \left[C(t+2\delta t) - C(t-2\delta t)\right]}{12\delta t} \tag{2}$$

where: C is the filtered membrane's deflection signal, and; δt is the time interval between measurements.

$$VC(t) = 1.3\left[V(t)\left(\frac{C(t)}{chest\ depth}\right)\right] \tag{3}$$

where: the trauma rig's *chest depth* = 255.5 mm which corresponds to the 50% adult male [18].

Table 1. Test Matrix (Direct Impact)

Test Series	Device	Impact Location	Target Velocity (m/s)	No. of Repetitions
1	Clay Headform	Left	25±1	30
2	Clay Headform	Right	25±1	30
3	Clay Headform	Front	25±1	30
4	Clay Headform	Back	25±1	30
5	Clay Headform	Crown	25±1	30
6	Clay Headform	Left	35±1	30
7	Clay Headform	Right	35±1	30
8	Clay Headform	Front	35±1	30
9	Clay Headform	Back	35±1	30
10	Clay Headform	Crown	35±1	30
11	BLSH	Left	25±1	30
12	BLSH	Right	25±1	30
13	BLSH	Front	25±1	30
14	BLSH	Back	25±1	30
15	BLSH	Crown	25±1	30
16	BLSH	Left	35±1	30
17	BLSH	Right	35±1	30
18	BLSH	Front	35±1	30
19	BLSH	Back	35±1	30
20	BLSH	Crown	35±1	30
21	Clay Block	n/a	25±1	30
22	Clay Block	n/a	35±1	30
23	BTTR	n/a	25±1	30
24	BTTR	n/a	35±1	30

2.2 Body Armour Tests

A total of 18 body armour samples (Level II - NIJ 0101.04) fabricated by the same manufacturer but from different batches were tested with 9 mm, 124 gr, FMJ bullets (350±9 m/s) using the clay backing fixture and the BTTR identified previously (Figure 5). The number of impacts per armour sample varied between 3 and 5 shots depending on the size of the test panel. The same test methodologies, signal processing, and data analysis techniques presented in Section 2.1 were used in this test series. The time required to complete testing, including the system verification procedures, was recorded for each sample evaluated.

Clay Block BTTR

Figure 5. Body Armour Testing

3. RESULTS

3.1 Direct Impact

Overall, the average standard deviations for all tests (SD_{avg}) were 7% for headform clay indentation and 2% for peak total force measured with the BLSH in comparison with a SD_{avg} of 1% for the input condition (projectile velocity). Details per impact location and test velocity are provided in the following tables.

Table 2. Clay Headform Results

Impact Location	Velocity		Indentation			Velocity		Indentation	
	Average (m/s)	Std Dev %	Average (mm)	Std Dev %		Average (m/s)	Std Dev %	Average (mm)	Std Dev %
Left	25.1	1.4%	34.8	7.3%		35.2	0.8%	55.9	5.2%
Right	25.3	1.0%	35.7	9.6%		35.1	0.9%	62.0	5.4%
Front	25.3	1.2%	30.1	5.5%		35.0	0.6%	48.5	6.9%
Back	25.2	0.8%	29.4	6.4%		35.1	0.5%	52.4	7.7%
Crown	25.2	1.0%	37.7	7.7%		35.0	0.8%	58.9	7.5%

Table 3. BLSH Results

Impact Location	Velocity		Peak Total Force			Velocity		Peak Total Force	
	Average (m/s)	Std Dev	Average (N)	Std Dev		Average (m/s)	Std Dev	Average (N)	Std Dev
Left	25.2	0.9%	6297	1.1%		35.1	0.4%	9297	1.2%
Right	25.2	0.9%	5487	3.2%		35.0	0.6%	9142	1.8%
Front	25.4	0.9%	6752	2.1%		34.9	0.9%	9291	2.2%
Back	25.2	1.0%	6461	2.1%		35.1	0.9%	8656	2.6%
Crown	25.2	1.4%	6480	4.5%		35.1	0.7%	8900	1.5%

Clay headform indentation measurements for the front and back locations were lower than the average for all impact locations (dashed line) as illustrated in Figure 6. For the BLSH, lower peak force values were recorded for the right location at 25 m/s and at the back location at 35 m/s.

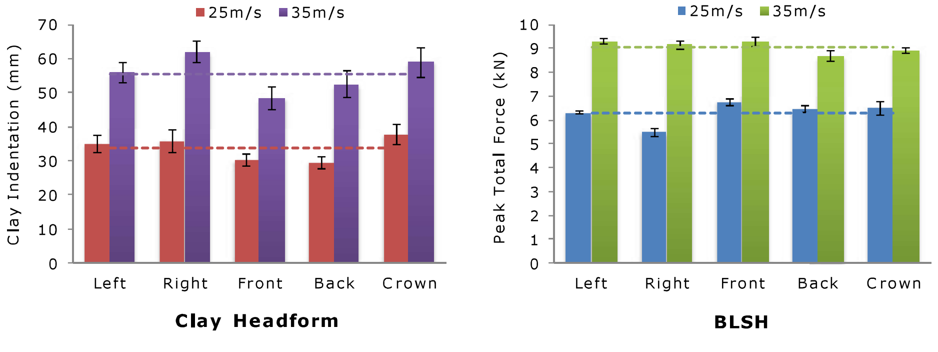


Figure 6. Average Headform Test Results (error bars represent ±1 standard deviation)

The SD_{avg} was 11% for clay block indentation compared to 5% for the chest velocity-compression parameter (VC_{max}) measured with the BTTR. For the clay block tests, higher variability was observed for impacts at 35 m/s (SD=13.8%) in comparison with the 25 m/s impacts (SD=8.5%) Table 4, Figure 7. The BTTR variability was similar at the two test velocities for the peak deflection-C_{max} (SD=1.3% vs. 1.0%) and the peak viscous criterion-VC_{max} (SD=5.5% vs. 4.5%).

Table 4. Clay Block and BTTR Results

Clay Block			
Velocity		Indentation	
Average (m/s)	Std Dev	Average (mm)	Std Dev
25.2	0.9%	23.1	8.5%
35.1	0.7%	43.2	13.8%

BTTR					
Velocity		C_{max}		VC_{max}	
Average (m/s)	Std Dev	Average (mm)	Std Dev	Average (m/s)	Std Dev
25.2	1.4%	23.5	1.3%	0.58	5.5%
35.0	0.9%	32.9	1.0%	1.05	4.5%

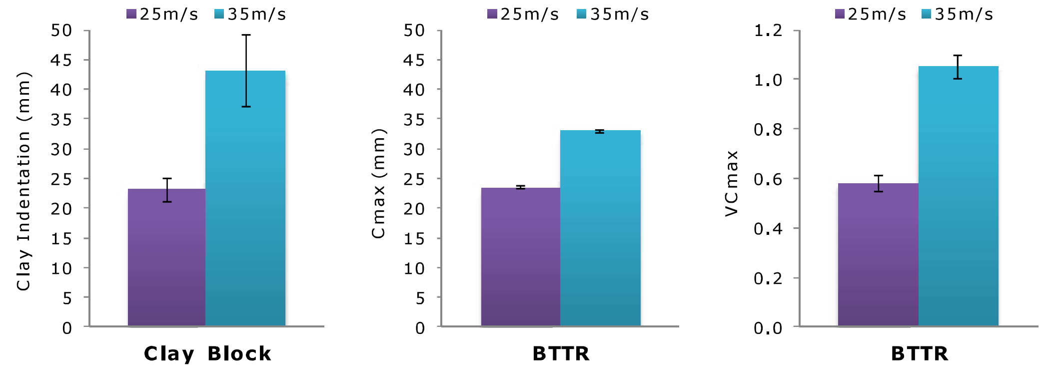


Figure 7. Average Torso Test Results (error bars represent ±1 standard deviation)

For similar test velocities, higher clay indentation values were recorded with the headforms in comparison with the clay blocks. For example, at 25 m/s the average clay headform indentation corresponded to 33.6 mm in comparison with 23.1 mm for the clay block. Furthermore, the standard deviations at 25 m/s for the clay block and headform are similar while the SD at 35 m/s is higher for the clay block than for the headform.

3.2 Body Armour

A total of 26 and 27 valid shots were obtained for the clay block and BTTR tests, respectively. In comparison with the previous test series, a lower standard deviation was observed for the tests using the clay block (5.7% vs. 8.5-13.8%) while the opposite trend was noted for the BTTR VC_{max} results (7.1% vs. 5.5-4.5%), Table 5. No complete perforation was recorded.

Table 5. Body Armour Test Results

Clay Block			
Velocity		Indentation	
Average (m/s)	Std Dev	Average (mm)	Std Dev
350.7	1.2%	34.7	5.7%

BTTR					
Velocity		C_{max}		VC_{max}	
Average (m/s)	Std Dev	Average (mm)	Std Dev	Average (m/s)	Std Dev
351.5	1.1%	33.0	3.0%	2.62	7.1%

The average time required to complete the evaluation of one body armour sample was 37 min for the clay method in comparison with 21 min for the BTTR (Figure 8). Post-test duration for sample ID No. 7 was not recorded. Pre and post tests for the clay method consisted in measuring the clay indentation resulting from a 1 kg steel ball being dropped from a 2 m height [17]. For the BTTR, pre and post tests were conducted with the built-in 2.2 kg pendulum (Figure 9). Each pre and post test series included five consecutive drop tests. Validation tests are meant to be practical and reproducible, not necessarily representative of ballistic impact conditions. Pre-test results are used to confirm if the response of the surrogate (e.g. clay, BTTR's membrane) is within tolerance before armours are evaluated. Post-test validation results are used to verify if the response of the surrogate changed while testing body armours. A large discrepancy between pre and post tests indicates a problem with the equipment (e.g. cooled clay, damaged membrane) and thus invalidates the armour test results.

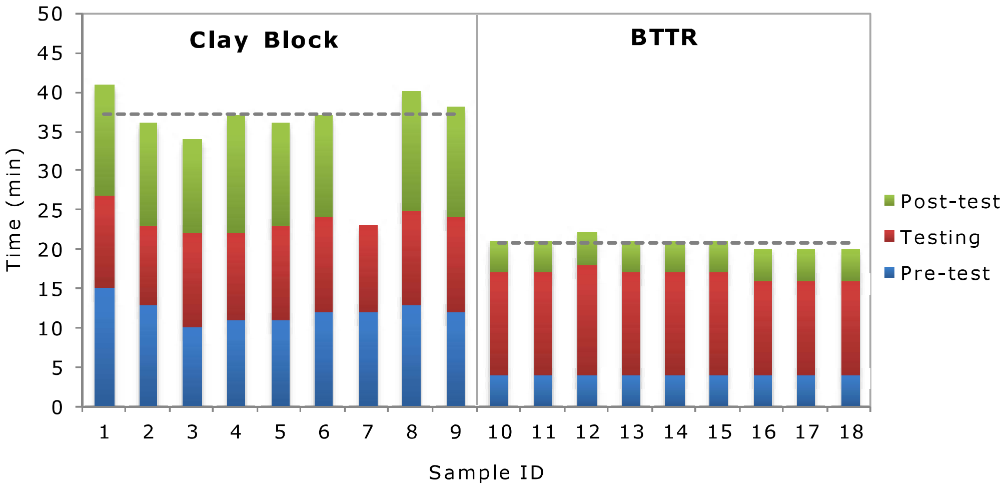
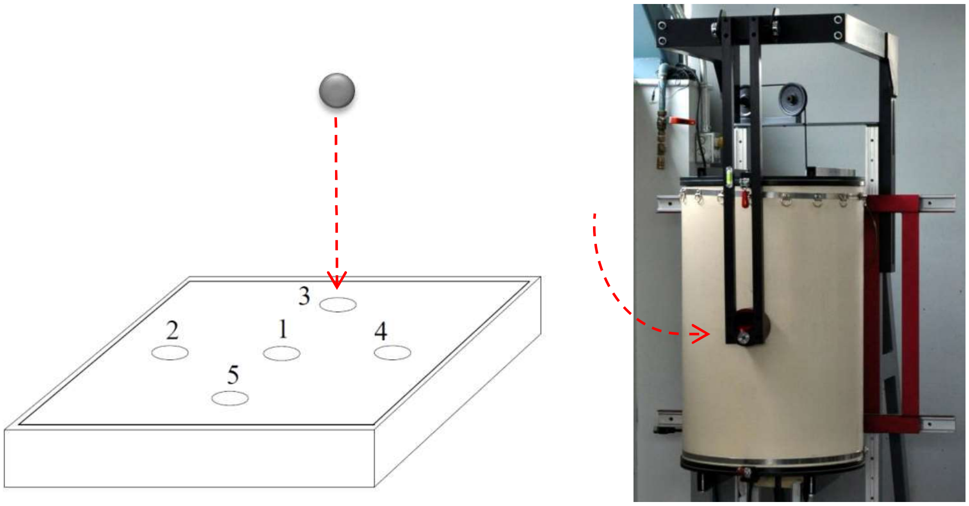


Figure 8. Body Armour Test Duration (dashed line represents the average)



Steel Ball Drop on Clay

BTTR's Pendulum

Figure 9. Pre and Post Test Validation Methods

4. CLAY VS. SENSOR METHODS

4.1 Direct Impact

Data was normalized to combine the results obtained at the two test velocities. Each value (clay indentation, peak total force, or VC_{max}) was divided by the average response of the 30 repetitions. Data distribution for each test method is illustrated using histograms (Figure 10). The dashed lines correspond to the normal distributions estimated with the respective mean and standard deviation values. For both the BLSH and the BTTR, a lower distribution was observed in comparison with the clay test devices.

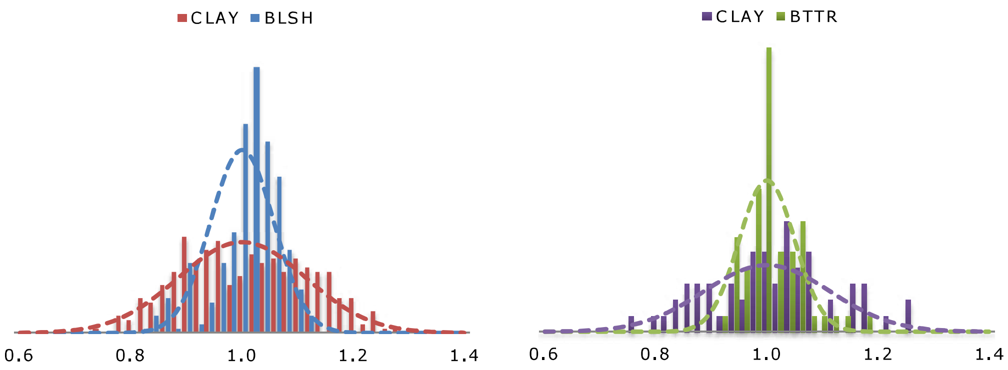


Figure 10. Direct Impact Test Data Distribution (normalized values)

These results suggest that sensor based methodologies have a lower measurement variability in comparison with the existing clay methods. Practically, this can lead to further armour optimization by providing an additional margin between the highest expect measurement value (identified by "A" and "B" in Figure 11) and a pass/fail limit prescribed by the test standard "C". From a test methodology perspective, lower variability provides greater statistical confidence in the results or it can reduce the number of test repetitions required to achieve the same level of confidence as for the clay methods.

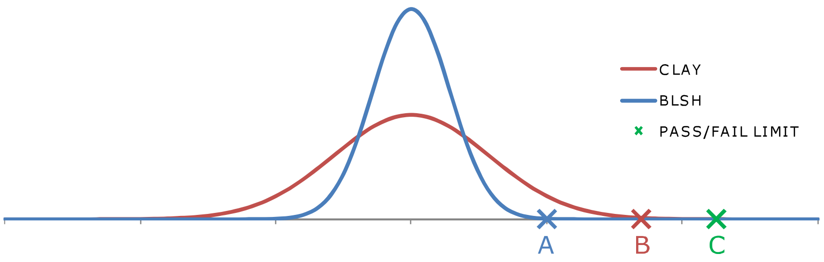


Figure 11. Maximum Measurement vs. Pass/Fail Limit

4.2 Influence of Body Armour

When testing with body armour samples, lower peak deflection measurement variability was observed for the sensor based method (SD=3.0%) in comparison with clay indentation (SD=5.7%). The standard deviation of the proposed BABT indicator for the BTTR, VC_{max}, was higher (7.1%) in comparison with clay indentations (Figure 12), most likely due to the different interaction of the armour with the test device. It may also be noted that the measured responses are not symmetrically distributed leading to approximations.

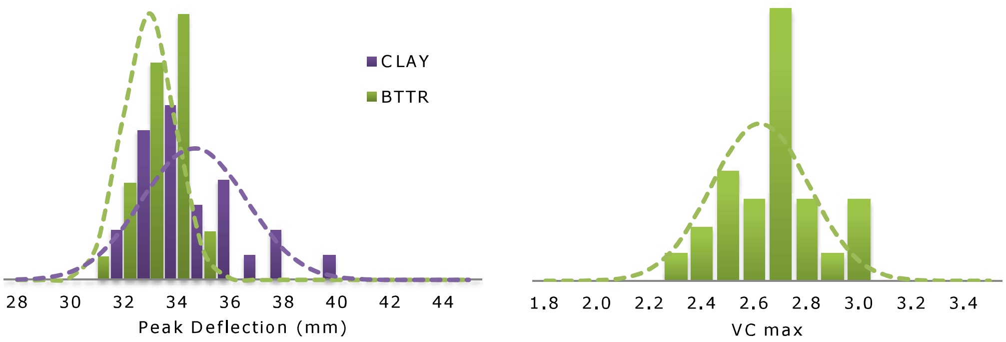


Figure 12. Body Armour Test Data Distribution

Explanations for a decrease in the clay response variability may include a number of factors such as differences in how the armour is supported by the backing medium, shape differences of the armour samples on the flat clay block or curved BTTR membrane, armour constraint methods, and other random errors. A systematic evaluation of all factors would be required to quantify the contribution of each parameter.

The opposite trend was observed for the BTTR measurements when compared to clay, i.e. a higher variability when testing body armour samples. The average standard deviation results shown in Figure 13 suggest that the variability of the test samples corresponds to approximately 2%.

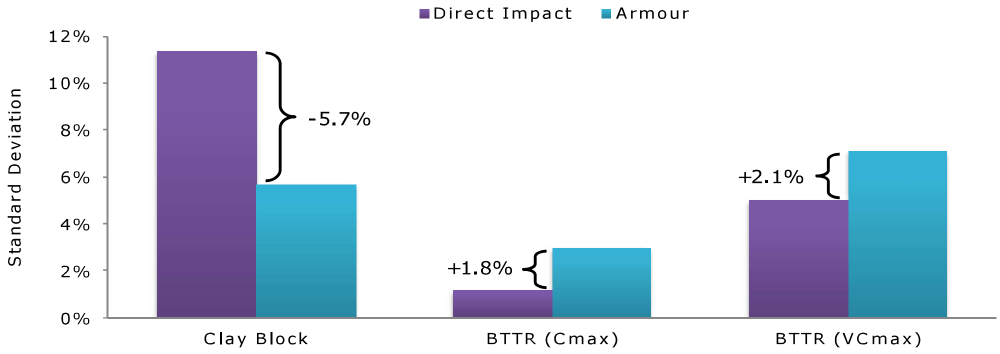


Figure 13. Standard Deviation for Direct Impact and Body Armour Testing

On average, the overall test duration was reduced by 17 min (44%) per sample with the BTTR in comparison with the standard clay method (Figure 14). The time required to complete the 3 test shots on the armour samples was comparable between the clay method (12 min) and the BTTR (13 min). However, more effort was required (+18 min) for the pre and post tests to complete the ball drops, record indentation measurements, and repair the clay surface in comparison with the pendulum tests used with the BTTR.

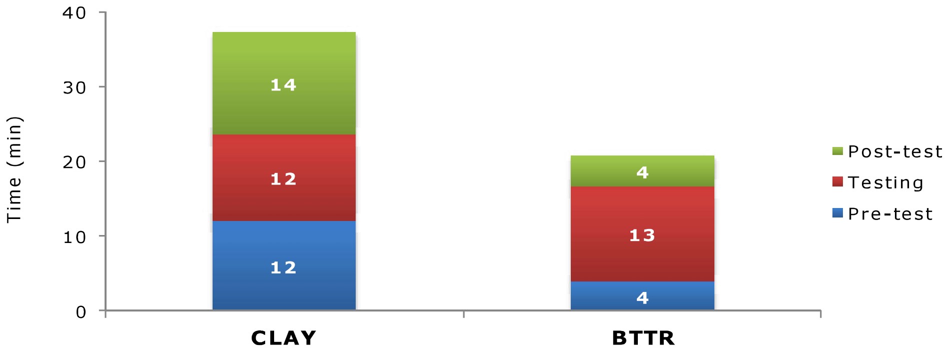


Figure 14. Average Body Armour Test Duration

5. CONCLUSIONS

With measurement variability comparable to the established test standards, the sensor based methods evaluated in this study can be considered as a viable alternative to certify helmet and body armour.

Under controlled impact conditions, the average standard deviation obtained with the instrumented headform was 2% of the peak total force and 5% of the viscous criterion parameter for the instrumented torso. In comparison with the clay method, these results suggest that further armour optimization would be possible because the outcomes are more predictable. Alternatively, lower testing effort may be possible by reducing the number of tests to achieve the same level of statistical confidence in the results.

The sensor based methods required a lower test effort. The results of the body armour evaluation showed that testing time can be reduced by 44%, from 37 to 21 min.

Future work will focus at identifying the major sources of variability for each sensor based test method. This knowledge is essential to propose adequate controls to ensure that the measurements truly reflect the BABT attenuation performance of the armour system being evaluated and to develop test procedures to achieve repeatable and reproducible results [19].

Additional benefits of the sensor based systems in relation to clay based systems are noteworthy. With the increased biofidelity of such systems and their validation with biological systems, greater insight into the behind armour-body interactions and assessment of injury potential is possible. With this, armour systems can be designed to provide better protection with greater certainty through robust test methodologies.

References

[1] Bass, C., Salzar, R., Lucas, S., Davis, M., Donnellan, L., Folk, B., Sanderson, E., and Waclawik, S. M., Injury Risk in Behind Armor Blunt Thoracic Trauma, *International Journal of Occupational Safety and Ergonomics*, vol. 12, pp. 429-442, 2006.

[2] Freitas, C. J., Mathis, J. T., Scott, N., Bigger, R. P., and Mackiewicz, J., Dynamic Response Due to Behind Helmet Blunt Trauma Measured with a Human Head Surrogate, *International Journal of Medical Sciences*, vol. 11, pp. 17, 2014.

[3] Cannon, L., Behind armour blunt trauma--an emerging problem, *J R Army Med Corps*, vol. 147, pp. 87-96, 2001.

[4] Anctil, B., Keown, M., Bourget, D., and Pageau, G., A Novel Test Methodology to Assess the Performance Ballistic Helmets, 22nd International Symposium on Ballistics, Vancouver, Canada, 2005.

[5] Anctil, B., Bayne, T., Bourget, D., Pageau, G., Binette, J.-S., Rice, K., and Toman, A., An Alternative to Plastilina for Evaluating the Performance of Body Armours, Personal Armour Systems Symposium, Brussels, Belgium, 2008.

[6] Cooper, G. J. and Pearce, B. P., Experimental Evaluation of a Rig to Simulate the Response of the Thorax to Blast Loading, *"The Journal of Trauma: Injury, Infection and Critical Care"*, vol. 40, pp. S38-S41, 1996.

[7] Jönsson, A., Arvebo, E., and Schantz, B., Intrathoracic Pressure Variations in an Antropomorfic dummy Exposed to Air Blast, Blunt Impact and Missiles, *The Journal of Trauma*, vol. 28, pp. S125-S131, 1988.

[8] Tam, W., Development of a behind armour injury simulator, 3rd meeting of the Task Group on Behind Armour Blunt Trauma, Washington, USA, 1999.

[9] Bolduc, M. and Anctil, B., Improved Test Methods for Better Protection, a Proposal for STANAG 2920, Personal Armour Systems Symposium, Quebec City, Canada, 2010.

[10] Hewins, K., Anctil, B., Stojsih, S., and Bir, A. C., Ballistic Blunt Trauma Assessment Methodology Validation, Personal Armour Systems Symposium, Nuremberg, Germany, 2012.

[11] Tam, W., Dorn, M., and Gotts, P., A New Method for Quantifying Behind Armour Blunt Trauma, presented at Personal Armour Systems Symposium, 2000.

[12] Anctil, B., Bourget, D., Pageau, G., Rice, K., and Lesko, J., Evaluation of Impact Force Measurement Systems for Assessing Behind Armour Blunt Trauma for Undefeated Ballistic Helmets, Personal Armour Systems Symposium, The Hague, The Netherlands, 2004.

[13] Lehowicz, L. G., *Testing of Body Armor Materials - Phase III*. Washington, DC: The National Academies Press, 2012.

[14] Nair, V. N., Anderson-Cook, C., Bass, C., Budinger, T. F., Cushing, M. J., Easterling, R., Fricker, R. D., Fuller, P. N., Radovitzky, R. A., and Seglie, E., *Review of the Department of Defense Test Protocols for Combat Helmets*. Washington, DC: The National Academies Press, 2014.

[15] DoD, Performance Specification - Helmet, Advanced Combat: Natick Soldier Center, 2007.

[16] NIJ, Ballistic Helmets, vol. NIJ Standard-0106.01. Washington DC: US Department of Justice, 1981.

[17] NIJ, Ballistic Resistance of Body Armor, vol. NIJ Standard-0101.06. Washington DC: US Department of Justice, 2008.

[18] Schneider, L. W., Robbins, D. H., Pflüg, M. A., and Snyder, R. G., Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family, Volume 1, U.S. Department of Transportation, National Highway Trafic Safety Administration, Washington, D.C., Final Report DOT-HS-806-715, 1985.

[19] Philippens, M. M. G. M. and Anctil, B., Results of a Round Robin Ballistic Load Sensing Headform Test Series, Personal Armour Systems Symposium, Cambridge, United Kingdom, 2014.