THE MICROCLIMATE IN PROTECTIVE FIRE FIGHTER FOOTWEAR: FOOT TEMPERATURE AND AIR TEMPERATURE AND RELATIVE HUMIDITY

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Abstract:

The study material consisted of two models of protective firefighter footwear. The tests were conducted on subjects in a laboratory using an ergometric treadmill. The parameters of footwear microclimate were continuously recorded using T/RH sensors. For the leather footwear, the highest foot temperature was recorded in the 50th minute of the experiment (35.8°C in the dorsal region and 37.3°C in the plantar region) and for the polymer footwear in the 60th minute of the experiment (35.4°C in the dorsal region and 37.0°C in the plantar region). In the leather footwear, the temperature of the air surrounding the feet rose from 31.0°C to 35.4°C, and then declined, but did not return to the initial level during the rest period. In turn, in the polymer footwear, the temperature rose from 29.0 to 34.7°C, and then decreased to 33.7°C following the rest period. The highest relative air humidity was recorded in the polymer footwear (96.6%), while in the leather footwear it amounted to 91%. Testing the dynamics of the microclimate during footwear use provides complete information about changes in the temperature of the skin of the foot and the temperature and relative humidity of the footwear microclimate.

Keywords:

protective firefighter footwear; foot temperature; footwear microclimate

1. Introduction

The wide variety of fire-fighting tasks leads to a huge variety of rescue operations conducted under very difficult, and often extreme, conditions [23]. In the course of their work, fire-fighters may be simultaneously exposed to high temperature, water, hazardous chemicals, strong impacts, sharp objects, etc. The tactical and operational activities of fire-fighters require the use of personal protective equipment, including protective footwear meeting the requirements of relevant standards harmonized with Directive 89/686/EEC [6, 22]. Fire-fighter footwear is classified as specialised equipment, which means that it must be appropriate for the specific characteristics of the work environment [1, 20]. However, the protective requirements that footwear must meet compromises its biomechanical and hygienic properties [5]. For instance, the application of steel toecaps and anti-puncture insoles unfavourably increases the rigidity and weight of the footwear. Performing work in excessively heavy footwear results in higher energy expenditure, which may lead to overexertion, pain, and fatigue. Efforts to provide full protection considerably lower the hygienic properties of footwear. Protective materials and elements often prevent the effective dissipation of heat and sweat, which are profusely produced during physical exercise. High temperature and humidity inside footwear may cause a sensation of discomfort. In addition, excessive humidity may promote the growth of microorganisms (fungi and bacteria) and cause chronic foot diseases [15]. High temperature and humidity inside footwear also affect blood flow, putting a strain on the vascular system in the lower extremities [16].

Under normal conditions of use, relative humidity inside footwear amounts to 60–65 % [3, 18]. However, microclimate humidity in impermeable protective footwear may reach more than 80% after just a few minutes of use, causing significant discomfort [16]. The amount of sweat secreted by the skin inside footwear changes with the microclimate temperature, work intensity, individual traits of the user, as well as the footwear construction and materials [2]. The human foot secretes on an average 2.5–3.0 g of sweat per hour. The amount of sweat secreted increases considerably during walking (up to an average level of 7.2 g/h) and during hard physical work performed at high temperature (up to 15 g/h). The intensity of sweat secretion is also linked to the number of sweat glands, which are distributed unevenly on the surface of the foot [9]. They are mostly located in the plantar region (approx. 366 glands per 1 cm²) with the highest concentrations being found under the heel and between the toes. In contrast, in the dorsal region, there are approx. 126 sweat glands per 1 cm². Protective footwear additionally increases skin temperature. According to some authors [2, 18], humans experience a sensation of comfort at foot temperatures in the range of 20 °C–33 °C and a sensation of discomfort at temperatures in the range 35 °C–38 °C.

The basic prerequisite for evaluating the comfort of use of protective footwear (including fire-fighter footwear) is to use appropriate methodology for assessing its functional and hygienic properties. Currently, methods evaluating the comfort of use of protective footwear may be divided into instrumental tests of individual footwear materials, tests on human subjects under predetermined climate conditions, simulation tests using

thermal foot models, and questionnaire surveys [8, 11–13, 19]. The most widespread methods involve evaluation of the hygienic properties of footwear materials by testing their samples for water vapour permeability, sorption properties, and heat transfer parameters [10, 14, 21, 24]. Furthermore, nonstandard tests on human subjects have been used to assess footwear microclimate under simulated conditions of use [10].

The objective of the present study was to examine microclimate dynamics 'in vivo' in two types of protective fire-fighter footwear. The study was conducted on human subjects under conditions of simulated work – at a laboratory with a treadmill ergometer. It was hypothesised that the microclimate inside protective footwear is determined by footwear construction and material type.

2. Research methodology

2.1. The protective footwear tested

The study investigated two types of protective fire-fighter footwear different in terms of construction and material, namely: leather ankle boots (model A) and nitrile rubber boots (model B). The selected types of fire-fighter footwear are examples of multifunctional protective footwear with particularly intricate structure designed for protection against many hazardous and dangerous factors (Fig. 1).

The first tested model of footwear was made of thermal- and water-resistant grain cow leather and heat-resistant rubber soles. The ankle boots were assembled by means of adhesive bonding. The footwear was lined with a laminate containing a vapour-permeable membrane. The midsole was made of artificial cellulose skin and reinforced with cardboard. The footwear was equipped with a zipper in the front and shoelaces on both sides of the zipper to adjust the fit of the upper.

The other tested model was all-rubber footwear made of flame- and thermal-resistant nitrile rubber that was also resistant to many widespread chemicals such as fuels, fats, oils, weak and diluted acids, and some organic solvents.

Both footwear models were equipped with steel toecaps that could withstand impacts of up to 200 J and steel insoles protecting the foot against puncture. The average weight of leather footwear was 2026 g and that of rubber footwear was 2043 g.

2.2. Human subjects

The study was conducted on a group of 10 healthy men who were active fire-fighters working with fire-fighting units. The subjects were qualified based on valid health and safety certificates required for their workplaces. The group was homogeneous in terms of age (25–35) years), body mass index (20.1–32.6) and years of work (5–10).

Figure 1. Scheme presenting experimental setup

The subjects underwent an additional medical examination to exclude cardiovascular and metabolic diseases as well as skin conditions in the lower extremities.

Each subject was given an outfit consisting of a two-part track suit made of cotton (50%) and polyester (50%), cotton shorts, cotton T-shirt and socks made of cotton (60 %) and polyamide (40 %).

The study was approved by the Ethical Review Board, Central Institute for Labour Protection–National Research Institute in Warsaw (approval no. 52/2009 of July 2, 2009).

2.3. The procedure of footwear microclimate testing

The tests were conducted in a laboratory at constant climate conditions: air temperature of $(23 \pm 2) ^\circ\text{C}$, relative humidity of $(50 \pm 5) \%$, and air movement rate of 0.10 m/s [7]. As the tested fire-fighter footwear may be used under extremely varied conditions, the tests were conducted in a standard atmosphere.

Workload simulation was conducted using a treadmill ergometer (VIASYS Healthcare™, Germany) with adjustable speed of the running belt (Fig. 1).

Measurements and continuous recording of changes in foot temperature as well as air temperature and relative humidity inside footwear were conducted over 20 min of rest followed by 60 min of walking on the treadmill at a speed of 5 km/h and another 30 min of rest after walking. The duration of the walking stage (60 min) was sufficient to examine the stable phase of temperature and humidity curves.

Measurements of the microclimate between the foot and the footwear involved: temperature in the dorsal and plantar regions of the foot ($T [^\circ\text{C}]$) and relative humidity ($\text{RH} [\%]$). The microclimate parameters were measured using an integrated temperature and humidity sensor (ElproHotbox SE, Germany) with a diameter of 5 mm and length of 51 mm enabling continuous monitoring of air inside the footwear in terms of its humidity (accuracy $\pm 1.5 \%$) and temperature (accuracy $\pm 0.3 ^\circ\text{C}$). Furthermore, the local temperature of the skin of the foot was measured using a sensor operating with an accuracy of $\pm 0.3 ^\circ\text{C}$ (Elpro, Swiss) with a diameter of 2.5 mm and a

length of 1 mm, and a portable recording device (HOTBOX, Germany) with special software enabling continuous recording of measurement data from the humidity and temperature sensors and transfer of these data to a PC (Fig. 1).

During microclimate measurements, one integrated temperature and humidity sensor was placed inside the footwear between the sock and the insole, medially under the longitudinal arch of the foot. An additional temperature sensor was placed in the central area of the dorsal region of the foot, where the surface of the skin comes in contact with the footwear outer most intensively. Measurements were conducted continually with readings carried out every 3 minutes.

3. Study results and discussion

Measurement results for foot temperature as well as the temperature and relative humidity of air inside the footwear are given in the charts below (Figs. 2 - 5). The recorded curves illustrating mean foot temperature values for both footwear models exhibit an upwards trend, but with different dynamics resulting from differences in the footwear designs and materials.

In the case of the leather footwear, following an initial slow increase in foot temperature at rest, a rapid and pronounced rise in foot temperature was recorded between 0 min and 20 min of walking on the treadmill, with the temperatures in the plantar region being higher than in the dorsal region. In the period between 20 min and 60 min of walking, the foot temperature stabilised and gradually declined. The lowest foot temperature was recorded at 50 min of walking ($35.8 ^\circ\text{C}$ in the dorsal region and $37.3 ^\circ\text{C}$ in the plantar region).

The temperature curves recorded for the nitrile rubber footwear exhibit similar dynamics, but the average temperature both in the dorsal and plantar regions are lower than those observed for the leather footwear. Over time, this difference significantly decreases. The highest foot temperature in nitrile rubber footwear was observed after 50 to 60 min of walking and amounted to $35.4 ^\circ\text{C}$ in the dorsal region and $37.0 ^\circ\text{C}$ in the plantar region. According to literature data [3, 18], the temperature of the skin of the foot may vary from $25 ^\circ\text{C}$ to $40 ^\circ\text{C}$, with the comfort zone extending from $20 - 33 ^\circ\text{C}$ for casual footwear. If the upper

Figure 2. Temperature in the plantar region of foot

Figure 3. Temperature in the dorsal region of foot

Figure 4. Changes in the temperature of air inside footwear

threshold is exceeded, then the thermoregulatory mechanisms of the human body are triggered: the skin starts to secrete more sweat, which in turn removes heat by evaporation. The results show that the comfort threshold determined for casual footwear was exceeded in both footwear models studied.

Similar patterns were observed in terms of changes in the temperature of air inside footwear, measured under the longitudinal arch or the foot. In the leather footwear, the air temperature increased from the initial value of 31.0–31.7 °C to a maximum of 35.4 °C after approx. 50 min of walking on the treadmill. Subsequently, the temperature declined, but did not return to the initial value after a period of rest. The temperature of air inside the nitrile rubber footwear was slightly lower: it increased from 29.0 to 29.6 °C during the initial period of rest to 34.7 °C after 60 min of walking, and subsequently declined to 33.7 °C after the final 30 min of rest.

Microclimate sensations are largely influenced by relative humidity levels of the air inside the footwear. The optimum humidity is thought to be 60–65 % [9]. As the presented data show, the optimum humidity levels were significantly exceeded in both tested variants of protective footwear. The highest rise in humidity was observed during the first three minutes after putting on the footwear (from approx 50% to approx. 65% in the leather footwear and to approx. 80 % in the nitrile rubber footwear). Subsequent increases in humidity were much less dramatic. Thirty minutes after the beginning of the walking exercise, relative humidity in the leather footwear stabilised at 79–80 %. In contrast, in the vapour-resistant nitrile rubber footwear, relative humidity rose to a very high level of 96.6 % and remained so 10 min into the final rest period. It should be noted that relative humidity declined quite quickly in the leather footwear after the end of the walking exercise.

Apart from aspects of the cognitive study were performed to check the suitability of metrological developed method. Calculated by reference to the data standard deviations and coefficients of variation confirmed the relatively small deviation from measurements (Table 1).

In accordance with our hypothesis, humidity and temperature rose more in the all-rubber footwear than in the leather footwear. This fact is attributable to the construction and material of the

Figure 5. Changes in the relative humidity inside footwear

two footwear models. In the vapour-resistant nitrile rubber footwear (modelB – knee-high), sweat cannot evaporate to the external environment, so all vapour produced inside the footwear undergoes condensation upon contact. This causes continued levels of high moisture and secondary wetting of the socks, as well as of the liner and insole. In turn, the relative humidity results for the leather footwear did not exceed the humidity discomfort threshold (80 %), which is due to its superior evaporation properties (model A – calf-length) and the good sorption parameters of the footwear materials. The collected data suggest that leather footwear enables effective removal of moisture away from the feet and socks. This moisture becomes partially evaporated to the external environment and partially absorbed by the internal footwear elements, from which it may be removed through desorption after taking off the footwear [4].

4. Summary

Fire-fighting and rescue footwear is designed for extreme events that may occur in places such as airports, urban areas, rural and forest areas, industrial areas, military grounds, etc. Research into the comfort of use of such footwear should go beyond the mere requirements of relevant standards harmonized with Directive 89/686/EEC. In the case of thermal comfort, it is necessary to examine the microclimate inside footwear, measured as a function of temperature and humidity during use. Microclimate testing on human subjects gives a complete set of data concerning the effect of footwear construction and materials on foot temperature, as well as on the temperature and relative humidity of air inside the footwear. The protective materials used in firefighter footwear hinder effective heat and moisture transport. Therefore, so-called support textiles (liners, insoles, socks, inserts) may play an important role in the mechanisms of moisture removal as they facilitate drainage along the fibres and yarn up to a level above the footwear upper (models A and B), where it can evaporate due to ventilation during walking. New solutions should be sought to increase the capacity of footwear to absorb the large amounts of sweat that the feet produce during exercise; these could include replaceable insoles facilitating sweat removal (they may be additionally antibacterial, abrasion-resistant, and covered with aluminium foil protecting the foot against high

temperatures from the bottom). Another interesting option is the use of modern materials with high sorption capacity and dynamics (e.g., containing superabsorbents) and membranes enabling appropriate air circulation while preventing humidity.

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