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Physiological tests on firefighters whilst using protective clothing

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In addition to the intense effort of firefighters during rescue operations and an adverse thermal environment, the properties of clothing can also hinder the performance of occupational activities. The heat load of firefighters during diversified effort in a climate chamber was compared for two types of protective clothing (barrack [B] clothing and barrack under special-purpose [S] clothing) at two levels of air temperature (20 and 30 °C). During testing, physiological parameters of heat strain were measured and subjective ratings were collected. There was a small increase in physiological parameters and subjective ratings at 20 °C in S clothing compared to the results in B clothing, whereas those differences were substantial at 30 °C. So, the structure of S clothing, which ensures protection of firefighters against high temperatures and flames, and its watertight layer make it significantly more difficult for the body to give off heat.

Keywords: firefighters; protective clothing; physical effort; thermal strain; thermal comfort

1. Introduction

During rescue operations, it is common for firefighters to carry out high-intensity work tasks, most often in a hot environment, which affects the accumulation of heat in the body.

The clothing used at present exerts high load on a firefighter during execution of their professional tasks. Tests of the thermal insulation of protective clothing for firefighters and estimation of the ratio of the thermal comfort felt have shown that a firefighter dressed in protective clothing is only able to feel thermal comfort when the air temperatures are low and the physical effort is minor [1]. Although, on one hand, thermal insulation is desired as clothing protects the firefighter from the external environment, it can, on the other, become a barrier hindering heat transfer between the firefighter's body and the environment. When that happens, sweat produced by the body cannot evaporate during physical effort. This results in an increased internal temperature, which may lead to increased skin blood flow, higher heat rate or increased activity of the sweat glands, and eventually causes thermal strain. To minimize thermal strain, it is important that underwear and the structure of protective clothing should be well chosen to allow dispersion of body heat, so that thermal strain can be reduced to the lowest possible level.

The problem of thermal strain and discomfort among firefighters is demonstrated, among other things, by survey results. Lee et al. [2], who surveyed 1694 firefighters from four countries (Australia, Japan, Korea and the USA), also found that there was a problem connected with 'overheating'. In a vote concerning additional solutions to be introduced into clothing, 'automatic body cooling' was the fifth most popular option among the voters. In Poland, surveys among 810 firefighters have also demonstrated the great need to reduce the heat load [3]. When asked about the components that clothing for firefighters should have, 48% of the respondents answered 'a cooling system'. This answer was second in the list of expectations with regard to new protective clothing solutions among firefighters.

Typical protective clothing ('outer' clothing; popular special-purpose garment [PSPG]) for firefighters has a multilayer structure and is composed of a non-flammable external fabric, a vapour-permeable membrane that provides waterproofing, a heat-insulating layer and a non-flammable lining. The materials should be so structured to provide non-flammability on both the external and internal sides [1,4].

In Poland, a typical protective garment (PSPG) must meet the requirements related to flame propagation, resistance to convection heat transfer, heat radiation and waterproofing, as well as tensile strength and tearing strength, and the requirements of tolerances for variations in dimensions and visibility due to changes in temperatures, as specified in Standard No. EN 469:2008 [5]. The requirements relating to the structure of clothing are also contained in other documents [6–8]. These requirements also pertain to the colour of the external fabric, length of jackets, structure of trousers or markings with an arrangement of warning tapes.

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According to the assumptions made, from a physiological point of view, underwear should be worn under the protective clothing (PSPG) that transfers sweat from the firefighter's skin, thereby increasing comfort of use. In contrast, surveys by Bartkowiak and Miśkiewicz [4] indicate that under the protective clothing (PSPG), firefighters wear 'barrack clothing'. When asked the question 'What do you now wear under your protective clothing (PSPG) during fire-rescue operations?', 88% of the respondents (among 683 firefighters) answered 'barrack clothing'. This clothing does not have any protective properties and is made from cotton fabric [7]. Most commonly, it is worn under protective clothing during fire-rescue operations, as underwear, whereas while waiting for a call to a fire-rescue operation it is used as outerwear by the firefighters [3]. Surveys among firefighters have demonstrated that 56% of them would like to use active thermal underwear and wear it under their protective clothing [4].

The aim of the study was to compare thermal loads on firefighters during physical exercise of various intensity, at two ambient temperature levels, with two sets of clothing with different structural properties. The analyses of thermal loads on firefighters using the special-purpose garment will be used to obtain better knowledge about the right choice of underwear and protective wear for work tasks under rescue operations, and they will provide criteria to create better specifications for a special-purpose garment for firefighters.

2. Materials and methods

2.1. Study subjects

The studies involved 10 firefighters selected through qualification tests, which included a medical interview and a physical endurance test. Table 1 presents the physical characteristics of the subjects participating in the thermal load tests. The study subjects gave written consent to participate in the study.

The studies were carried out with the consent of the Polish Committee of Ethics and Supervision over Research on Humans and Animals (Komisja Etyki i Nadzoru nad Badaniami na Ludziach i Zwierzętach) at the Polish Ministry of Internal Affairs and Administration (Ministerstwo Spraw Wewnętrznych i Administracji [MSWiA]).

2.2. Test conditions

The studies were carried out in the climatic walk-in test chamber under moderate (20.0 ± 0.1 °C) and hot (30.0 ± 0.1 °C) environmental conditions. In both cases, the air velocity was 0.5 m/s and the relative humidity was 30%.

2.3. Protective clothing

In the studies, two types of protective clothing were used: one air and water vapour-permeable type (barrack [B] clothing) and one barrier type (barrack under special-purpose [S] clothing) for firefighters.

The characteristics of B clothing are: Kermel/viscose fabric made from 50% aramid fibres and 50% viscose fibres; very mechanically resistant to tearing; it has non-flammable fabric properties owing to aramid fibers, and viscose fibers provide very good comfort of use; and water and oil-resistant finish.

The characteristics of S clothing are: outer fabric made from 94% Nomex® III, 5% para-aramide and 1% anti-static fibres; membrane made of 50% polyethylene [PE] and 50% polyurethane, flame retardant [PUFR]; thermal barrier made of 100% of meta-aramid fibres; lining made of 50% Nomex® and 50% viscose flame retardant [FR].

Two types of clothing sets were used in the studies, as listed in the following:

- active thermal underwear including a long-sleeved vest, long johns and barrack clothing (Figure 1a) – B clothing (total weight 1.74 kg);
- active thermal underwear including a long-sleeved vest, long johns and barrack and special-purpose clothing (Figure 1b) – S clothing (total weight 5.35 kg).

For each set mentioned, cotton socks, shoes with an ankle upper, gloves and a helmet were used (total weight 2.0 kg).

2.4. Physical effort load

The studies inside the climatic walk-in test chamber used an electric treadmill, a shelf at a height of 1.8 m and a 20-kg box. The firefighters carried out a cycle of subsequent activities that lasted for 30 min in total [9]:

Table 1. Physical characteristics of firefighters participating in the thermal load tests using protective clothing.

				Physical endurance	
Age (years)	Body weight (kg)	Body height (cm)	Body surface (m^2)	L/min	ml/min/kg
26.20 ± 3.46	81.10 ± 9.18	181.10 ± 7.00	2.00 ± 0.13	3.55 ± 0.26	44.0 ± 3.6

Note: $M \pm SD$ values are given.

Figure 1. Sets of clothing used in the study: (a) barrack clothing; (b) barrack under special-purpose clothing.

- walking on an electric treadmill at a treadmill speed of 5 km/h for 5 min;
- crawling on an electric treadmill at a treadmill speed of 0.3 km/h for 2 min;
- taking a 20-kg box down from a shelf suspended at a height of 1.8 m and putting the box back on the shelf, repeated five times;
- walking on an electric treadmill at a treadmill speed of 5 km/h to get a full 30 min of physical exercise.

2.5. *Measured physical and biological parameters*

During the tests, the following parameters were measured:

(1) internal temperature measured in the gastrointestinal tract (T_{abd}) using a temperature monitoring system (Vital Sense, USA);
(2) local skin temperatures and relative humidity at four locations as per Standard No. EN ISO 9886:2004 [10], measured using i-Button wireless sensors (Ecotone, USA);
(3) heart rate measured using an FX 2000 (Emtel, Poland) cardiac monitor and wirelessly using a Polar Electro Oy monitor (Polar, Finland);
(4) the body and clothing weights prior to and after the test, in order to determine the sweating intensity, using an F 150 S-D2 balance (Sartorius, Germany);
(5) temperature and relative humidity at the chest under the underwear, measured using a Hygro-Lab meter (Rotronic AG, Switzerland), in order to visualize the results obtained;
(6) arterial blood pressure (Omron, Poland) before and after the test.

Subjective assessments of thermal sensation and perceived exertion were obtained in accordance with European Standard No. EN ISO 10551: 2019 [11] and Borg [12], respectively.

2.6. *Indications to discontinue the tests and safety of subjects*

The test duration was limited by the adopted physiological values, which included internal temperature of 38.0 °C, heart rate corresponding to 80% of the maximum value depending on the subject's age, 100% relative humidity under the clothing, at not less than two measurement sites, and subjective signs of tiredness.

To ensure subject safety, there was a doctor present at the tests [13]. The subject could also communicate by voice with the investigators located in the laboratory room. The subject was also allowed to stop the treadmill on their own.

2.7. Indicators calculated

The measurements made during the tests were used to calculate the indicators described in the following, which served as the basis to compare the tests differing in the type of clothing at two air temperature levels.

Based on the local measurements of skin temperatures, the average weighted skin temperature (T_{sk}) was calculated as per Standard No. EN ISO 9886:2004 [10].

Heat storage (S) was determined according to the following formula:

$$S = \left(3.55 \cdot m_{cp}/A_{Du}\right) \cdot (0.9\Delta t_{abd} + 0.1\Delta t_{sk}) \cdot T_{eks}{}^{-1}, \quad (1)$$

where m_{cp} = initial body weight; A_{Du} = body surface; ΔT_{abd} = difference in gastrointestinal tract temperature; ΔT_{sk} = difference in average weighted skin temperature; T_{eks} = exposure duration.

The physiological cost of the exercise was determined by calculating the difference between the heart rate level at rest and at the last minute of the physical exercise [14].

The intensity of the physical exercise was calculated from the heart rate level according to Standard No. EN ISO 8996:2004 [15].

3. Results

3.1. Description of the statistical analysis

The results presented are derived from experiments carried out according to the intrapersonal scheme. This means that a single person was exposed to different experimental conditions several times. In the first experiment, this was a two-factor scheme: the clothing factor had two levels (B and S clothing). The same is true for the temperature factor (20 and 30 °C). Therefore, we are dealing with four measurements.

This scheme of analysis does not only imply the analysis of data according to the intrapersonal scheme (tests for dependent trials). Because of this, the analysis of data no longer included analysis of variance according to the intrapersonal scheme, as it would only use the observations where there are valid data for all of the measurements. Instead, the comparisons were carried out in pairs using *t* tests for dependent trials.

3.2. Heat storage

Calculations related to the level of heat storage are presented in Figure 2. The level of heat storage in the firefighters' bodies (Figure 2) was nearly 40 W·m^{-2}, regardless of the clothing they used, when the test conditions included air temperature of 20 °C. In these tests, the differences

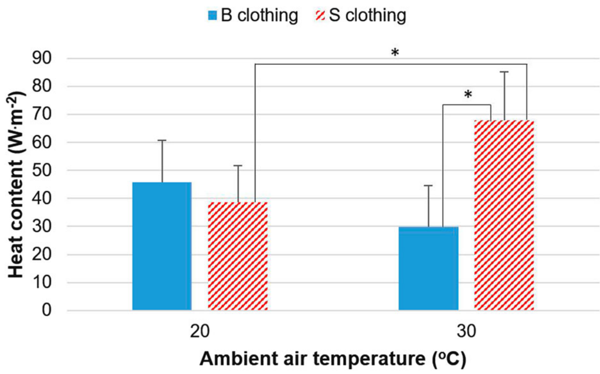

Figure 2. Heat storage levels in the body during thermal load tests with firefighters. Note: B clothing = barrack clothing; S clothing = barrack under special-purpose clothing. Error bars denote *SD*. $*p < 0.05$ between the test variants B and S clothing, and for S clothing also between the two air temperature conditions.

between the B and S clothing test variants were not statistically relevant. When the test conditions included the air temperature of 30 °C, a level of heat storage more than twice as high was found for the S clothing test variant compared to the tests for the B clothing variant, and the results were statistically meaningful. Moreover, the level of heat storage was greater for S clothing at the air temperature of 30 °C compared to the test variant at the lower air temperature, and this difference was also relevant statistically.

3.3. Sweating intensity

The results presented in Figure 3 suggest that the differences in sweating intensity found between the tests involving two types of firefighter clothing were statistically relevant, which is true for the differences between both the applied ambient air temperatures and the tests involving

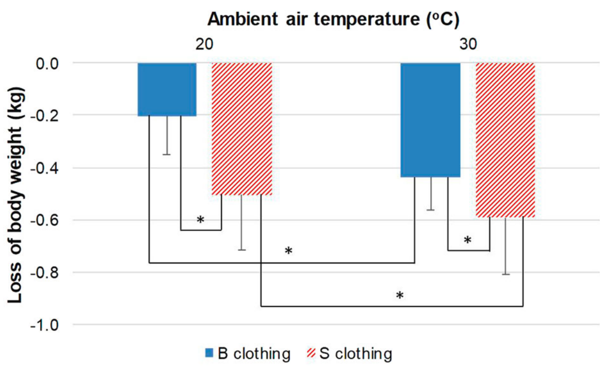

Figure 3. Sweating intensity as the loss of body weight during thermal load tests with firefighters. Note: B clothing = barrack clothing; S clothing = barrack under special-purpose clothing. Error bars denote *SD*. $*p < 0.05$ between the test variants B and S clothing, and between the conditions 20 and 30 °C for both B and S clothing.

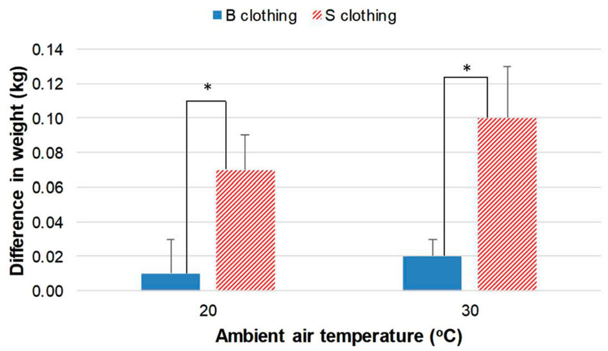

Figure 4. Changes in barrack clothing weight during thermal load tests with firefighters. Note: B clothing = barrack clothing; S clothing = barrack under special-purpose clothing. Error bars denote *SD*. $*p < 0.05$ between the test variants B and S clothing.

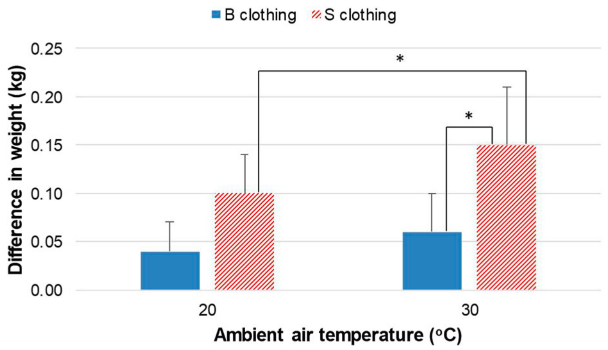

Figure 5. Changes in underwear weight during thermal load tests with firefighters. Note: B clothing = barrack clothing; S clothing = barrack under special-purpose clothing. Error bars denote *SD*. $*p < 0.05$ between the test variants B and S clothing.

the different types of clothing. The level of sweating was proportionate to the air temperature conditions.

The comparison of moisture accumulation by the barrack clothing in the B and S clothing test variants is presented in Figure 4. According to the results presented in Figure 4, at both ambient air temperatures, moisture accumulation by the barrack clothing was greater in the tests that involved the use of S clothing than in the tests where S clothing was not used, and the difference was statistically relevant. In the tests with and without S clothing, there were no significantly relevant differences in moisture accumulation by the barrack clothing between the ambient air temperatures of 20 and 30 °C.

Figure 5 presents the levels of moisture accumulation by underwear in the tests involving different ambient temperature variants. The differences in the levels of moisture accumulation by underwear (Figure 5) found between the test variants involving the use of B and S clothing were statistically relevant at the ambient air temperature of 30 °C. Furthermore, the level of moisture accumulation by underwear was greater for S clothing at the air temperature of 30 °C compared to the lower air temperature, and this difference was also relevant statistically.

Table 2. Physical effort intensity ($W{\cdot}m^{-2}$) in different test phases at the air temperature of 20 and 30 °C and with two types of clothing (B and S).

	B clothing		S clothing	
Test phase	20 °C	30 °C	20 °C	30 °C
Walking	165.6	191.7	198.8	201.3
Crawling	183.5	211.0	204.4	222.8
Lifting	323.7	390.0	377.3	382.4
Walking	176.4	210.0	262.0	312.0
Average	212.3	250.7	260.6	279.6

Note: B clothing = barrack clothing;
S clothing = barrack under special-purpose clothing.

For S clothing, both in the test at the air temperature of 20 °C and in the test at the air temperature of 30 °C, the level of moisture accumulation was the same and amounted to 0.03 ± 0.01 kg.

3.4. Physical effort intensity

The intensity of physical effort was calculated for the TL person (case study). The results are compared in Table 2.

Although the differences between the determined intensity of physical effort were notable in the tests that involved the use of B clothing depending on the air temperature, there were significantly fewer differences in these values when S clothing was used (Table 2).

3.5. Physiological cost

The physiological cost of physical effort as the difference in heart rate during tests is presented in Figure 6. At the ambient air temperature of 20 °C, the physiological cost of physical effort was comparable between the conditions of using B and S clothing. It was found that at the air temperature of 30 °C, the physiological cost of physical effort while wearing S clothing was nearly twice

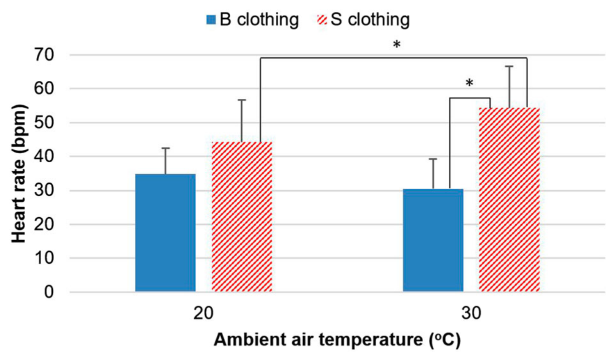

Figure 6. Physiological cost of the physical exercise as a change in heart rate during thermal load tests with firefighters. Note: B clothing = barrack clothing; S clothing = barrack under special-purpose clothing. Error bars denote *SD*. $*p < 0.05$ between the test variants B and S clothing.

as high as the physiological cost of the physical effort expended while wearing B clothing, and the difference was statistically relevant. Furthermore, the physiological cost levels while wearing S clothing were also found to differ with statistical relevance between the temperatures of 20 and 30 °C.

3.6. *Thermal sensation assessment*

Thermal sensation assessments in the different test phases at two air temperature levels and with two types of clothing used are presented in Table 3.

On average, thermal sensations in the tests when the air temperature was 20 °C (Table 3) were assessed to fall within the range of 0–2; it was only in the last test phase that the assessments of S clothing were above 2. In the tests involving the use of B and S clothing at the temperature of 20 °C, no significant differences were found between the thermal sensations.

As regards the tests at the temperature of 30 °C, all of the assessments in the tests involving the use of B clothing were less than 2 (Table 3). In the tests involving the use of S clothing, the average thermal sensation assessments were above 2 in the second and fourth test phases. In these test phases, the thermal sensation assessments were higher (worse) for tests involving the use of S clothing than for tests involving the use of B clothing, and the difference was statistically relevant.

3.7. *Assessment of perceived exertion*

The results related to the assessments of perceived exertion are presented in Table 4.

In the tests at the air temperature of 20 °C, the average assessments of perceived exertion (Table 4) in the tests involving the use of B clothing were below 11, and when S clothing was used the assessments were above 11. The differences between B and S clothing variants were not statistically relevant.

At the higher air temperature (30 °C), the assessments of perceived exertion were still below 11 in the tests involving the use of B clothing, whereas in the tests involving the use of S clothing the assessments were above 12 (Table 4). The assessments of perceived exertion while wearing S clothing were higher than those concerning B clothing in the second and fourth test phases (walking), and the difference was statistically relevant.

The comparison of the type of clothing with regard to the different ambient air temperatures leads to a conclusion that in the tests involving the use of B clothing, the assessments of perceived exertion were similar at both of the ambient air temperatures, i.e., below 11 (Table 4), and they did not show any significantly relevant differences. As regards tests involving the use of S clothing, the assessments of perceived exertion (Table 4) at the air temperature of 30 °C were higher than those for the lower air temperature (20 °C) in the second and fourth test phases (walking), and the difference was statistically relevant. In that case,

Table 3. Thermal sensation assessments in different test phases at the air temperature of 20 and 30 °C and with two types of clothing (B and S).

	Air temperature of 20 °C		Air temperature of 30 °C	
Test phase	B clothing	S clothing	B clothing	S clothing
Start	1.1 ± 0.8	0.6 ± 0.5	0.6 ± 0.5	0.5 ± 0.3
Walking	1.3 ± 0.9	1.7 ± 0.7	1.7 ± 0.7	2.3 ± 0.7*
Lifting	0.8 ± 0.5	1.5 ± 0.9	1.5 ± 0.5	1.7 ± 0.8
Walking	1.4 ± 0.7	2.2 ± 0.9	1.9 ± 0.6	2.6 ± 0.7*

* $p < 0.05$ between the B and S clothing test variants.
Note: $M \pm SD$ values are given. B clothing = barrack clothing; S clothing = barrack under special-purpose clothing.

Table 4. Assessments of perceived exertion in different test phases at the air temperature of 20 and 30 °C and with two types of clothing (B and S).

	Air temperature of 20 °C		Air temperature of 30 °C	
Test phase	B clothing	S clothing	B clothing	S clothing
Start	–	–	–	–
Walking	10.5 ± 1.4	11.3 ± 1.0	10.8 ± 1.3	12.5 ± 1.9*
Lifting	10.8 ± 1.2	11.7 ± 1.6	10.9 ± 1.1	12.1 ± 2.1
Walking	10.8 ± 1.3	11.5 ± 1.3	10.9 ± 1.4	12.4 ± 2.0*

*$p < 0.05$ between the B and S clothing test variants.
Note: $M \pm SD$ values are given. B clothing = barrack clothing; S clothing = barrack under special-purpose clothing.

the assessments of perceived exertion were above 11 at both of the ambient air temperatures.

4. Discussion

Tests involving firefighters were carried out to compare thermal loads exerted on the firefighter's body depending on the ambient air temperature and type of clothing at different levels of load due to physical effort.

An analysis of thermal comfort for S clothing without any items added, carried out by one of the authors of this article, has shown that because of the relatively high heat insulation of this type of clothing, which is $0.419 \pm 0.012\,m^2{\cdot}°C{\cdot}W^{-1}$ (2.7 clo, serial method), a person is able to feel comfortable during physical effort of moderate intensity when the air temperature is below 15 °C [1]. This leads one to conclude that all of the ambient air temperature levels used in the tests were higher than the conditions allowing for the user's thermal comfort. On the other hand, these conditions are frequently encountered by firefighters at work [16,17].

4.1. Air temperature of 20 °C

A short-lasting effort during the tests did not cause significant heat storage, which was comparable to tests involving both types of clothing at the air temperature of 20 °C. However, already under these conditions, the sweating intensity was significantly higher in the test variant involving the use of S clothing than in the tests involving the use of B clothing.

Barrack clothing, because of the practice of using it, was employed for all types of tests. In the tests involving the use of S clothing, the barrack clothing was characterized by significant moisture content that was several times higher than that in the test variant involving the use of B clothing. The weight of underwear in the test variant involving S clothing was marginally higher than in the test involving the use of B clothing.

The determined intensity of effort in the tests involving the use of S clothing was higher by 20–30 $W{\cdot}m^{-2}$ compared to the test involving the use of B clothing, and when the box was lifted this value was higher by as much as 70 $W{\cdot}m^{-2}$. The average value of this parameter for both variants of clothing allowed one to assign the effort to the third metabolic class (high metabolic rate, range 200–260 $W{\cdot}m^{-2}$) [15]. The physiological cost at the discussed air temperature was comparable to the tests involving the use of both types of clothing.

Subjective assessments of thermal sensations and perceived exertion tended to be higher in the tests involving the use of S clothing than in the tests involving the use of B clothing.

In summary, air temperature conditions of 20 °C can be considered comfortable for tests involving the use of B clothing, when there is a short-lasting effort of high intensity. However, when S clothing was used, sweating intensity was significantly higher than that for B clothing, indicating thermal strain and inclination of the body to give off heat through convection and radiation, and, additionally, thermoregulatory sweating was initiated to evaporate sweat and thereby give off heat [18–21].

4.2. Air temperature of 30 °C

At the air temperature of 30 °C, heat storage in the test involving the use of S clothing reached a level that was more than twice as high as in the test involving the use of B clothing. It was also found that the levels of heat storage in the tests involving the use of S clothing were significantly higher compared to the tests at the lower air temperature. In addition, the sweating intensity was significantly higher when S clothing was used than when B clothing was used. The levels of sweating were also significantly higher both when B clothing was used and when S clothing was used compared to the tests at the lower air temperature.

Air temperature conditions of 30 °C usually cause sweating to occur so that the excess heat can be given off [18,19]; however, when S clothing was used, the intensity of the heat transfer processes was greater than in the tests involving the use of B clothing.

In the test involving the use of S clothing, moisture accumulation by the barrack clothing was five times higher than in the test involving the use of B clothing. The weight of underwear was also significantly greater in the test involving the use of S clothing than in the test involving B clothing, although in the test involving the use of S clothing the weight of underwear was also greater at the air temperature of 30 °C compared to the temperature of 20 °C.

As for the intensity of effort, the differences between the test involving the use of S clothing and the test involving the use of B clothing were more minor than those at the lower air temperature (by approximately 10 $W{\cdot}m^{-2}$), indicating that physical effort under such temperature conditions exerts great load on the body, even when light clothing is used [22–25]. While in the tests involving the use of B clothing, the average intensity of physical effort was assigned to the third metabolic class, in the tests involving the use of S clothing it was assigned to the fourth metabolic class (very high metabolic rate, $>260\,W{\cdot}m^{-2}$).

At the ambient air temperature of 30 °C, significant activity of the blood circulation system was observed, manifested as an increased heart rate level. This is a response to increased heat storage in the body. During the expenditure of physical effort in a hot environment, the redistribution of blood takes place, which involves a reduction in the visceral and renal blood flow, and the directing of blood to the skin to enable heat dissipation on its surface [26].

In the tests involving the use of S clothing, subjective assessments of thermal sensations and perceived exertion tended to be higher than in the tests involving the use of B clothing, and these differences were significant in the stage involving walking.

In summary, at the air temperature of 30 °C, the differences between tests involving the use of B and S clothing were significant. All of the measured and calculated physiological parameters reached a level that was higher in the tests involving the use of S clothing than in the tests involving the use of B clothing, and sometimes these differences were manifold. These results indicate a significant thermal strain in users of S clothing, in contrast to tests involving the use of B clothing. When B clothing was used, the levels of the measured indicators, except for the sweating intensity, did not differ significantly from tests at the lower air temperature. The assessments of thermal sensations in the tests involving the use of B clothing were below 2 (warm), whereas the assessments of perceived exertion were below 11, indicating that the effort was felt as relatively low. In the tests involving the use of S clothing, the assessments of thermal sensations were near 3 (hot), whereas the assessments of perceived exertion were at the level of 12–13, which represents quite a high effort.

4.3. Variants of clothing

Differences in the levels of physiological and subjective values between the variants of clothing are discussed above in sections 4.1 and 4.2.

It should be noted that the weight of S clothing was more than twice the weight of B clothing (S clothing, 5.35 kg; B clothing, 1.74 kg), which resulted in a higher thermal load in users of this variant of clothing compared to tests involving the use of B clothing. Dorman and Havenith [27] analysed the impact of the weight and structure of protective clothing. The tests conducted by these authors indicate that the metabolic cost of the physical effort expended may increase within the range of 2.4–20.9% when different types of protective clothing are used in comparison to the test conditions. In addition, the authors of the aforementioned paper emphasize that heavy and stiff clothing may limit efficient performance of professional activities.

The transfer of heat and moisture to the surroundings through the layers of S clothing is affected not only by the aforementioned but also by the fact that the protective properties of this type of clothing, which has the form of a high-temperature and flame-resistant layer and a waterproof membrane, significantly hinder the flow of heat and moisture from the user's body to the external layer of the clothing. Here, it would be beneficial to point out the results on moisture accumulation by special-purpose clothing. Namely, for all of the air temperature and physical effort variants, moisture accumulation by special-purpose clothing increased by only 0.03 ± 0.01 kg, whereas the moisture accumulation by underwear and barrack clothing worn under the special-purpose clothing was several times greater.

5. Conclusions

The comparison of the results of tests studying the thermal loads exerted on the firefighter's body, depending on ambient air temperature and two types of clothing at different conditions related to physical effort, has demonstrated that, regardless of the ambient air temperature, the physiological parameter values and the subjective assessments (assessments of perceived exertion and thermal sensations) were higher when S clothing was used.

The structure of S clothing, which ensures protection of firefighters against high temperatures and flames, and the present watertight layer make it significantly more difficult for the body to give off heat through convection, radiation and sweat evaporation. Also, S clothing is more than twice as heavy as B clothing, which translates into a higher physiological cost of the work performed, on the one hand, and, on the other, hinders the transfer of heat to a greater degree than B clothing, which is lighter.

It should be noted that the activities undertaken during the tests were close to those undertaken during rescue operations and, as demonstrated in the tests involving the use of the special-purpose clothing, even a short-lasting, 30-min effort can result in high levels of physiological reactions, which should be followed by a rest to prevent exhaustion.

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References

[1] Młynarczyk M. Ubranie specjalne dla strażaków – wymagania normatywne i badania własne [Special purpose clothing for firefighters – normative requirements and own studies]. Bezpieczeństwo Pracy. Nauka i Praktyka. 2018;5:11–15. Polish.
[2] Lee JY, Park J, Park H, et al. What do firefighters desire from the next generation of personal protective equipment? Outcomes from an international survey. Ind Health. 2015;53(5):434–444. doi:10.2486/indhealth.2015-0033
[3] Dąbrowska A, Bartkowiak G, Szmechtyk T. Potrzeby i oczekiwania strażaków wobec inteligentnej odzieży ochronnej z systemem zagrożeń – wyniki badań ankietowych [Needs and expectations of firefighters with regard to smart protective clothing with a risk system – results of surveys].

Bezpieczeństwo Pracy. Nauka i Praktyka. 2019;4:22–25. Polish.
[4] Bartkowiak G, Miśkiewicz P. Preferencje strażaków w odniesieniu do odzieży spodniej i bielizny – wyniki badań ankietowych [Firefighters' preferences in respect of underwear – results of surveys]. Bezpieczeństwo Pracy. Nauka i Praktyka. 2018;9:14–17. Polish.
[5] European Committee for Standardization (CEN). Protective clothing for firefighters – performance requirements for protective clothing for firefighting. Brussels: CEN; 2008. Standard No. EN 469:2008.
[6] Rozporządzenie Ministra Spraw Wewnętrznych i Administracji zmieniające rozporządzenie w sprawie umundurowania strażaków Państwowej Straży Pożarnej [Regulation of the Polish Minister of Internal Affairs and Administration amending the regulation on firefighter uniforms for the State Fire Service]. Journal of Laws of the Republic of Poland 18 May 2018; item 982. Polish.
[7] Zarządzenie nr 7 Komendanta Głównego Państwowej Straży Pożarnej zmieniające zarządzenie w sprawie wzorców oraz szczegółowych wymagań, cech technicznych i jakościowych przedmiotów umundurowania, odzieży specjalnej i środków ochrony indywidualnej użytkowanych w Państwowej Straży Pożarnej [Regulation No 7 of the Polish Chief of the State Fire Service amending the regulation on models and detailed requirements, technical characteristics and quality items for uniforms, special-purpose clothing and personal protection equipment used by the State Fire Service]. Official journal of the National Headquarters of the State Fire Service od Poland 16 July 2018; item 15. Polish.
[8] Rozporządzenie Ministra Spraw Wewnętrznych i Administracji zmieniające rozporządzenie w sprawie wykazu wyrobów służących zapewnieniu bezpieczeństwa publicznego lub ochronie zdrowia i życia oraz mienia, a także zasad wydawania dopuszczenia tych wyrobów do użytkowania [Regulation of the Polish Minister of Internal Affairs and Administration amending the regulation on the list of products intended to provide public safety or protection of life and health and assets, and rules of approving such products for use]. Journal of Laws of the Republic of Poland 18 May 2018; item 984. Polish.
[9] European Committee for Standardization (CEN). Protective clothing against liquid and gas chemicals, including aerosols and solid particles. Part 2: eequirements concerning gas-resistant protective clothing (type 1) intended for fire rescue teams (ET). Brussels: CEN; 2005. Standard No. EN 943-2:2005.
[10] European Committee for Standardization (CEN). Ergono mics – evaluation of thermal strain by physiological measurements. Brussels: CEN; 2004. Standard No. EN ISO 9886:2004.
[11] European Committee for Standardization (CEN). Ergono mics of the physical environment – subjective judgement scales for assessing physical environments. Brussels: CEN; 2019. Standard No. EN ISO 10551:2019
[12] Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc. 1982;14:377–381.
[13] European Committee for Standardization (CEN). Ergono mics of the thermal environment. Medical care for patients exposed to extreme hot and cold environments. Brussels: CEN; 2002. Standard No. EN ISO 12894:2002.
[14] Meyer J-P, Martinet C, Payot L. Heart rate as an index of thermal stress. Proc Hum Factors Ergon Soc Annu Meet. 2000;44(29):359–362.
[15] European Committee for Standardization (CEN). Ergono mics of the thermal environment – determination of metabolic rate. Brussels: CEN; 2004. Standard No. EN ISO 8996:2004.
[16] Korenkiewicz I. Narażenie zawodowe funkcjonariuszy Państwowej Straży Pożarnej [Professional exposure of the State Fire Service officers]. Białystok: Państwowa Inspekcja Sanitarna, MSWiA; 2004. Polish.
[17] Wejman M, Przybylski K. Identification of hazards at work stations of professional firefighters. Sci Papers Poznan Univ Technol. 2013;59:69–84.
[18] Traczyk WZ, Trzebski A. Fizjologia człowieka z elementami fizjologii stosowanej i klinicznej [Human physiology with elements of applied and clinical physiology]. Warsaw: PZWL; 1990. Polish.
[19] Roades RA, Tanner GA. Medical physiology. Boston (MA): Little, Brown and Company; 1995.
[20] Greger R, Windhorst U. Comprehensive human physiology. From cellular mechanisms to integration. Vol. 2, Chapter N – regulation of body temperature. Heidelberg: Springer-Verlag Berlin; 1996.
[21] Kozłowski S, Nazar K. Wprowadzenie do fizjologii klinicznej [Introduction to clinical physiology]. Warsaw: PZWL; 1999. Polish.
[22] Marszałek A. Fizjologiczne reakcje organizmu człowieka podczas pracy w odzieży ochronnej w gorącym środowisku [Physiological reactions of the human body during work in protective clothing in a hot environment]. Bezpieczeństwo Pracy. Nauka I Praktyka. 2006;3:11–15. Polish.
[23] Marszałek A, Bartkowiak G, Łężak K. Physiological effects of a modification of the construction of impermeable protective clothing. Int J Occup Saf Ergon. 2009;15(1):61–73. doi:10.1080/10803548.2009.11076789
[24] Rossi RM, Bolli W, Stämpfli R. Performance of firefighters' protective clothing after heat exposure. Int J Occup Saf Ergon. 2008;14(1):55–60. doi:10.1080/10803548.2008.11076747
[25] Tochihara Y, Ohnaka T. Environmental ergonomics. The ergonomics of human comfort, health and performance in the thermal environment. Boston (MA): Elsevier; 2005. (Elsevier Ergonomic Book Series. Vol. 3, Sec. 6 – protective clothing).
[26] Rowell LB. Cardiovascular adjustments to thermal stress. JT Shepard, FM Abboud, editors. Washington (DC): American Physiological Society; 1983. Sec. II, Vol. III, Part 2; p. 967–1027.
[27] Dorman L, Havenith G. The effects of protective clothing on energy consumption during different activities. Eur J Appl Physiol. 2009;105:463–470. doi:10.1007/s00421-008-0924-2