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Bulletproof Vest Thermal Insulation Properties vs. User Thermal Comfort

Abstract
Ballistic protection equipment, such as a bulletproof vest or helmet, is a soldier's most important means of preserving life and health. The bulletproof vests discussed in this paper are designed to protect the user's chest from injury without disturbing the ability to perform his duties. One of the ergonomic aspects of personal protection equipment is the thermal stress caused by the use of specific equipment. In the case of ballistic vests this aspect can be assessed by testing the vest's thermal insulation properties, which is to say, by determining to what extent the vest impedes the transmission of heat from the human body to its surroundings. The purpose of the study discussed in this article is an assessment of the thermal insulation properties of bulletproof vests and a determination of the user's thermal sensation. Tests of thermal insulation properties were performed using bulletproof vests used by the uniformed services.

Key words: *thermal manikin, thermal insulation, bulletproof vest, uniform.*

Introduction

Ballistic protection equipment, such as a bulletproof vest or helmet, is a soldier's most important means of preserving life and health. So far, bulletproof vests have mainly been used by law enforcement agencies, but they are now more commonly available to other users (e.g. security workers or the public).

Peleg's work contains a discussion of injuries caused by terrorist activity in Israel [1]. Two groups of injury victims are compared: soldiers wearing vests and defenceless civilians. The research conducted by Peleg showed that there were many fatalities (37 people) among civilians, while in the military group only 5 soldiers were killed. Ballistic vests are designed to protect the human chest, which was also confirmed by the analysis made by Peleg. Chest injuries after terrorist attacks accounted for 23% of the total number of patient cases. Among the civilians 27% had chest injuries, while in the military group only 15% of soldiers suffered from the same [1]. Peleg's work also indicated that a higher Injury Severity Score (ISS)[1)] (ISS > 25) was recorded among the civilians (41% vs. 23%). The conclusions of Peleg's paper are that civilians should also be given a chance to protect their life and health by using ballistic vests. Civilians travelling to dangerous areas are especially exposed to the risk of injury [1].

Specific items of clothing, such as ballistic vests, should not only perform protective functions, but also should not influence the users' bodies negatively [2]. The level of discomfort caused by bulletproof vests results from both decreased energy loss from the human body and heat transfer disturbances (inter alia by the secretion of sweat) due to the weight and size of the vest, and the ambient temperature and level of physical effort required by the officer [3, 4]. The problem of the reduction in the thermal load with the use of special underwear for vests has also been addressed by Wickwire [2]. In addition, research conducted by Lee, Tai, and Chen [5] indicates that a vest not only needs to be functional, but should also provide a sense of comfort. This comfort is assessed through the feelings of users, taking into account both physical and mental sensations [5]. The vests currently used are heavy and uncomfortable, which decreases users' mobility, which affects not only on the effectiveness of the work performed, but it also impedes proper reactions to dangerous situations [1].

Research carried out in Poland and other countries is aimed towards improving the vest user's comfort by either reducing the weight of the vest and improving its sweat transfer properties by the use of special underwear [2], or with the use of so-called quick-dry materials on the vest's internal lining [5]. Using a waterproof-breathable inner lining can substantially enhance comfort in the static mode and slightly enhance it in the exercise mode. Waterproof-breathable fabric can help disperse heat generated during exercise and improve the comfort of the bulletproof vest [5].

Literature provides data regarding tests with volunteers in which various physiological parameters were analysed [6, 7]. However, there is little information on the thermal insulation properties of the uniforms or bulletproof vests [4]. Describing the comfort of clothing is very difficult indeed because the user's physiology and psychology as well as the external surroundings may differ.

Many factors influence the maintaining of thermal balance. These can be divided into environmental factors: air temperature, radiation mean temperature, water vapour partial pressure and air flow speed; and into individual factors such as

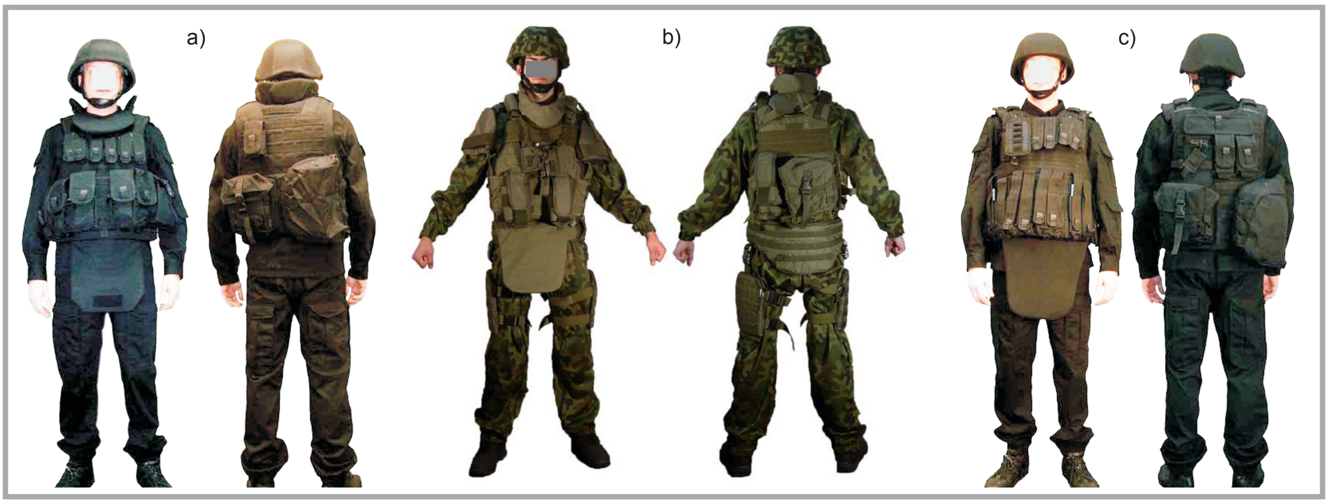

Figure 1. Bulletproof vest: a) type A, b) type B, c) type C.

the energy output related to the intensity of the work performed (otherwise called the metabolic rate), and the transfer of heat through clothes, also called clothing thermal insulation.

To determine the work environment the Predicted Mean Vote (PMV) index was assessed in [8]. The index takes into consideration all the aforementioned elements and makes it possible to determine the thermal feeling of a human by one value only.

The PMV index with a range of –1 to +1 reflects the Extended Comfort Zone. For a PMV above +2 and below –2, the thermal environment is determined as a hot or cold, which could cause thermal stress in the user. The thermal comfort sensation results from maintaining a thermal balance between the human and its environment, i.e. between endogenous heat (produced within the body as a result of cell processes) and exogenous heat (obtained from the outside, e.g. by consuming food) [8 - 10].

Objective of the study

The study aimed to determine the thermal insulation of bullet- and fragment-proof vests which are used by law enforcement agencies supervised by the Polish Ministry of the Interior and Administration. In practice, there are two types of ballistic inserts used in vests (soft and hard ones). Hence the studies aimed to check whether this element had a major influence on the thermal insulation of the whole vest. Furthermore on the basis of the thermal insulation of vests tested, compared with that of the whole uniform, the vest user's sensation was determined, i.e. the PMV index was defined, used to assess the thermal sensation of a human. An analysis of the PMV index was made for different activity levels (metabolic rates). On the basis of the data obtained it was possible to infer how the use of vests influenced users' sensations and within what range of environment parameters the vests should be used.

The ballistic vests were designed within the framework of key project No. POIG.01.03.01-10-005/08 'Modern ballistic body armours and covers for transportation means as well as for buildings made on the basis of textile composites'.

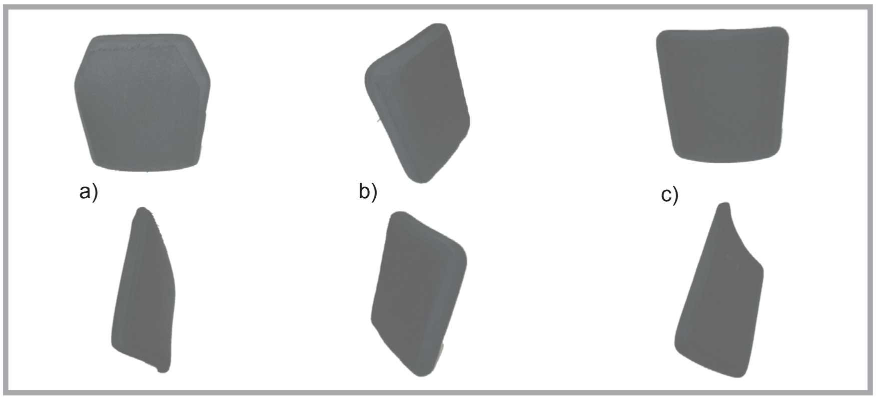

Figure 2. Additional, hard, composite ballistic inserts - a) front, b) side and c) back.

Material and methods

Materials

The design of ballistic vest type A (***Figure 1.a***) was developed by the Institute of Security Technology "Moratex" [11]. The vest consists of several basic parts: front, back, groin cover, collar attached with a hook and loop tape, as well as pockets and ammunition/equipment pouches attached with the molle system. Additionally, the front and back parts include pockets inside the external lining of the vest where additional, hard, composite ballistic inserts (front and back) can be placed. The soft ballistic inserts (made of UHMWPE sheets Dyneema® SB 21) fill the vest lining to the maximum.

Ballistic vests type B (***Figure 1.b***) and C (***Figure 1.c***) were developed by the Institute of Security Technology "Moratex" in collaboration with an external company (MIWO MILITARY). These are ballistic vests integrated with a quick-connect "QR" grip allowing the wearer to remove the vest quickly when necessary (e.g. a quick evacuation when shot, when in danger of drowning) [12]. The soft ballistic inserts fill the vest lining to the maximum. The vests allow four additional hard inserts to be mounted (front and back, and two on the sides). Ballistic vest type C is a basic version. According to the guidelines, ballistic vest type B is equipped with many additional elements. In addition to the external lining with a quick-connect system, to which pockets and ammunition pouches are attached, it also includes covers for the neck, shoulders, groin, and a hip belt with ammunition pouches, providing extra space for equipment.

All vests tested can be worn over a uniform, field jacket, or winter jacket.

The Institute of Security Technologies "MORATEX" developed ergonomic 3D-shaped composite ballistic inserts (***Figure 2***) for bullet- and fragment-proof vests that meet the requirements of the PN-V-87000:2011 standard. To generate additional hard ballistic inserts, pressurised technology with a fibre composite was applied (composite made of UHMWPE sheets of Dyneema® HB 50). The process resulted in an anatomically designed final composite inserts providing user comfort and compatibility with the bullet- and fragment-proof vest. The ballistic insert idea was submitted to the Polish Patent Office as a patent application entitled: „Additional set of ballistic inserts for bullet- and fragment-proof vests" [13].

Since the bulletproof vests (with soft ballistic inserts) weighed respectively, A – 7.0 kg (size L), B – 9.1 kg (size L) (with hip belt of 4.0 kg), and C – 7.2 kg (size L), tests were carried out on a manikin sitting on a chair because the standard manikin hanging method might cause damage to it. Before starting the tests, the thermal insulation value of the chair itself was determined, to be subtracted afterwards from the vest's thermal insulation value.

Examination of the thermal insulation of vests equipped with hard ballistic inserts revealed that their weight increased by 3.0 kg (for vests A and C) and 4.4 kg (for vest B), respectively.

The tests performed made it possible to determine the thermal insulation of a whole set of safety armour composed of uniforms of the respective agencies (which included jacket, trousers and shoes) and respective ballistic vests. During the tests, cotton underwear was put on under the uniform (***Figure 3***).

Methodology

Tests of thermal insulation properties were carried out using the following research equipment: a 16-segment thermal DIANA manikin (type TM 3.2/R110) [14], a climate chamber (type WK23'), and microclimate measuring instruments (Indoor Climate Analyser 1213 – by Bruel&Kjaer; measurement deviation: air temperature ±0.1 °C, air velocity ±0.05 m/s).

The thermal manikin named Diana is female. It should be noted at this juncture, however, that the anatomic structure of the manikin in the case of thermal insulation tests is of no significance. Studies by Kuklane [15] showed that there was no difference between the thermal insulation value obtained during tests on a thermal female manikin and a male one.

The tests were performed according to the ISO 15831:2004 standard [16]. In the case of this type of tests the measurement error was based on the precision of sensors measuring air temperature and velocity. The measurement error for a thermal manikin is not usually defined. It was assumed that each single test of thermal insulation consists of 2 experiments whose results (in accordance with the ISO 15831:2004 standard [16]) could not differ by more than 4%, which was also the manner in which the tests described in this article were carried out.

Thermal insulation is expressed in the SI m^2°C/W unit or in the clo unit (1 clo = 0.155 m^2°C/W). The total thermal insulation I_t was determined using 2 methods: "serial" – by a sum of insulation values for individual segments (*a*), and "parallel" – calculated as the insulation in relation to the entire manikin (*b*), according to the following formulas (***Equation 1***) [17 - 19]: where: t_{si} – manikin skin temperature at individual segments in °C, t_a – ambient temperature in °C, H_{ci} – amount of power consumed by the manikin at individual segments in W/m^2.

$$I_t = \sum_1^n f_i \left[\frac{(t_{si} - t_a) \times a_i}{H_{ci}} \right] \quad (a)$$
$$I_t = \frac{\left[\left(\sum f_i \times t_{si} \right) - t_a \right] \times A}{\sum H_{ci}} \quad (b) \qquad (1)$$

$f_i = \frac{a_i}{A}$ with a_i – surface of segment *i* in m^2 and A – total manikin surface in m^2.

Figure 3. *Underwear worn under uniforms.*

The project included, according to the standard above, determination of the effective thermal insulation I_{cle} of both the uniforms and bulletproof vests. This value is calculated based on the difference between the total insulation and the insulation limit of the layer around the naked manikin [18, 20].

Then, according to the ISO 15831:2004 standard [16], tests of the ballistic vests' thermal insulation were carried out with the vests equipped with soft and hard ballistic inserts.

The PMV indices were calculated in accordance with the ISO 7730:2005 [21] standard on the basis of the values obtained.

To demonstrate the dependence between hard and soft ballistic inserts, a statistical analysis of local insulation values was carried out. Non-parametric tests were applied, i.e. the signs test and Wilcoxon signed-rank test (at an assumed significance level of $p < 0.05$).

In order to verify the results obtained from the statistical analysis the percentage difference was calculated between test variants for par-

Table 1. *Effective thermal insulation levels for uniforms.*

Uniform for officers using vest:	Effective thermal insulation m^2°C/W		Effective thermal insulation clo	
	Icl serial	Icl parallel	Icl serial	Icl parallel
A	0.184	0.126	1.187	0.813
B	0.180	0.144	1.161	0.929
C	0.158	0.110	1.019	0.710

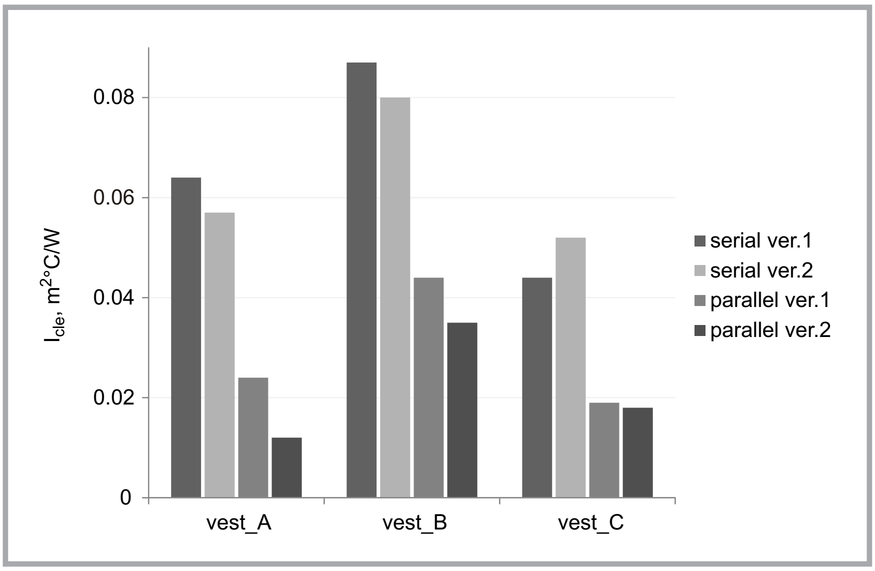

***Figure 4.** Effective thermal insulation for bulletproof vests with soft (ver. 1) and hard (ver. 2) ballistic inserts.*

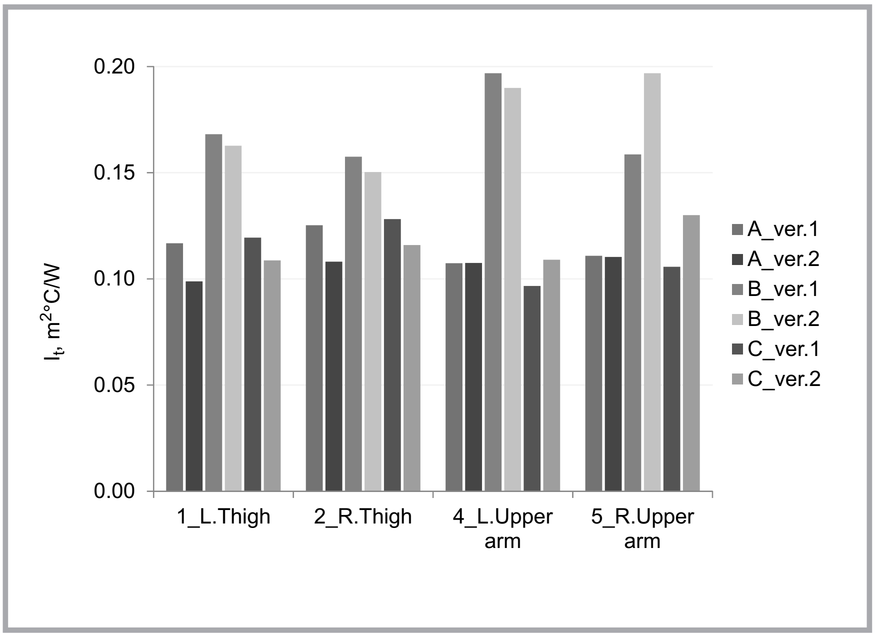

***Figure 5.** Local thermal insulation value of segments for thighs and upper arms for particular variants of ballistic vests.*

ticular segments taking into account the type of vest examined. As was mentioned before a difference above 4% was assumed as the significance criterion (resulting from entries in the ISO 15831:2004 standard [16], where the permissible error for the experiments carried out within the framework of a single test is exactly this value).

Results

Thermal insulation of uniforms

Within the framework of the project, effective thermal insulation values were determined for uniforms with user vests type A, B and C. The results of the tests are given in ***Table 1***.

According to the data obtained, it was found that user vest types A and B are similar in terms of their thermal insulation value. The lowest thermal insulation was found for the uniforms with user vest type C.

The uniforms' thermal insulation (1.02 – 1.19 clo) was similar to that of clothes used for protection from cold weather (underwear, T-shirt, shirt, trousers, jacket, socks, shoes and a highly insulated jacket – 1.18 clo) [22].

Thermal insulation of ballistic vests

Insulation properties of the three types of vests - A, B and C were measured using a thermal manikin - Diana. The tests were carried out on vests equipped with soft ballistic inserts (ver. 1) and with hard ones (ver. 2) (***Figure 4***). Analysis of the results showed that vest type B featured the highest thermal insulation level, and vest type C – the lowest level.

For vests A and B the use of hard ballistic inserts (ver. 2) resulted in the reduction of effective thermal insulation by 8 - 11%, for vest C, in turn, an 18% increase in this value was noted.

To get a broader picture of thermal insulation distribution in ballistic vests, an analysis of local thermal insulation values was made using selected segments of the thermal manikin. Given that the vest itself has no direct influence on all 16 segments, only selected segments were further analysed, i.e. 1 – left thigh, 2 – right thigh, 3 – pelvis, 4 – left upper arm, 5 – right upper arm, 6 – chest, 7 – back.

Data obtained from tests with ballistic vests with soft (ver. 1) and hard (ver. 2) inserts were subject to statistical analysis. On the basis of the results obtained it can be concluded that in all the instances (except for vest A for the upper arms segments) statistically significant differences were noted between the variants tested.

To verify the results obtained from the analyses, the percentage difference for test variants was calculated for a particular segment, taking into account the type of vest tested.

From an analysis of the thigh segments (1 - 2) (***Figure 5***), it can be inferred that in all the cases the addition of hard ballistic inserts (ver. 2) resulted in the reduction of thermal insulation within the range of 3 - 18%. The smallest differences were noted for vest B, and the highest for vest A. The direct influence on the thigh segments was caused by the crotch protection, whereas in the case of vest B it was by the additional lap belt with pockets strapped around the thighs. In theory, putting on additional inserts does not change the thickness of a vest at those segments, therefore there should not be a considerable difference in values. It should be remembered, however, that additional inserts made the vest stiffer, which had an effect on its adjustment to the surface of the manikin. In addition the thigh segments overlapped with the pelvis segment and were partly covered by the vest.

Arm protectors, present only in vest B, had a direct influence on the upper arm segments (4 - 5) (***Figure 5***). For vest A no significant differences were noted between the tests (this conclusion corresponds to data obtained in the statistical analysis). In the case of vest C the thermal insulation values increased at those segments (11 - 19%). Likewise the increase can be explained by the stiffening of the vest, which, as a consequence, most probably resulted in the creation of an additional insulating layer of air warmed up by the thermal manikin. In the case of vest B no significant differences were observed on the left arm (< 4%), whereas on the right there was an increase in local thermal insulation by 19%. Again this phenomenon could be caused by making the front and reverse side of the vest stiffer, resulting in a different position of the manikin's arms.

The use of hard ballistic inserts had a direct influence on segments such as the pelvis, chest and back (***Figure 6***). In the case of the pelvis segment a reduction in thermal insulation by 33-34% was noted for vests A and B, whereas for vest C an 8% increase in this value was observed. An analysis of the chest segment showed that only for vest A was there a reduction in thermal insulation noted (by 14%); in other cases this value increased (4% for vest B and 9% for vest C). The reduction in local thermal insulation can only be explained by the worse adjustment of a stiff vest to the manikin's body. With regard to the back segment only an increase in the thermal insulation values was noted, ranging from 14% (vest B) to 23 % (vest A).

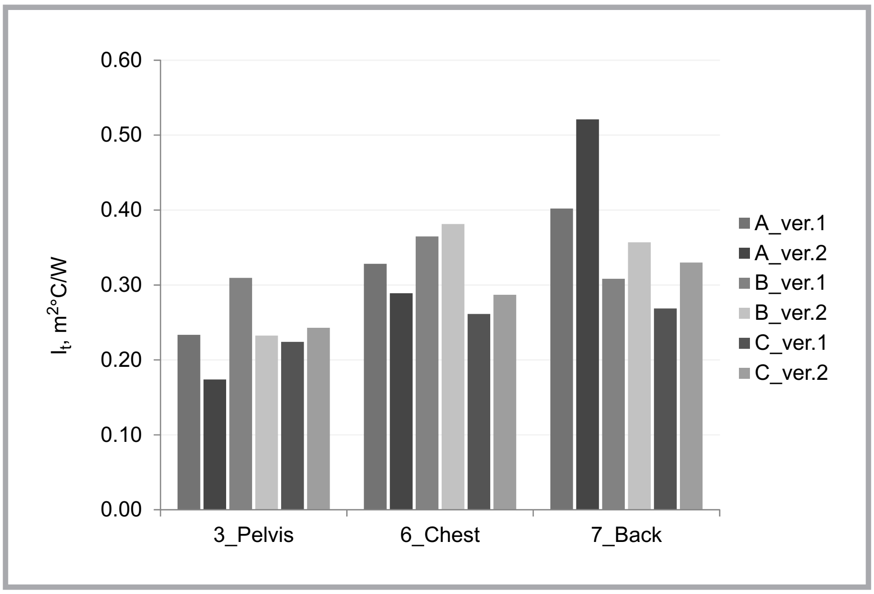

Figure 6. *Local thermal insulation value of segments for pelvis, chest and back for particular variants of ballistic vests.*

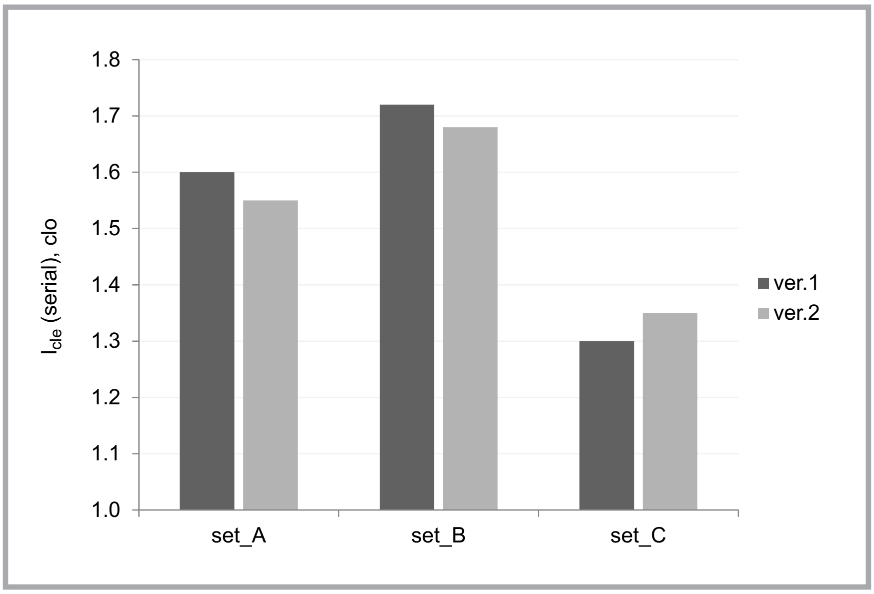

Figure 7. *Effective thermal insulation (serial method) of the entire set with soft (ver.1) and hard (ver.2) ballistic inserts.*

Uniform and ballistic vest

To give a better presentation of the problem of discomfort experienced by officers on duty, the above values of the effective thermal insulation of the uniform and bulletproof vest were added together (***Figure 7***).

Since the thermal insulation of ballistic vests used by the different agencies are similar, the highest influence on the thermal insulation of the entire set can be attributed to the uniform. Also in this case the thermal insulation values of sets A and B are similar and remain within the range of 1.51 – 1.56 clo. The lowest value was found for the set used by set C.

For the entire set (the uniform and ballistic vest), the thermal insulation value remained within the range of 1.3 – 1.7 clo. Furthermore for the vest's thermal insulation, with both soft and hard ballistic inserts, the percentage share was determined in relation to the whole set tested (composed of a vest and appropriate uniform). It can be concluded that vests with soft inserts constituted from 22% (vest C) to 33% (vest B) of the percentage share (***Figure 8.a***). Vests with hard inserts constituted 24 - 25% (for vests A and C, respectively) and 31% (vest B) (***Figure 8.b***). The increased percentage share of vest B in relation to the other ballistic vests was linked to the construction of ballistic armours composed of a vest and lap belt.

Analysis of thermal sensations using the predicted mean vote (PMV) factor

To determine the optimal work environment, the PMV factor was analysed for individual sets (uniform and vest) depending on the metabolic rate and ambient (environment) temperature. The assessments used mean values of metabolic rates for individual classes: 165 and 230 W/m^2. For the air parameters, the

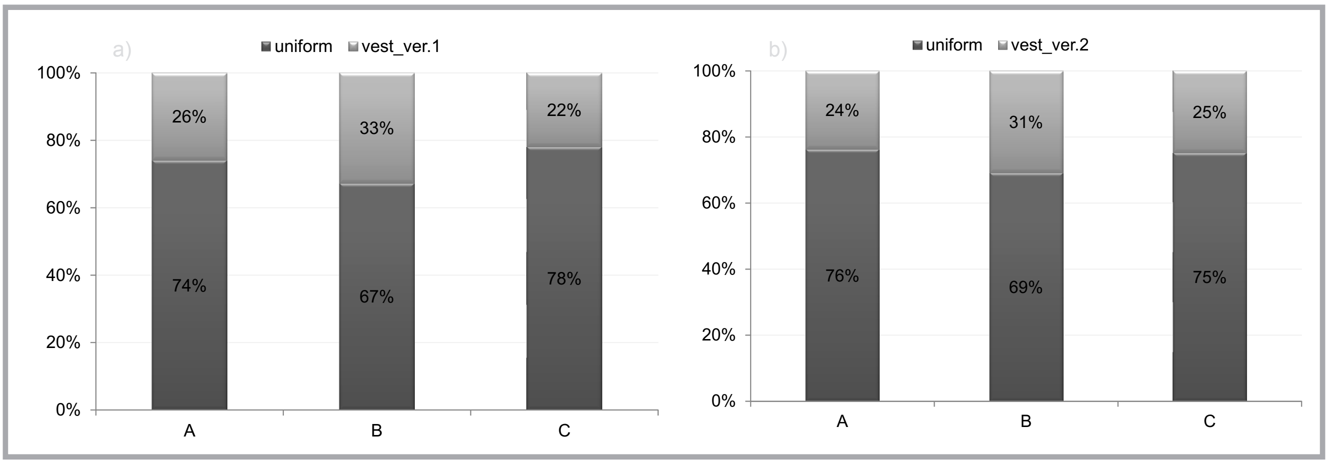

Figure 10. *Percentage share of vests with: a) soft and b) hard inserts and uniforms in thermal insulation value for the entire protection set.*

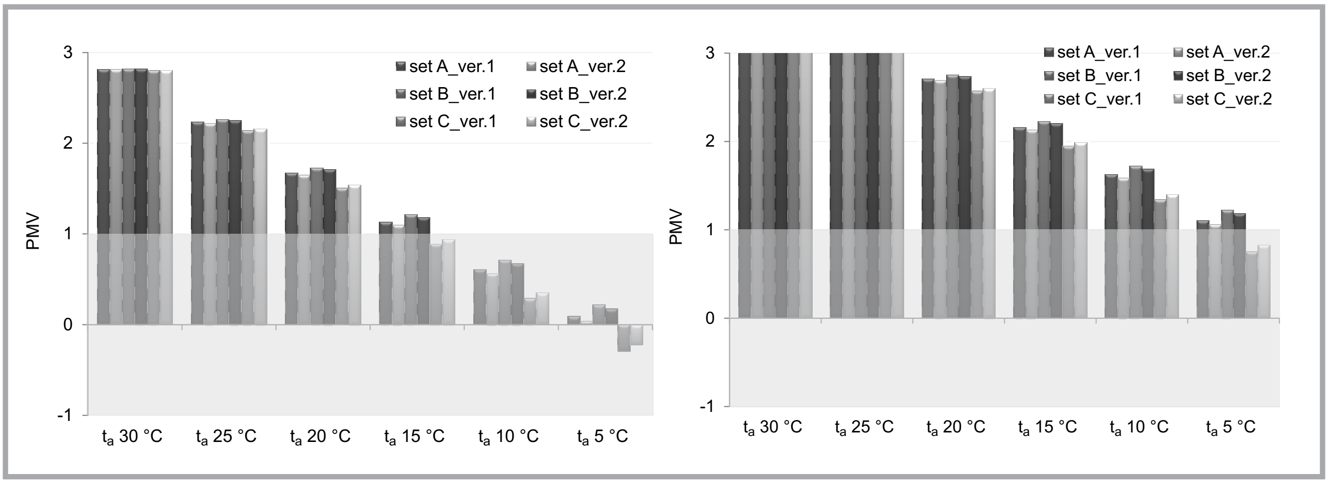

Figure 12. *PMV index for metabolic rate: a) 165 W/m*^{2} *and b) 230 W/m*^{2}.

following assumptions were made: the radiation temperature equals the air temperature, the airflow velocity 0.5 m/s, and the relative humidity 50%. The diagrams given below present the dependence of the PMV factor on temperature with regard to the thermal insulation values of the specific sets. The "comfort zones" are also indicated.

Metabolic rate 165 W/m^2

In the case of the medium intensity work (class 2 metabolic rate) and for ambient temperatures above 15 °C, all officers (excluding officers in set_C) are outside the limits of thermal comfort (***Figure 9.a***).

Metabolic rate 230 W/m^2

For the class 3 metabolic rate, thermal comfort experienced by officers using vests type A, B and C is possible at temperatures below 5 °C. Regarding officers using vest type C, thermal comfort can also be experienced at 5 °C (***Figure 9.b***).

Conclusion

On the basis of the tests conducted the following conclusions have been formulated:

1. Thermal insulation of a vest is determined by its construction and type of ballistic inserts used. The bigger the area of the body covered by the vest the bigger the insulation value. Moreover the use of hard inserts in vests, in the majority of cases, caused a reduction in thermal insulation, attributable to worse adjustment of the vest to the human body.
2. In all instances, differences between the thermal insulation of vests filled with soft and hard inserts were statistically significant, with the difference in thermal insulation of the vests being even 34%.
3. The thermal insulation of the summer uniform used by appropriate uniformed services was up to 1.19 clo, which corresponds to the thermal insulation of clothing used in winter conditions.
4. The thermal insulation of ballistic vests constituted up to 33% for soft inserts and up to 31% for hard inserts of the total thermal insulation of the set consisting of a uniform and vest. It can be concluded that this percentage is significant and the search for solutions to reduce the thermal load of users should also cover ballistic vests..
5. The sets composed of a uniform and bullet-proof vest examined should be used in ambient air which does not exceed 5 °C to avoid thermal stress on a human body.

Summary

The tests completed covered the thermal insulation of ballistic vests designed for the uniformed services within the framework of the POIG.01.03.01-10-005/08 project. References provide cases of bulletproof vest tests with volunteers; however, there is little information on the thermal insulation properties of uniforms or bulletproof vests alone.

The tests completed made it possible to determine the thermal insulation values of bulletproof vests and uniforms separately, and for both elements used together. The highest thermal insulation value of ca. 0.4 clo was observed for vest type B, which can be compared to the thermal insulation level of a work jacket or heat protective jacket [22].

For the whole set (uniform and ballistic vest), the highest value of 1.56 clo can be compared to the thermal insulation values of chemical protective clothing (undershirt, underpants, work coveralls, highly insulated coveralls, socks, and shoes – 1.42 clo) or clothing designed for work in cold environments (underwear, T-shirt, fitted trousers, highly insulated coveralls, calf-length socks, shoes – 1.50 clo) [22].

Analysis of the estimates obtained showed that for officers wearing the entire set during medium-intensity work, the comfort limits remain in an air temperature below 15 °C. It can be assumed that the work done by an officer on-duty wearing ballistic protection qualifies as a class 4 metabolic rate. In this case thermal comfort is expected in an air temperature below 5 °C. It should be noted, however, that the uniform elements were not designed for winter use. From the tests and analyses performed it can be concluded that users of this sort of clothing are exposed to thermal stress if the ambient temperature is above 5 °C. Therefore it is this necessary to explore further solutions for the reduction of thermal insulation in ballistic vests.

Application of hard inserts resulted in a poorer adjustment of the vest to the surface of the thermal manikin and, in consequence, a decrease in thermal insulation by even 34%. In light of the fact that future studies should aim at developing vests with the lowest thermal insulation, the use of hard inserts seems reasonable (in terms of the thermal sensation of users). However, in terms of the weight of the ballistic vest, the use of hard inserts resulted in an increase in the overall mass of the vest by even 4.4 kg. An optimal solution seems to be an additional frame construction as it would enable the free flow of air between the surface of the uniform and outer part of the ballistic vest.

Acknowledgment

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Editorial note

1) *ISS is an anatomical scoring system that provides an overall score for patients with multiple injuries.*

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