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Ergonomics Assessment of Composite Ballistic Inserts for Bullet- and Fragment-Proof Vests

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Personal protective equipment worn by uniformed services (e.g., the police and the military) must ensure protection against bodily injuries. However, a high degree of protection is always associated with significant discomfort. This article presents the results of an assessment of the ergonomics parameters of new special-purpose products, ballistic inserts with improved ballistic resistance, and an assessment of the impact of the burden related to their use on the psychomotor performance of the subjects. An obstacle course and subjective ergonomics assessment questionnaires were used in tests. Thermal discomfort was also assessed. Psychological testing included tests enabling an assessment of the subjects' cognitive and psychomotor performance, and a subjective assessment of mental load. The tests did not show any decrease in the comfort of use of the new inserts with improved ballistic resistance compared to the inserts currently used.

ballistic insert   bullet- and fragment-proof vest   practical performance test   psychology test   ergonomics assessment

1. INTRODUCTION

The bullet- and fragment-proof vests (BVs) used on a daily basis in internal security are intended chiefly to ensure protection from rounds fired from various handguns, e.g., revolvers, pistols, carbines and rifles. Originally, BVs did not contain rigid elements (ballistic inserts); these were first used only when materials of appropriate strength, i.e., steel, titanium and ceramics, were developed. A standard insert comprises several dozen aramid fibre layers bound to one another. The fibres used in the external layer and on the wearer's side often have different properties, e.g., the fibres used in the external layers have higher tearing strength, while those in the inner layers are more elastic, which gives them greater ability to absorb kinetic energy. In recent years, much research has been conducted on designing composite ballistic inserts for BVs [1, 2, 3, 4, 5]. In particular, research has focused on using composite fibres to improve the ballistic strength of the inserts [3].

As all BVs are heavy and uncomfortable, their users' agility during combat actions suffers, which may lead to a decrease in their safety. The effectiveness of protection is reduced despite the use of very durable materials in BVs and inserts [6]. Therefore, when designing and testing new ballistic products, it is necessary to assess their impact on the processes related to their use; in particular, the physiological and psychological aspects [7, 8]. Wickwire, Bishop, Green, et al. studied the effect of wearing fitted synthetic-fibre

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underwear (80% cationic polyester, 20% elasthane), which ensured evacuation of moisture from the skin, and cotton underwear (100% cotton) under BVs [4]. Pre- and post-blood and urine samples were collected to determine the percentage change in plasma volume (%ΔPV) and urine-specific gravity. Skin temperature and heart rate were measured, too. The subjects simulated work for 2 h; there was no significant influence of the type of underwear worn on the recorded values of physiological parameters. However, the results of the questionnaire designed to record the subjects' subjective feelings indicated that they found synthetic-fibre underwear more comfortable than loosely fitted cotton underwear. To assess the new designs of BVs with moisture-absorbing, quick-drying fabric, skin temperature and heart rate variability were measured. In particular, heart rate variability was analysed with the activity of sympathetic nerves (ASN) and the activity of parasympathetic nerves (APSN) [5]. The results of the tests indicated that precise assessment of physiological comfort required an ASN assessment in static mode and an APSN analysis in an exercise situation. An assessment in dynamic conditions enabled a better assessment of comfort than an assessment in static conditions. Fowler presented results on ballistic vests equipped with two types of inserts [9]. The assessment focused on fit, mobility and thermal acceptability. The tests involved questionnaires the subjects completed. The results led to the conclusion that there were no significant differences in mobility, comfort of use or thermal acceptability; nonetheless, the subjects found one of the tested inserts to be more acceptable to wear. This confirms the need for comprehensive ergonomics assessments, with objective and subjective methods. Because of the stress related to using protective equipment, user acceptance is the decisive factor determining acceptance or rejection of the protection.

The objective of this study was to assess whether ballistic inserts made of composite materials with improved ballistic strength influenced their users' assessment of their parameters, the ability to perform work, thermal comfort, efficiency and sense of satisfaction.

2. METHODS

2.1. Materials

The products tested were BVs currently used in internal security, with side, front and back pockets for ballistic inserts. The ergonomics tests involved front ballistic inserts only. All the inserts had the same 250 × 300-mm profiled shape. Standard inserts, labelled STANDARD, were the reference sample for the new inserts, labelled WKP 112 and WKP 14 (made by the Institute of Security Technologies MORATEX[1], Łódź, Poland). Table 1 shows the characteristics of the tested inserts.

TABLE 1. Characteristics of Ballistic Inserts

Code	Material	Weight (kg)	Ballistic Resistance Class [10]
WKP 112	ceramic-composite with hexagonal plates	2.10	K3A K3B
WKP 14	ceramic-composite with a monolithic plate	3.18	K3A K3C K5A
STANDARD	composite	2.40	—[a]

Notes. WKP 112, WKP 14 = inserts made by the Institute of Security Technologies MORATEX in Łódź, Poland; STANDARD = reference insert; K3A = resistance to a PS 7.62 × 39 mm round weighing 7.9 ± 0.1 g, at impact speed 720 ± 15 m/s; K3B = resistance to an SS109 5.56 × 45 mm round weighing 4.0 ± 0.1 g, at impact speed 950 ± 15 m/s; K3C = resistance to an FMJS 7.62 × 51 mm round weighing 9.6 ± 0.1 g, at impact speed 840 ± 15 m/s; K5A = resistance to an AP 7.62 × 51 mm round weighing 9.7 ± 0.1 g, at impact speed 820 ± 15 m/s; PS, FMJS, AP = types of ammunition. a = secret or sensitive data on products used by the military services.

[1] http://www.moratex.eu/en/

2.2. Subjects

The ergonomics assessments were conducted on a group of 10 men employed in a military formation supervised by Poland's Ministry of the Interior. The basic criterion of selecting the subjects was their use of BVs. The subjects' mean (*SD*) age, height and weight were 32.07 (2.1) years, 183.0 (6.8) cm and 85.5 (9.8) kg, respectively. All subjects had an up-to-date medical certificate required for military service. They wore cotton underwear, their own uniforms and BVs with ballistic inserts, which were replaced in the course of the tests. Each subject went through the entire sequence of tests (for the three ballistic inserts) in one day. The order of testing was randomized for each subject; they did not know which insert they were testing. The Committee for Ethics in Scientific Research at the Central Institute for Labour Protection – National Research Institute (CIOP-PIB) approved the tests.

2.3. Measures

2.3.1. Thermal comfort

A subjective assessment of thermal comfort was made; it covered the sense of warmth, and moisture in clothing and on the skin due to perspiration [11, 12]. The sense of warmth was assessed on a 7-point scale from –3 (*cold*) to +3 (*hot*). In the moderate climate in which the laboratory practical performance tests of the ballistic products took place, 0 (*neutral*) was considered comfortable. Moisture in clothing was assessed on a 4-point scale from 1 (*dry*) to 4 (*wet*), 1 (*dry*) was comfortable. Moisture on the skin was assessed on a scale from 1 (*skin dryer than normal*) to 8 (*sweat dripping in many spots*, a negative grade), 2 (*normally dry skin*) was considered comfortable.

2.3.2. Subjective ergonomics assessment

Practical performance tests were conducted in the laboratory, in normal conditions, i.e., at a temperature of 20 ± 2 °C and relative humidity of 65% ± 5%. Each subject performed the following test sequence:

- putting on and adjusting a BV with a ballistic insert (~10 min);
- solving psychological tests (3 min per test);
- doing a set of physical exercises in the BV on an obstacle course (30 min);
- solving psychological tests (3 min per test);
- taking off the BV (~5 min);
- filling out a questionnaire to assess comfort of use and thermal comfort (20 min).

The subjects rested for 60 min without a BV between the tests.

The physical exercises involved the following [13, 14]:

- walking in an upright position, 100 m at 6 km/h;
- walking in a bent down position, 1.3–140.0 m;
- walking on a horizontal plane in a straight position, 125 m;
- walking in an upright position, at 3 km/h;
- jogging or running on a treadmill, 133 m at 8 km/h;
- jogging or running on a treadmill on a 20% slope, 80 m at 2.4 km/h;
- walking on a level treadmill, 267 m at 4 km/h;
- crawling in a 70-cm-high tunnel, 70 m;
- climbing up and down a ladder, 20 m;
- filling a bin with rubber pieces, 20 times;
- carrying over a distance of 10 m and stacking 20 sand bags, each weighing 12 kg;
- simulating getting into and out of a car, at least 5 times;
- aiming a weapon in a standing, kneeling and prone position, at least 5 times;
- turning sideways in a prone position, at least 5 times in each direction;
- sitting down on and getting up from the floor (e.g., in a vehicle or a transport helicopter), at least 5 times.

All subjects performed the same exercises. The inserts were assessed on the basis of the users' opinions expressed in a questionnaire [15, 16], and of the opinion of the person administering the tests, who assessed the performance of the exercises.

2.3.3. Psychological performance

Tests of practical performance and psychological performance of users of BVs with ballistic inserts took place at the same time. The following three tests were used to assess cognitive and psychomotor performance necessary in difficult and dangerous jobs [17] and to assess mental load.

Grandjean's scale: subjective method for assessing mental load

Grandjean's scale is a subjective method for diagnosing mental load [18, 19, 20]. It consists of 14 subscales in the form of 100-mm strips with terms describing opposite feelings at their ends, pertaining to one's mood, e.g., *relaxed–tense* (6 subscales), or fatigue, e.g., *energetic–lazy* (8 subscales). The subjects were required to mark on each subscale the point which best described their feelings at the time of the assessment. The time for filling out Grandjean's scale is not limited; it usually takes ~2 min.

Tests of attention and perceptiveness (TUS): objective method for assessing attention and perceptiveness

TUS involve crossing out two signs, as per instructions, out of a row of graphically similar signs in the same category, e.g., letters or digits [21]. Three minutes were allowed for the test, which had two equivalent versions: 3/8 and 6/9 digital versions. The following indicators were considered:

- speed of work: indicator of the speed of mental work;
- number of overlooked signs: indicator of the correct performance of a task;
- number of errors: indicator of the correct performance of a task.

The psychometric characteristic of TUS is satisfactory.

Complex reaction time (CRT): objective method for assessing reflexes

The CRT test assesses the speed and stability of responses to acoustic and visual signals during a complex task. The subjects respond to four signals in accordance with a strictly defined key:

- red light: right foot (push the right pedal of the test device);
- green light: left foot (push the left pedal of the test device);
- yellow light: no response;
- acoustic signal: right hand (push the button held in the right hand).

The test lasted ~3 min. It was performed with a MCZR/ATB response time meter (ATB INFO-ELEKTRO, Poland). The following test parameters were used as reflex indicators:

- mean response time (milliseconds);
- interval, i.e., the difference between the shortest and the longest response time (milliseconds);
- number of errors.

The psychological tests were conducted in two sessions: BEFORE and AFTER each experiment. Each session lasted ~10 min. The order of the tests was the same: Grandjean's scale, TUS and CRT.

2.3.4. Statistics

The data collected in the study were analysed with the following methods:

- Shapiro–Wilk test to assess the normality of distribution of the variables;
- Wilcoxon test to assess the differences between each set of pairs of the variables (BEFORE and AFTER);
- Levene's test to check the homogeneity of variance;
- analysis of variance (ANOVA) to compare the means of changes in variables (BEFORE–AFTER) in the three types of inserts.

The overall analysis was performed with Statistica 9.1.

3. RESULTS AND DISCUSSION

3.1. Thermal Comfort

Table 2 shows the results of the tests of BVs. The results indicate that BVs with all types of inserts generated additional heat in the subjects, which is normal. When responding to the question on

TABLE 2. Subjective Opinions on Warmth and Moisture in Relation to Bullet- and Fragment-Proof Vests

	Responses (n = 10)		
Characteristic	**WKP 112**	**WKP 14**	**STANDARD**
Sense of warmth			
0 = *neutral*	0	0	1
+1 = *quite warm*	7	5	5
+2 = *warm*	3	5	4
+3 = *hot*	0	0	0
Moisture in clothing			
1 = *dry*	1	0	0
2 = *a little damp*	2	3	6
3 = *damp*	6	5	2
4 = *wet*	1	2	0
Moisture on skin			
1 = *some body parts are moist*	4	3	5
2 = *larger body parts are moist*	2	1	1
3 = *some body parts are wet*	3	2	2
4 = *most body parts are wet*	0	1	0
5 = *sweat dripping in some spots*	1	3	1
6 = *sweat dripping in many spots*	0	0	1

Notes. WKP 112, WKP 14 = inserts made by the Institute of Security Technologies MORATEX in Łódź, Poland, STANDARD = reference insert.

"a sense of warmth" (scale: 0 to +3), most subjects selected +1 or +2. Nobody selected +3 (*hot*).

The weight of BVs with ballistic inserts caused significant effort during tests of practical performance: the subjects sweated profusely. The limited evaporation capacity resulted in increased thermal load and discomfort. The subjects' opinions on moisture in clothing and on the skin during the tests reflected this: most selected 2 (*a little damp*) or 3 (*damp*) on a 1–4 scale. Only 2 subjects assessing STANDARD and WKP 14 inserts and only 1 subject assessing WKP 112 (the lightest insert) selected 4 (*wet*).

When assessing moisture of the skin on a 1–6 scale, most subjects selected 1 (*some body parts are moist*): 4 subjects assessing WKP 112, 3 subjects assessing WKP 14 and 5 subjects assessing the STANDARD insert. Nobody selected 6 (*sweat dripping in many spots*).

3.2. Subjective Ergonomics Assessment

Figure 1 shows the percentage of negative responses to the following questions on inserts:

1. Does the BV, due to its weight, cause musculoskeletal discomfort (e.g., sore muscles, back of the neck or spine)?
2. Is other equipment (personal protection equipment) used with the BV?
3. Is the design of the BV compatible with other equipment, e.g., the helmet, or is that equipment put aside when the BV is used?
4. Does the use of the BV cause thermal discomfort?
5. Does the use of the BV restrict the movements of the head, neck, shoulders or legs?
6. Does the design of the BV (its nonadjustable parts) cause compression and obstruct the flow of blood?
7. Does the design of the BV (after it is adjusted and fitted) make breathing difficult?
8. Does the BV restrict kneeling (on one knee)?
9. Does the BV restrict sitting (on the floor)?
10. Does the BV restrict getting into and out of a car?
11. Does the BV restrict crawling face down and on the back?

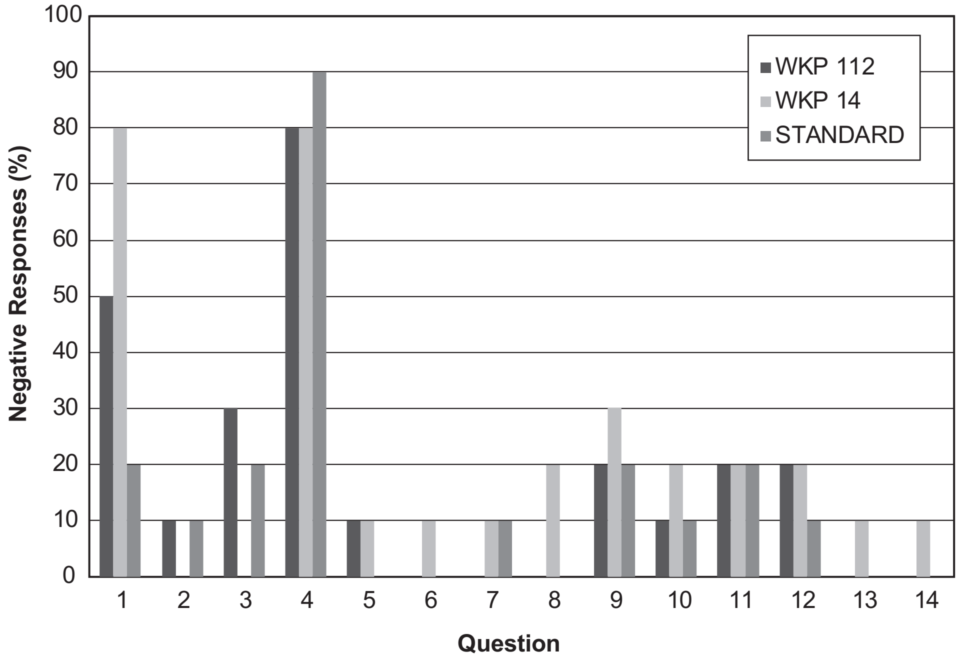

Figure 1. Negative responses in a questionnaire on 3 ballistic inserts. *Notes.* WKP 112, WKP 14 = inserts made by the Institute of Security Technologies MORATEX in Łódź, Poland, STANDARD = reference insert. For questions, see section 3.2.

12. Does the BV restrict turning sideways in a prone position?
13. Does the BV restrict assuming a shooting position and using weapons?
14. Does the design of the clothing enable covering with protective material the area of the body that should be protected, after a proper size of the BV has been selected?

The data collected in the questionnaire led to detailed conclusions on the subjects' observations on the use and functionality of the inserts. The following problems were the most frequent ones: thermal discomfort caused by the BV (question 4), musculoskeletal discomfort caused by excessive weight of the BV (question 1) and restrictions related to sitting (question 9).

The responses to the questionnaire resulted in the following conclusions on ballistic inserts. The shape (profile) of the inserts did not cause discomfort due to compression; this shape fit the users' body. The rigidity of the inserts was adequate as it did not reduce much performance of physical exercises (there were few negative responses). The difference in the weight of the new ballistic inserts (WKP 112 and WKP 14) affected the subjective perception of musculoskeletal load. However, a comparison with STANDARD inserts did not confirm this finding. The difference in the weight of the inserts did not affect, e.g., getting into and out of a car, crawling or assuming a shooting position. On the other hand, the difference in the weight of the inserts affected the users' thermal comfort to a small degree only during the practical performance tests in the laboratory. Nevertheless, it must be emphasized that WKP 112, which was rated the best with regards to subjective thermal comfort, was the lightest insert. This may indicate a direction for further work aimed at enhancing the comfort of use of this type of ballistic protection device. Those conclusions are consistent with those of Barker, Black and Cloud [22].

There were individual cases of negative observations in relation to difficulties in breathing (2% for WKP 14 and STANDARD); restrictions related to getting into and out of a car (1% for WKP 112); turning sideways in a prone position (1% for STANDARD); restricted movements of the head, the neck and the shoulders (2% for WKP 112 and WKP 14); compression and obstructed blood flow (1% for WKP 14); and restrictions in assuming shooting positions and handling weapons (1% for WKP 14).

3.3. Psychological Performance

3.3.1. Grandjean's scale: mental load

The results of the tests performed on the three ballistic inserts indicate that self-assessed mental load regarding the mood and the fatigue of the subjects testing different kits, conducted BEFORE and AFTER the tests with respective kits, were similar. The subjects felt strong, interested in the situation, awake; they were also in a good mood and calm.

An analysis of the significance of the differences between the results on Grandjean's scale obtained BEFORE and AFTER, performed with the Wilcoxon test, indicated one statistically significant difference ($p \leq .05$) in the test of WKP 112, on the *refreshed–tired* subscale (Table 3; $Z = .192$, $p = .028$).

This result demonstrates a shift in the feelings of the subjects in the direction of greater fatigue AFTER, compared to the feelings BEFORE the exercise for insert WKP 112. On the other hand, an analysis of significance regarding the mean values of changes on Grandjean's scale between the tests of the three ballistic inserts (ANOVA) did not indicate any statistically significant differences ($p > .05$). This demonstrates that the small changes in the mental load of the subjects testing the three inserts were similar.

3.3.2. Reflexes: results of CRT

In the case of CRT and the basic indicator of the test, i.e., reaction time, participation in the tests of each ballistic insert led to improved reflexes, i.e., reduced mean reaction time AFTER compared with BEFORE (Table 4). However, a statistically significant improvement in reflexes was recorded only in the test of WKP 112 (Wilcoxon test: $Z = 2.251$, $p = .024$).

Similarly, for interval, another reflex indicator, the results AFTER were better than BEFORE, i.e., the interval was shorter. However, those changes were not significant (Wilcoxon test, $p > .05$).

For the number of errors indicator, the number AFTER the tests on WKP112 and WKP 14 was lower than BEFORE. However, the changes were not significant. The use of STANDARD inserts did not result in any changes in the number of errors in the reflex test.

TABLE 3. Significance of Differences (BEFORE–AFTER) Between Mean Results on Grandjean's Scale in Tests of WKP 112

Subscale	Mean Difference BEFORE–AFTER (mm)	*Z*	*p*
positive mood–negative mood	1.7	0.845	.398
strong–weak	2.1	0	1
relaxed–tense	–4.9	1.784	.074
happy–depressed	4.0	0.840	.401
refreshed–tired	–6.0	2.191	.028*
interested–bored	1.6	0.204	.838
energetic–lazy	1.1	0.415	.678
vigorous–exhausted	5.6	1.540	.123
exhilarated–angry	0.5	0.415	.678
awake–sleepy	4.2	1.937	.053
stimulated–sedated	3.0	0.829	.407
efficient–inefficient	2.3	1.303	.193
attentive–distracted	2.4	1.244	.214
able to concentrate–unable to concentrate	1.0	0.840	.401

Notes. $*p \leq .05$; BEFORE, AFTER = psychological tests before and after the experiment, respectively; Z = value of the Z statistic in the Wilcoxon test; WKP 112 = insert made by the Institute of Security Technologies MORATEX in Łódź, Poland.

The mean values of changes in all three indicators of the reflex test in the tests involving the different inserts were not significantly different from one another (ANOVA). This indicates that as far as reflexes are concerned, the results of using the ballistic inserts were similar.

3.3.3. TUS

The results of the analysis of changes in TUS observed in the testing of the three different ballistic inserts demonstrated that for the speed of work indicator, the mean number of signs seen in 3 min increased slightly AFTER the experiments with WKP112 and STANDARD inserts compared to BEFORE. On the other hand, the mean number of signs the subjects saw decreased in the test of WKP 14. However, according to the Wilcoxon test, the changes were not significant ($p > .05$).

The mean number of errors, another indicator of TUS, was greater AFTER than BEFORE in the experiment with WKP 112, smaller in the experiment with WKP 14 and unchanged in the experiment with the STANDARD insert. However, according to the Wilcoxon test, the changes were not significant ($p > .05$).

For the number of overlooked items indicator, the results of the tests with WKP 112 and STANDARD were worse AFTER than BEFORE; the number of overlooked items increased (Table 5). The change for STANDARD was statistically significant (Wilcoxon test: $Z = 2.521$, $p = .012$). The results of the test with WKP 14 were better AFTER than BEFORE; fewer items were overlooked. However, the change was not statistically significant ($p > .05$).

ANOVA showed that the mean values of the changes that took place for all indicators of TUS during the tests with each ballistic insert were not significantly different. This demonstrates that according to TUS, the effects of using different inserts were similar.

4. CONCLUSIONS

The innovative feature of the ergonomics assessment this paper presented consists in the ability to perform a comprehensive assessment of special-purpose products in controlled conditions that resemble real life. The results demonstrated that there were no clear indications that changing the

TABLE 4. Basic Statistics for the Mean Reaction Time Indicator During the Complex Response Time (CRT) Test for 3 Ballistic Inserts (*N* = 10)

	Reaction Time					
	BEFORE			AFTER		
Statistic (ms)	WKP 112	WKP 14	STANDARD	WKP 112	WKP 14	STANDARD
M	51.8	51.4	50.9	48.1	48.6	49.2
SD	6.14	7.04	6.92	3.98	4.12	5.27
Range	41–64	42–64	42–65	41–53	41–55	40–57

Notes. BEFORE, AFTER = psychological tests before and after the experiment, respectively; WKP 112, WKP 14 = inserts made by the Institute of Security Technologies MORATEX in Łódź, Poland, STANDARD = reference insert.

TABLE 5. Basic Statistics for the Overlooked Items Indicator in Tests of Attention and Perceptiveness (TUS) [21] for 3 Ballistic Inserts (*N* = 10)

	Overlooked Items					
	BEFORE			AFTER		
Statistic	WKP 112	WKP 14	STANDARD	WKP 112	WKP 14	STANDARD
M	4.7	6.3	4.2	6.5	5.6	7.7
SD	4.35	5.74	2.97	4.95	2.76	6.24
Range	1–15	0–20	0–9	1–18	2–10	1–23

Notes. BEFORE, AFTER = psychological tests before and after the experiment, respectively; WKP 112, WKP 14 = inserts made by the Institute of Security Technologies MORATEX in Łódź, Poland, STANDARD = reference insert.

weight of the ballistic inserts by ~1000 g had a significant impact on the comfort of use of STANDARD ballistic inserts. It is important to point out that the significant improvement in the ballistic characteristics of the newly-designed WKP 14 was not associated with any significant changes in subjective discomfort compared to STANDARD inserts. The same conclusion is true for the users' ability to perform basic professional actions, e.g., moving, crawling, assuming a prone firing position and getting into or out of a car.

The statistical analysis of the results of psychological tests showed little impact of the different ballistic inserts on the subjects' mental and psychomotor performance (mood, fatigue, reflexes, attention and perceptiveness). So, the new ceramic-composite inserts, which have significantly greater ballistic resistance, will not increase the users' psychophysical load.

Thermal discomfort is the principal problem in using ballistic protection devices. The differences in the weight of the ballistic inserts have minimal impact on the subjective feeling of thermal discomfort, with a tendency for lighter inserts to result in higher subjective thermal comfort. The subjects considered the new-designed ceramic-composite insert WKP 112 to be the best inserts they tested.

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