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Evaluating the comfort of use of protective footwear: Validation of a method based on microclimate parameters and peripheral blood flow

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ABSTRACT

The paper presents validation evidence for a method of evaluating the comfort of use of protective footwear based on microclimate parameters and peripheral blood flow in the lower limbs. A study involving impedance plethysmography showed that the inherent construction characteristics of protective footwear hinder heat diffusion and moisture removal, influencing peripheral blood flow in the lower limbs. The temperature and relative humidity inside the footwear, the weight of secreted sweat, and the weight of the support textiles (socks and liners) were measured and compared to the plethysmographic parameters. The components of measurement uncertainty were carefully determined for each studied parameter and uncertainty budgets were created. These results were subsequently used to identify measurement errors that could affect the quality and reliability of laboratory tests.

1. Introduction

Protective footwear is used to protect the user from hazardous and harmful factors in the workplace. However, the protective features of footwear impair its biomechanical and hygienic properties [1].

It has been shown that sweating leads to increased moisture in the microclimate around the foot [2], often causing discomfort after exceeding 80% relative humidity [3], contributes to the development of pathogenic microorganisms and foot diseases [4]. Additionally, heat stress puts a strain on the vascular system in the lower limbs. At an air temperature of 33 °C, blood flow equals approx. 44 cm^3/min, while at 20 °C, it is approx. 8 cm^3/min [3].

The laboratory methods and functional tests used to date are insufficient in terms of evaluating the comfort of use of protective footwear. These methods include instrumental tests of individual footwear materials, experiments involving human subjects under fixed climatic conditions, simulations using thermal foot models, and questionnaire surveys [5–8]. We developed a new method of protective footwear evaluation employing a non-invasive and objective technique based on the determination of peripheral blood flow. It was shown that during the use of protective footwear, heat and moisture diffusion into the environment is hindered due to the specific features of footwear construction, which affects blood circulation in the lower limbs. This effect was studied using impedance plethysmography, and preliminary results were reported in another paper by the authors [9].

The results of a study involving a larger group of subjects were described in our previous work [10]. It was shown that the dynamic processes of heat and moisture exchange that take place inside protective footwear have a significant effect on the user's comfort, as found in our paper [3]. The developed research method was validated by means of available statistical tools. Initially, we

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designed a research strategy and selected parameters to be estimated in the validation process. It was assumed *a priori* that measurement uncertainty and accuracy could be affected the microclimate inside the footwear (that is, temperature in the dorsal and plantar regions of the foot and relative humidity). Other selected factors included test time (duration), the speed of the ergometric treadmill, as well as the weight of socks and liners. We also took into consideration random effects (the dispersion of measurement results) and blood flow parameters. Subsequently, tools for the estimation of measurement uncertainty of the various parameters were specified. Next, we calculated the relative contribution of the measurement uncertainty components to the compound measure of relative uncertainty. Based on that, uncertainty budgets were created to identify anomalies and evaluate measurement reliability.

2. Materials and experimental procedure

Human subjects ($n = 30$) and the experimental protocol were described in detail in the first part of paper [10], which was focused on analysis of the parameters of blood flow in the lower limbs. Experiments were conducted on 30 subjects forming a homogeneous group in terms of age and BMI. The tests involved three stages (warm-up, exercise proper, and rest) during which the impedance of low-intensity high-frequency current was measured. The principal objective of that experiment was to visualize changes in blood volume in the lower limbs caused by wearing protective footwear under simulated workplace conditions. The methodology for measuring temperature and humidity inside the footwear and blood flow in the lower limbs was described in detail in the paper mentioned above [10].

In turn, the current manuscript is devoted to the metrological validation of the previously developed method. The results obtained during the previous plethysmographic study were confronted in the present work with selected factors that may significantly affect the comfort of workers wearing protective footwear, such as temperature of the microclimate inside the footwear, relative humidity, weight of secreted sweat, and weight of socks and liners.

In the current paper, impedance plethysmography was used as a validator for those components of the microclimate that may exert a significant effect on the comfort of use of protective footwear.

3. Validation and statistical analysis

Validation of the presented measurement method involved such parameters as accuracy, precision, and measurement uncertainty. Also measurement errors were identified. Our method of evaluating the comfort of use of protective footwear was validated in reference to the relevant standards [11,12]. Validation was conducted based on the results of laboratory measurements of microclimate, blood flow, and sock and liner weight increases, previously published in another work by the authors [3]. Detailed statistics of the various parameters tested in the validation procedure were determined (the parameters included the microclimate inside footwear, plethysmographic measurements, as well as changes in the weight of socks and liners). Grubb's test was used to check for outliers, which were expunged from the dataset. The repeatability limit for measurements of changes in the weight of socks and liners was calculated using formula (1):

$$r = 2.8 * S_r \tag{1}$$

where S_r – standard deviation of the repeatability of changes in the weight of socks and liners.

Estimation of the measurement uncertainty of the presented method for evaluating the comfort of use of protective footwear involved the following components of uncertainty:

- Measurement uncertainty for temperature in the dorsal region of the foot (u_1) was estimated using formula (2):

$$u_1 = \frac{0.2}{2} = 0.1\ [^\circ\mathrm{C}], \tag{2}$$

where $w_1 = \frac{u_1}{T} = \frac{0.1}{35} = 0.0028$. Temperature ($T$) was measured using a thermohygrometer, whose expanded measurement uncertainty amounted to $\pm 0.2\ [^\circ\mathrm{C}]$ at a confidence level of approx. 95% and an expansion coefficient of $k = 2$. We also estimated standard combined uncertainty for a single temperature measurement in the dorsal and plantar regions of the foot according to Eq. (3):

$$u_c = T * w_c\ [^\circ\mathrm{C}], \tag{3}$$

where

$u_c = \sqrt{w_1^2 + w_3^2 + w_4^2}$, $\quad u_c = T * \sqrt{w_1^2 + w_3^2 + w_4^2} = 28.8 * \sqrt{0.0028^2 + 0.0053^2 + 0.012^2} = 0.387[^\circ\mathrm{C}]$, and:

$w_1, \ldots, w_4$ – denote components of standard combined uncertainty u_c. Thus, expanded measurement uncertainty for temperature equaled $\pm 0.8\ [^\circ\mathrm{C}]$ at a confidence level of approx. 95% and an expansion coefficient of $k = 2$.

- Measurement uncertainty for temperature in the plantar region of the foot was estimated according to the same protocol as that for the dorsal region of the foot.
- Measurement uncertainty for relative humidity in footwear, denoted as W, was determined using Eq. (4):

$$u_1 = \frac{1.4}{2} = 0.7\ [\%], \tag{4}$$

where $w_1 = \frac{u_1}{W} = \frac{0.7}{90} = 0.0078$. Combined standard uncertainty for a single measurement of relative humidity was estimated based on formula (5):

$$u_c = W * w_c[\%], \tag{5}$$

where

$w_c = \sqrt{w_1^2 + w_3^2 + w_4^2}$,

$u_c = W * w_1^2 + w_3^2 + w_4^2 = 87.6 * \sqrt{0.0078^2 + 0.0053^2 + 0.0141^2} = 1.49\ [\%]$ and:

$w_1, \ldots, w_4$ – denote components of standard combined uncertainty u_c. Thus, expanded measurement uncertainty for a single measurement of relative humidity in footwear equaled $\pm 3.0\ [\%]$ at a confidence level of