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METHODOLOGY OF ESTIMATING TEMPERATURE MEASUREMENT UNCERTAINTY IN A SYSTEM FOR ENDURANCE TESTS

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Abstract: The team consisting of the article authors developed a non-invasive method and a system for measuring temperature during an endurance test. A thermocouple which provided the required accuracy of changes in temperature dynamics measurements was used for the purpose of the required research.
The paper presents the methodology for estimating uncertainty of temperature measurement done with the presented system, using a method based on the GUM guide and a comparison with results obtained using the Monte Carlo method.

Key words: temperature measurement, measurement uncertainty, CPET.

1. INTRODUCTION

The endurance test is carried out in order to obtain an accurate assessment of athletes physical performance, but also for patients with cardiac or pulmonary disorders. The most commonly performer endurance test is the cardiopulmonary test CPET (cardiopulmonary exercise test) and spiroergometry [1, 2, 3].

The CPET diagnostic evaluation is non-invasive, reliable and safe. It is based on an analysis of gases exhaled during increasing effort (in a breath by breath system). During the test, data is being recorded on among other: changes in concentration of exhaled gases: oxygen (pO_2) and carbon dioxide (pCO_2), minute lungs ventilation, blood oxygen saturation (SpO_2), heart rate (HR) and blood pressure (BP), and the amount of work carried out by the test subject per unit of time – the power (WR) as well as a subject evaluation of effort (according to Borg scale) [4].

The results of the study allow to evaluate changes of physical performance and metabolic parameters occurring in the body during the trial and allow to program the intensity of physical training during a sports training.

The authors decided to add a temperature measurement at specific points in the human body [1] to the basic parameters measured during the CPET.

Due to the fact that during physical stress the phenomenon of the significant increase in the amount of high energy metabolic processes occurs, the temperature of the human body can rise substantially above the normal temperature. The increase in body temperature is one of the signals perceived by the brain as an indication of fatigue [5, 6, 7].

2. MEASUREMENT METHOD

To study the temperature changes dynamics of human skin at selected points, it was decided that the contact method will be used in order to ensure the required accuracy. A thermocouple probe in a Teflon coat was used as the sensor due to the fact that the component is resistant to the adverse influence of a chemically aggressive environment. This solution allows to reduce the impact of, among other things, the presence of perspiration on human skin on the result, while ensuring adequate dynamics of the measurement with the use of the thermocouple placed in a Teflon coat.

The analysis of the preliminary results obtained allowed to define the requirements to be met by the measurement system. The parameters of this system are: measurement resolution of at least 0.01°C, the sampling frequency of at least 4 Hz, measurement of two points of the body at the same time [1].

The expected range of temperature of the human skin ranges from 32°C to 41°C, so it was decided that the role of the sensors will be fulfilled by type T class 1 thermocouples supplied by the company Termoaparatura Wrocław.

The block diagram of the created research bench is shown in Figure 1 [1].

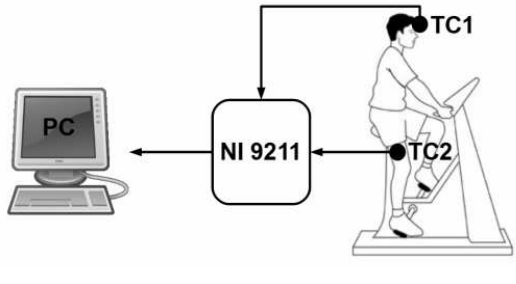

Fig. 1. The block diagram of the system for the measurement of temperature during an endurance test: TC1, TC2 – thermocouples type T [1]

To acquire measurement signals the 24-bit NI 9211 module, which allows simultaneous measurement from two sensors at a maximum frequency of 7 Hz, was used.

The main component of the constructed system is a designed specialized application that enables measurement, recording, visualization and data archiving.

3. ESTIMATING THE TEMPERATURE UNCERTINTY OF THE SYSTEM FOR ENDURANCE TEST

The paper presents methodology for estimating uncertainty of temperature measurement during an endurance test.

Estimating the uncertainty of the system used to measure the dynamic of temperature changes was carried out based on the guidelines set out in the GUM guide [8, 9]. The analysis was performed for a single measurement channel.

The function of the temperature measurement error $e(T)$ is as follows:

$$e(T) = \Delta T_s + \Delta T_k + \Delta T_c + \Delta T_{DAQ} \tag{1}$$

where:
ΔT_s - random error of temperature measurement,
ΔT_k - temperature calibrator limiting error,
ΔT_c - type T temperature sensor limiting error, specified by the manufacturer,
ΔT_{DAQ} - measurement signals acquisition card limiting error, defined in the device specification.

The uncertainty of temperature measurement, assuming no correlation between the uncertainties of the measured values, is defined by the formula [8, 9, 10]:

$$u(T) = \sqrt{u^2(\Delta T_s) + u^2(\Delta T_k) + u^2(\Delta T_c) + u^2(\Delta T_{DAQ})}. \tag{2}$$

Thus, in order to determine the uncertainty of the temperature measurement $u(T)$ one should take into account the variance resulting from the random error $u^2(\Delta T_s)$, temperature calibrator limiting error $u^2(\Delta T_k)$, the used sensor limiting error $u^2(\Delta T_c)$ and the variance resulting from the limiting error of the data acquisition system $u^2(\Delta T_{DAQ})$.

The value $u^2(\Delta T_s)$ was determined as the Type A variance, while the remaining components of the uncertainty $u(T)$ were determined as Type B variance, based on data provided by the manufacturer in specifications of: the temperature calibrator, the sensor and the acquisition card.

It is assumed that the best measurand estimate is the arithmetic mean value.

3.1. The uncertainty component – estimated by Type A method

In this article, the Type A uncertainty was designated the variation of temperature measurements results around the arithmetic mean value. To this aim, 4200 temperature measurements were made using a sensor placed in a temperature calibrator in which a temperature of 34.5°C was set.

Type A uncertainty was determined on the basis of the relationship:

$$u_A(T) = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(T_i - \overline{T})^2} \tag{3}$$

where:
$u_A(T)$ - temperature measurement uncertainty determined by Type A method,
n - number of temperature measurements,
T_i - the measured temperature value for i =1, 2, …n,
$\overline{T}$ - temperature arithmetic mean value.

The uncertainty value $u_A(T)$ is closely related to the variance $u^2(\Delta T_s)$ resulting from a random temperature measurement.

As a result of the conducted calculations, the following Type A uncertainty value has been achieved:

$$u(\Delta T_s) = 0.25 \cdot 10^{-3}°\text{C}.$$

3.2. The uncertainty component – estimated by Type B method

Variance $u^2(\Delta T_k)$ was determined assuming a rectangular distribution of the temperature calibrator probability limiting error ΔT_k, according to the following formula:

$$u^2(\Delta T_k) = \left(\frac{\Delta T_k}{\sqrt{3}}\right)^2. \tag{4}$$

The value of the limiting error ΔT_k was adopted on the basis of the manufacturer catalogue data [11], which shows that the error is:

$$\Delta T_c = \pm 0.5°\text{C}. \tag{5}$$

Variance $u^2(\Delta T_c)$ was determined assuming a triangular distribution of the error ΔT_c probability. In order to avoid this error, an analysis of the mathematical model of the probability distribution of observations was performed. On this basis, histograms of obtained results from measurements samples were created using 12 classes grouping (according to the Sturges formula) in order to verify the adopted hypothesis of the probability distribution.

Figure 2 presents the histogram of obtained measurement results.

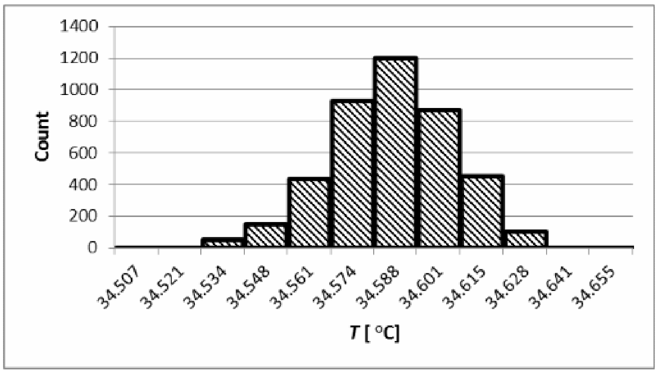

Fig. 2. Histogram obtained from measuring the temperature in the temperature calibrator

It was concluded from the shape of the histogram that there is a possibility of acceptance a model triangle distribution.

Therefore, the variance $u^2(\Delta T_c)$ was determined according to the following relation:

$$u^2(\Delta T_c) = \left(\frac{\Delta T_c}{\sqrt{6}}\right)^2 . \quad (6)$$

The limiting error δT_c value was adopted according to the PN-EN 60584-2 [12] norm, in which the manufacturing tolerance of type T class 1 thermocouple is:

$$\Delta T_c = \pm\ 0.5°C\ . \quad (7)$$

Whereas the variance $u^2(\Delta T_{DAQ})$ was calculated, assuming a rectangular probability distribution of ΔT_{DAQ} error according to the following formula:

$$u^2(\Delta T_{DAQ}) = \left(\frac{\Delta T_{DAQ}}{\sqrt{3}}\right)^2 . \quad (8)$$

The data contained in the catalogue of the NI 9211 acquisition module [13] shows that when measured using a type T thermocouple, the limiting error is:

$$\Delta T_{DAQ} = \pm\, 0.05°C\, . \quad (9)$$

On the basis of the conducted analysis it can be concluded that the estimated Type B uncertainty for the researched measuring system is 0.22°C.

3.3. Combined uncertainty

Combined standard uncertainty of the temperature measurement $u(T)$ was determined in accordance with relation (2) and for the analysed data is:

$$u(T) = 0.23°C\, . \quad (10)$$

3.4. Expanded uncertainty

The expanded uncertainty of temperature measurement $U(T)$, for the coverage factor $k = 2$ (which corresponds approximately to the coverage probability of 95%) [8], is:

$$U(T) = 2u(T) = 0.46°C\, . \quad (11)$$

The 34.57ºC temperature estimate uncertainty budget, determined on the basis of the results obtained during testing of the system for an endurance test is given in Table 1.

Table 1. The 34.57ºC temperature estimate uncertainty budget

Share in the complex variance $u^2_n(y)$	Sensitivity coefficient c_n	Probability distribution	Standard variance $u^2(x_n)$	Estimate of x_n quantity	Quantity X_n
-	-	-	-	34.57ºC	$\overline{T}$
62.50E-9ºC²	1.00ºC/ºC	normal	62.50E-9ºC²	0.00ºC	ΔT_s
8.33E-3ºC²	1.00ºC/ºC	rectangular	8.33E-3ºC²	0.00ºC	ΔT_k
0.04ºC²	1.00ºC/ºC	triangular	0.04ºC²	0.00ºC	ΔT_c
0.83E-3ºC²	1.00ºC/ºC	rectangular	0.83E-3ºC²	0.00ºC	ΔT_{DAQ}
0.23ºC	Standard uncertainty $u(T)$				
0.46ºC	Expanded uncertainty $U(T)$				

According to the above estimates of the uncertainty, the results of temperature measurement can be written as:

$$T = (34.57 \pm 0.44)°C.$$

4. VERIFICATION OF THE RESULTS BY MONTE CARLO METHOD

In order to compare the above results of the expanded temperature measurement uncertainty with the result obtained with Monte Carlo method [14] (for the same parameters analysed) – Table 2 shows values of these uncertainties. Estimating the temperature measurement uncertainty using the Monte Carlo method was performed in Mircosoft Excel for sample number M equal to 10^4. The expanded measurement uncertainty has been determined for the coverage factor $k = 2$, assuming the coverage probability $p = 95\%$.

Table 2. The 34.57ºC temperature estimate uncertainty budget obtained with Monte Carlo method

Quantity X_n	Estimate of x_n quantity	Standard variance $u^2(x_n)$	Probability distribution	Sensitivity coefficient c_n	Share in the complex variance $u^2_n(y)$
$\overline{T}$	34.57ºC	-	-	-	-
ΔT_s	0.00ºC	8.62E-8ºC²	normal	1.00ºC/ºC	8.62E-8ºC²
ΔT_c	0.00ºC	41.66E-3ºC²	triangular	1.00ºC/ºC	41.66E-3ºC²
ΔT_{DAQ}	0.00ºC	0.83E-3ºC²	rectangular	1.00ºC/ºC	0.83E-3ºC²
			Standard uncertainty $u(T)$		0.20ºC
			Expanded uncertainty $U(T)$		0.40ºC

Table 3. The 34.57°C temperature estimate expanded uncertainty

Estimate for the measured value of 34.57ºC	
Method 1	**(34.57±0.44)ºC**
Method 2	**(34.57±0.40)ºC**

Comparing the results of the estimated expanded uncertainty $U(T)$ (Table 3) one can see, that these results vary slightly among themselves, and that in the analysed case the value of the expanded uncertainty determined using the traditional method (under the law of uncertainty propagation) is greater than the value calculated using the Monte Carlo simulation. In both cases, the relative uncertainty of the temperature measurement is a maximum of 1.5%.

5. SUMMARY

The article presents the problem of temperature measurement uncertainty estimation of the system used for endurance tests. In order to determine the temperature measurement uncertainty, the authors presented the methodology of proceedings, which took into account both Type A uncertainty resulting from the random error and Type B uncertainty dependent on the limiting error of the used measurement sensor as well as the limiting error of the data acquisition system. Verification of the temperature measurement uncertainty results was made using the Monte Carlo method.

The results of the obtained analyses allow to determine which temperature measurement uncertainty can be expected when making measurements with the designed system.

For the case considered in the article, the relative temperature measurement uncertainty does not exceed 1.5%.

According to the authors, the processing uncertainty value for temperature sensors calculated on the basis of the developed methodology, confirms the legitimacy of their legitimacy for their application in measurements of dynamic temperature changes during the endurance test.

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METODOLOGIA SZACOWANIA NIEPEWNOŚCI POMIARU TEMPERATURY W SYSTEMIE PRZEZNACZONYM DO PRÓB WYSIŁKOWYCH

Zespół, składający się z autorów artykułu, opracował bezinwazyjną metodę pomiaru temperatury oraz system do jej pomiaru podczas próby wysiłkowej. Próbę wysiłkową przeprowadza się w celu uzyskania dokładnej oceny wydolności fizycznej u sportowców, ale także u pacjentów z chorobami kardiologicznymi czy pulmonologicznymi.

Zbudowany, przez autorów referatu, system pomiarowy składa się z: dwóch czujników termoelektrycznych, 24-bitowej karty pomiarowej NI 9211 oraz autorskiej, specjalizowanej aplikacji uruchomionej na komputerze osobistym. Przewidywany zakres zmian badanego obiektu, czyli temperatury skóry człowieka wynosi od 32°C do 41°C, dlatego zdecydowano, że rolę czujników będą pełniły termoelementy typu T klasy 1. Pomiar realizowany był jednocześnie z dwóch czujników umieszczonych w różnych punktach ciała badanych osób, z częstotliwością próbkowania 7 Hz.

W referacie zaprezentowano metodologię szacowania niepewności pomiaru temperatury systemem pomiarowym, przy zastosowaniu metody opartej na przewodniku GUM oraz porównano uzyskane wyniki z danymi uzyskanymi przy wykorzystaniu metody Monte Carlo.

Wyniki uzyskanych analiz pozwalają określić, jakiej niepewności pomiaru temperatury można się spodziewać dokonując pomiarów zaprojektowanym systemem. Dla rozpatrywanego w artykule przypadku niepewność względna pomiaru temperatury, nie przekracza 1,5%.

Obliczona, na podstawie opracowanej metodologii, wartość niepewności pomiaru temperatury w systemie do prób wysiłkowych, zdaniem autorów, potwierdza zasadność jego stosowania do celów tego typu pomiarów dynamicznych.

Słowa kluczowe: pomiar temperatury, niepewność pomiaru, CPET.