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Comparative Analysis of Impact Strength Tests of the Anti-Blow Multilayer Textile Lower Limb Protectors Devoted for the Police

Abstract
The article features the requirements and testing methodology for the assessment of the impact strength of multilayer lower limb protectors designed for the police, described in "HOSDB Blunt Trauma Protector Standard for UK Police. Limb and Torso Protectors" and BS 7971:2002 "Protective clothing and equipment for use in violent situations and in training". The paper also presents an analysis of laboratory test results of lower limb protectors, which were conducted in conformity with the requirements of both standard documents. An attempt was also made to compare them in terms of future application.

Key words: *anti-blow protection, test methodologies, BS 7971:2002, HOSDB, lower limb protector.*

Introduction

At the beginning of the 21st century research was undertaken at the Institute of Security Technologies "MORATEX" on new and advanced anti-blow protectors for the prevention troops of the Polish Police [1]. Models were developed which, after functional tests in real intervention and prevention actions, obtained the full approval of the Police Headquarters. However, there were no tools (standards, research stands) to carry out laboratory appraisal of these special products. The known documents (PN-EN, EN) described the requirements for protectors used in different sporting games [2], which could not be adapted for this new group of products due to their specific features resulting from their intended purpose. An analysis of the information available confirmed that. Well known and recognised European manufacturers of protectors did not specify the level of their protective properties (e.g. PROTECOP SA-France, Global Armour - United Kingdom, Med-Eng Systems Inc. - Canada, Hatch Corporation - USA), with the exception of helmets, or they specified the levels of protection according to the classification included in the unshared local documents, such as the German Technical Directives - TRL (e.g. MK Technology GmbH - Germany, Mehler Law Enforcement GmbH - Germany) [1]. The publishing of two of the eleven parts of Standard BS 7971 "Protective clothing and equipment for use in violent situations and in training", i.e.: Part 1:General requirements and Part 4: Limb protectors- requirements and test methods in 2002 in Great Britain was a milestone in this respect. It was developed based on the many years of experience and expertise of a team consisting of the representatives of the Association of Chief Police Officers in Scotland, Police Federation of England and Wales, vendors for the police and public security services, representatives of occupational medicine, manufacturers of personal safety equipment and SATRA Technology Centre [3]. The requirements of the said standard for both the research post itself and the level of properties, complete with useful anti-blow protectors for policemen, were adopted by the Polish Police Headquarters as obligatory for laboratory appraisal of these dedicated products.

Another document currently available containing the requirements and test methods for impact protectors, including limb protectors for a policeman, is "HOSDB Blunt Trauma Protector Standard for UK Police. Limb and Torso Protectors" developed by Chris Malbon [4]. It was published in 2007 by the Home Office Scientific Development Branch of Great Britain. It was the response to a demand from the British Work Team of the Public Order Department of the Association of Chief Police Officers (ACPO). This document, despite the title, has no rank of a Standard.

The article presents tests and analyses designed to determine both similarities and differences in the research methodologies described in the said documents with respect to the apparatus, measurements and interpretation, in terms of the selection of the most appropriate for use in the laboratory assessment of protectors, including limb protectors for a policeman. They were based on the guidelines described in HSDOB and BS 7971 and the results of laboratory tests of limb protectors carried out in accredited laboratories:

- In Britain, at INSPEC International Ltd in Salford, in accordance with the HOSDB methodology,
- In Poland, at the Institute of Security Technologies "MORATEX" Łódź, Poland according to the methodology described in the BS 7971-4:2002 standard.

Subject of tests

The subject selected for tests: anti-blow low limb protectors, one of the five compatible elements of the anti-blow kit developed at "MORATEX" and currently used by the Polish Police [5]. The decision on such a selection resulted from the fact that they consist of permanently inter-connected protectors: knee, shin and metatarsus. The two first, due to

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Figure 1. *Lower limb protectors.*

1
2
3
4

Figure 2. *Schematic system of layers in the lower limb protector (descriptions - see below in the text).*

the surface areas protected, are tested (acc. to BS 7971-4:2002) using different impactor-anvil patterns and various impact energies described in detail in points "Test stand equipment" and 4. of the article, hence they provide a good test-compare object.

The major objective of lower limb anti-blow protectors (***Figure 1***) consists in minimisation of the risk of knee, shin and metatarsus injury, complete with the ankles: external and internal, during assault with the use of blunt tools at low speeds. They have a multilayer structure. On the contact side of the user's body there are the following layers [6]:

- fabric of non-flammable fibres (item 1 in ***Figure 2***),
- foamed polyethylene material with closed cells (item 2 in ***Figure 2***),
- fabric of non-flammable fibres (item 3 in ***Figure 2***),
- semi-flexible profiled ABS shape (item 4 in ***Figure 2***).

The fabric of non-flammable metaaramide fibres used was manufactured by Theodolf Fritsche GmbH & Co. (Germany). Its characteristics are presented in ***Table 1***.

Figure 3. *Types of anvils for testing acc. to HOSDB [4]; a) cylindrical, b) semicircular, c) convex.*

The foamed material with a cellular structure was manufactured by POLTING FOAM (Poland). It's test results are presented in ***Table 2***.

The external shapes of the protectors were of ABS panels made by a company ATHLONE EXTRUSIONS P.L.C. (Ireland). The test results are presented in ***Table 3***.

Metrologic tests of all materials used in the anti-blow protectors of lower limbs, the results of which are presented in ***Tables 1 - 3***, were carried out at the accredited Metrologic Test Laboratory of the "MORATEX" Institute. The level of parameters obtained met the assumptions adopted.

Comparative analysis of laboratory equipment required for the tests

Test stand

The test stand for the impact strength tests of anti-blow protectors for policemen, described in the documents (HOSDB and BS 7971), have the form of thrust towers. They are used to exert a stroke on the test protector with energy of a value defined in those documents. Below the anvils they have sensors registering the values of force transferred to below the protector tested (sample), consisting of

Table 1. *Test results of the fabric made of non-flammable fibres.*

Item	Type of indicator	Unit	Value	Test method
1.	Surface mass	g/m^2	260 ± 14	PN-EN 12127:2000
2.	Maximum tensile force: - warp - weft	daN	 157±1 116±1	PN-EN ISO 13934-1:2002
3.	Tear strength: - warp -weft	daN	 9.1±1.0 7.5±1.0	PN-EN ISO 13937-2:2002
4.	Limited flame spreading: flame reaching top or vertical edge time of successive combustion time of successive glow presence of remnants occurrence of hole	 sec. sec. 	along / across absent 0 / 0 0 / 0 absent absent	PN-EN ISO 15025:2005
5.	Colour resistance to acidic and basic sweat: - change in sample colour - soil of white – polyamide - soil of white – cotton	degree	 5 4 5	PN-EN ISO 105-E04:2009
6.	Colour resistance to dry and wet friction: - warp - weft	degree	 4 4	PN-EN ISO 105-X12:2005

Table 2. *Test results for foamed material of cellular structure.*

Item	Description	Unit	Value	Test method
1.	Raw material		polyethylene	
2.	Apparent density	kg/m^3	30.0 ± 5.0	PN-EN ISO 845:2009
3.	Thickness	mm	5 ± 1 10 ± 1	PN-EN ISO 1923:1999

Table 3. *Test results for ABS panel.*

Item	Description	Unit	Value	Testing method
1.	Tear stress	MPa	35.8 ± 4.0	PN-EN ISO 527-1:1998
2.	Elasticity module at tension E	MPa	1995 ± 20	PN-EN ISO 527-1:1998
3.	Apparent density	kg/m^3	1040 ± 100	PN-EN ISO 845:2009

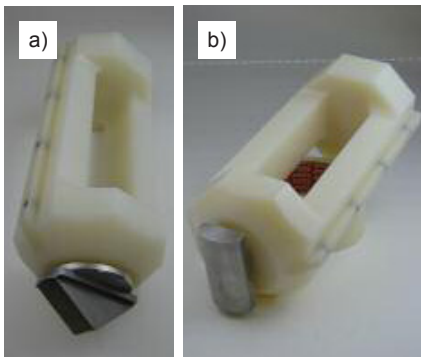

Figure 4. *Types of impactors for testing acc. to HOSDB [4]; a) bar type impactor b) wedge type impactor.*

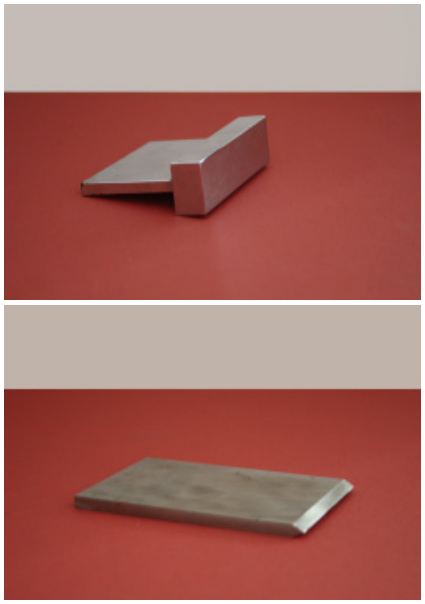

Figure 5. *Types of impactors for impact strength tests of lower limb protectors acc. to BS 7971; a) bar impactor, b) blade impactor.*

components of a finished product, i.e. for the lower limb protector: knee protector and shin protector.

Despite the differences in solutions of structural elements the operation of both stands is based on the same principle of vertical fall of the mass (impactor), with energy predefined in the requirements, onto a sample horizontally placed (on the anvil).

Test stand equipment

The test stand described in HOSDB [4] is equipped with a set of anvils, in shapes imitating the parts of the human body exposed to blows. Depending on the purpose of the given protector, one of three types of anvils is used for tests: cylindrical (***Figure 3.a***), semi-circular (***Figure 3.b***) or convex (***Figure 3.c***). Each of them is manufactured in 3 sizes, representing 5- (small), 50- (medium) and 95- (large) percent of the population of adults (men and women together) aged 18 - 65.

According to the HOSDB [4] one of the two impactors is a striking element:

- bar shaped (***Figure 4.a***) – imitating arms (thrown),
- wedge shaped (triangular) (***Figure 4.b***) – imitating the edges of a brick or some other "missile" thrown.

The test stand described in Standard BS 7971-4: 2002 point 6.4.2. [3] is also equipped with a set of impactors and anvils (***Table 4*** and ***Figures 5*** & ***6***) adjusted to the purpose of the protectors tested, however different from those required acc. to HOSDB.

The anvils and impactors described in the documents studied are designed to simulate real conditions of use during laboratory tests. Their shapes, according to the assumptions of the authors of both documents, reflect the tools of assault (impactors) and the protected parts of the body (anvils). The equipment of test stands required in the statements of the HOSDB and BS 7971 differs both in the shape and method of mounting, thus obviously affecting the difference in the testing methodologies and the interpretation of results obtained.

Testing methodologies

According to the methodology described in the HOSDB [4], there are two samples – finished products tested in the laboratory, with each partial protector, i.e. the element protecting the knee and that guarding the shin, being tested separately. According to point 5.4.4. of the said document, this test consists in:

- striking (at least 6 times) the first of the samples, fixed on a suitable anvil, with energy 20 ± 0.5 J with the use of a bar impactor, moving perpendicular to the longitudinal axis of the protector. Consecutive blows are placed at a distance of at least 15 mm from the central point of the previous stroke and at least 5 mm away from the central point edge of the protected to the nearest edge of the anvil. After every 6 strokes the value of the force transferred below tested sample is recorded,
- the stroke (at least 6 times) onto the next sample, also fixed, on the same anvil with the first sample, with energy of 20 ± 0.5 J, this time with the wedge impactor, moving perpendicular to the longitudinal axis of the protector, with the same threshold values as those of the first sample.

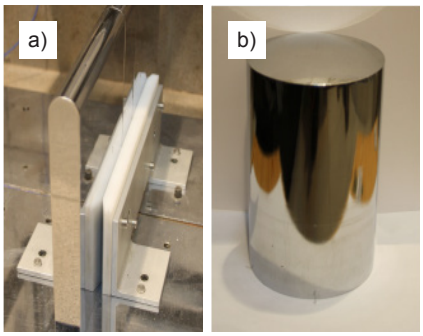

Figure 6. *Types of anvils for impact strength tests of lower limb protectors acc. to BS 7971; a) vertical plate, b) cylinder R50.*

According to the provisions of BS 7971-4:2002 [3], 2 samples-finished products are also laboratory tested, and similar to the HOSDB each partial protector, the element protecting the knee and that guarding the shin, are tested separately. The first sample is tested with the use of a bar impactor, the second – with a blade impactor.

The laboratory test, according to p. 6.4.3 of the BS 7971-4:2002, consists in:

- striking the test sample with a bar impactor or blade impactor. The sample is fixed on asuitable anvil (***Table 4***). The number of strikes oscillates between 1 and 6 depending on the size of the test surface. The energy of the stroke is a result of the level of protection assumed (the standard anticipates three levels) and the part of the body thus protected, amounting to 5J - 30J (***Table 5***). The central points of the

Table 4. *Types of impactors and anvils for testing lower limb protectors acc. to BS 7971-4:2002 [3].*

Area of body protected	Type of impactor	Type of anvil
Shin	Bar impactor Blade impactor	Vertical plate
Knee	Bar impactor Blade impactor	Cylinder R50

consecutive strokes are located at the following distances: not less than 40 mm from each other and not less than 30 mm from the edge of the protected zone. After every stroke the value of the force transferred to below the test sample (for tests with the bar impactor) is recorded or the size of damage on the internal surface (in tests with the use of a blade impactor) is registered.

Comparison of both methodologies presented shows that both according to the HOSDB and BS 7971-4:2002, laboratory tests of the impact strength are carried out on finished products, not on sample packages. The number of the samples tested is also the same. However, both documents basically differ in the requirements set forth for the level of the impact energy: acc. to the HOSDB, regardless of the type of impactor and element of the protector tested, this parameter has a constant value, equal to 20 ± 0.5 J. According to Standard BS 7971-4:2002, its value is differentiated between 5 J and 30 J (***Table 5***) and depends on the precise definition of the purpose of the given protector (what does it protect, against what the protection and in what hazardous situation it will be used).

Guidelines for the interpretation of test results

In accordance with the provisions of the HOSDB [4], the results obtained in laboratory tests are processed to calculate, at a 95% level of trust, the upper value of the transferred force anticipated (UPL) acc. to the following formula:

$$UPL = \overline{X} + t_{crit} S \sqrt{\frac{n+1}{n}}$$

where,

$\overline{X}$ average value of the transferred force

t critical value t, read from the Table (appendix B in the HOSDB document; page 31) for the given level of trust

S standard deviation of the transferred force

n number of strokes

The test is deemed completed with a positive result when the UPL calculated does not exceed the value of 10,000 N (10 kN). Apart from the average value of the transferred force, the standard deviation also has a significant influence on the UPL value. The greater the dispersion of results the higher the UPL value.

Under the provisions of Standard BS 7971-4:2002:

- in impact strength tests with the use of a bar impactor the average value of the transferred force is calculated. The admissible values of this parameter for lower limb protectors in terms of different levels of protection are presented in ***Table 5***,
- in the impact strength test with the use of a blade impactor, possible damage to the internal surface of the samples tested is measured. The result obtained is deemed positive when the size of the damage to the internal surface of the protection does not exceed 0.5 mm.

The test is deemed completed with a positive result when the results of tests with both types of impactors meet the requirements (***Table 5***).

Table 5. *Requirements for the impact strength of lower limb protectors acc. to BS 7971-4:2002 [3].* ***Note*** *[3]: *- hazard level: low. Intended use: where opponents are expected to be bare handed or at some distance, **- hazard level: moderate. Intended use: where close contact with opponents is expected, ***- hazard level: high. Intended use: where close contact with determined opponents is expected and in training situations where impacts are deliberately taken and may be severe.*

Area of body protected	Average (maximum) value of transferred force, kN	Impact energy, J		
		Level of protection 1*	Level of protection 2**	Level of protection 3***
Shin	less than 8.0 (12.0)	5	15	30
Knee	less than 10.0 (15.0)			

Table 6. *Results of impact strength tests of lower limb (shin, knee) protectors, acc. to HOSDB methodology [7].* ***Note****: The large spread of transferred forces observed under the sample (e.g. for the knee protector the minimum value was 1904 N and the maximum value 7655 N) results from the location of the strike point. The minimum value appeared on hitting the corrugated area of the protector, while the maximum was recorded with a hit on its smooth area. The values also depend on the number of hits on the area tested as well as at a small distance between consecutive strikes.*

	Sample No	Bar impactor				Sample No	Wedge impactor			
		Value of transferred force, N	Average value of transferred force $\bar{x}$, N	Upper value of transferred force anticipated (UPL)			Value of transferred force, N	Average value of transferred force $\bar{x}$, N	Upper value of transferred force anticipated (UPL)	
				obtained, N	required, N				obtained, N	required, N
SHIN (anvil cylindrical, large)	1	2740 2923 3124 2599 2668 2766 6686 2560 3131 3283 3943 2695	3260	5403	≤ 10000	2	6757 1814 7102 1837 5905 6381 1902 4100 2259 4581 6969 1808	4284	8517	≤ 10000
KNEE (anvil: convex, medium)	1	1904 4241 3689 4388 3396 4919 7655 3141	4167	7545	≤ 10000	2	7712 7811 2682 4439 7933 4763	5890	10742	≤ 10000

Table 7. *Results of impact strength tests of lower limb protectors (shin, knee) acc. to aprocedure based on Standard BS 7971-4:2002.*

	Sample No.	Bar impactor			Impactor with blade	
		Value of the force transferred, kN	Average (maximum) value of transferred force		Size of damage	
			obtained, kN	required, kN	obtained, mm	required, mm
SHIN	1	2.50 2.70 2.90 3.00 2.80	**2.78 (3.00)**	less than **8.0 (12.0)**	0.00 0.00 0.00 0.00 0.00	less than **0.5**
	2	2.10 3.20 3.00 2.90 3.50	**2.94 (3.50)**		0.00 0.00 0.00 0.00 0.00	
	3	3.00 2.90 2.90 2.40 2.50	**2.74 (3.00)**		0.00 0.00 0.00 0.00 0.00	
	4	2.60 2.60 2.40 2.40 2.10	**2.42 (2.60)**		0.00 0.00 0.00 0.00 0.00	
KNEE	1	4.50 4.30	**4.40 (4.50)**	less than **10.0 (15.0)**	0.00 0.00	less than **0.5**
	2	3.00 3.50	**3.25 (3.50)**		0.00 0.00	
	3	2.70 2.60	**2.65 (2.70)**		0.00 0.00	
	4	2.90 3.40	**3.15 (3.40)**		0.00 0.00	

Impact strength test and discussion of results obtained

Tests of the impact strength of anti-blow lower limb protectors for a policeman, acc. to the requirements of the HOSDB document, were carried out at the laboratory of the British company INSPEC International Ltd in Salford, as recommended by the authors of the HOSDB. The elements tested were parts of the finished product protecting the shin and knee. It was carried out with the use of bar and wedge impactors. The results obtained are presented in ***Table 6*** [7].

Results of the impact strength tests of lower limb (shin) protectors carried out in accordance with HOSDB show that they meet the requirements set forth therein both in the bar impactor test and wedge impactor test. However, the elements of the protectors which guard the knee successfully passed the impact strength test only for the bar impactor.

Impact strength tests of the same type of lower limb protector acc. to a procedure based on standard BS 7971-4:2002 were carried out at the accredited Ballistic Test Laboratory of the "MORATEX" institute. They were conducted with the use of a bar impactor and blade impactor, at an impact energy of 15 J, corresponding to level 2 protection assumed, as agreed upon with the Police Headquarters. Their results are presented in ***Table 7*** [8].

The results obtained show that the lower limb protectors meet the requirements of BS 7971 for level 2 of protection, both in the shin and knee protecting parts.

Comparison of data presented in ***Tables 6*** and ***7*** shows that the requirements of the base documents, i.e. HOSDB and BS 7971 affect the final results of laboratory tests obtained for the same protectors. It showed that the elements used for testing: anvils, impactors, level of impact energy and their location as well as the interpretation itself of the value of force transferred to below the sample have an influence on the final appraisal of the product tested.

Conclusions

1. Despite the fact that they are both based on the same test running principle, the requirements described in those documents ('HOSDB Blunt Trauma Protector Standard for UK Police. Limb and Torso Protectors' and BS 7971 'Protective clothing and equipment for use in violent situations and in training') differ in the following ways:
   - the quantity and quality of equipment on the test stands (different types and shapes of anvils and impactors, described in detail in section 'Test stand equipment'),
   - test conditions: different selection of anvils and impactors with respect to the protected part of the body (***Figures 3 - 6***), different level of impacts and their topography (section 'Testing methodologies'),
   - final interpretation of the results obtained:
     - acc. to HOSDB partial, results are used to compute the upper value of the transferred force anticipated (section 'Guidelines for the interpretation of test results'). As shown by tests (***Table 6***), it depends, to a significant extent, on the uniformity of the level of partial results,
     - acc. to BS 7971 the mean value of the transferred force is calculated (thresholds of maximum values of the transferred force is also specified – ***Table 7***).
2. The HOSDB provisions do not specify any graduation of the protection level, unlike Standard BS 7971. For the protectors of limbs, each of the three levels of protection set out in BS 7971 is closely associated with the threat to the user - a policeman during interventions, and in preventive and training activities (***Table 5***).
3. The requirements defined in the document from HOSDB do not condition neither impact energy nor the threshold value of the force transferred to under the sample on the part of the body (knee or shin for a lower limb protectors) protected by the tested product (sample), which are specified in BS 7971.
4. Analysis of the results of tests of the anti-blow protectors of the lower limbs, carried out in accordance with the provisions of both the documents in question shows, that the fact of meeting the requirements of the BS 7971 standard by the anti-blow protectors is not unequivocal with meeting the requirements of the HOSDB document. This is due to the accumulation of differences related to the preparation of tests, performing them and interpretation of gathered results.

5. Comparison of the requirements specified in the analyzed documents, deepened with an analysis of the tests performed in accordance with them, allows authors of this article for stating a thesis, that the laboratory assessment of anti-blow protectors for lower limbs according to the BS 7971, thoroughly takes into account the various aspects of hazards during policeman work (***Table 5***) with the resulting potential injuries and it is better control "tool", than the HOSDB document. However, this requires precise definition of the end use of a protector by determining the required level of protection, starting with the stage of designing.

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