CITLIVOSTNÍ STUDIE TERMOFYZIOLOGICKÉHO MODELU ZALOŽENÉM NA FIALOVĚ PŘÍSTUPU

SENSITIVITY STUDY OF FIALA-BASED HUMAN THERMOPHYSIOLOGICAL MODEL

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Abstrakt

Použití ochranných obleků při práci v náročných podmínkách zvyšuje tepelný stres člověka, což může mít v určité míře špatný vliv na fyziologický stav jedince. K vyhodnocení tepelného stresu člověka byly vyvinuty tepelné indexy a termofyziologické modely, jako například FMTK model (model lidské termofyziologie založený na Fialově přístupu). Tento model byl prvotně vytvořen pouze pro průměrného člověka, což může způsobovat problém pro predikci fyziologického chování lidí, kteří do této definice nezapadají. V tomto příspěvku je provedena citlivostní studie FMTK modelu pro různé hmotnosti a s tím související různé hodnoty tělesného tuku a plochy pokožky jedinců. Výsledky jsou porovnány s predikovanými hodnotami pro průměrného člověka a je provedena studie smysluplnosti individualizace pro různé teploty okolního prostředí.

Klíčová slova: *termofyziologický model, tepelný stres, citlivostní studie*

Abstract

The use of protective clothing under extreme conditions leads to heat stress with undesired consequences on human physiology. For this purpose, the thermal indices and the thermophysiological models have been developed, like for example Fiala-based thermophysiological model, called FMTK. In terms of anthropometry and physiology, the model was originally developed for an average man, which can lead to problems with the prediction of heat stress for people who do not meet this definition. This article deals with the sensitivity study of FMTK model to weight, body fat content, and skin area. Results are compared with predicted values for averaged man and the relevance study of individualization for different ambient temperatures is presented.

Key words: *thermophysiological model, heat stress, sensitivity study*

1. INTRODUCTION

Even today, when automation and robotics affect almost all human activities, areas where the machine cannot completely replace humans remain. In the majority of such cases, humans are

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exposed to the extreme and dangerous conditions, which may adversely affect human health. Often it is necessary to use protective clothing in these cases, which protect human against these extreme conditions but on the other hand, the use of protective clothing increases heat stress of human, which can lead to the negative influence on his physiology. For predicting physiological responses of the human body, the indices of thermal stress and physiological models have been developed [1].

However, the variability of human body reaction to the same thermal stress is a general problem of physiological models' prediction. A lot of these models were primarily created for an average person (73.5 kg, skin area 1.86 m^2, 14.4 % of body fat [2]), which can be a problem for prediction of the physiological behaviour of people who do not meet a definition of a typical person. For this reason, approximately since the 1990s, scientists have been studying individualization of the physiological models. A lot of authors published articles in this context, for example, Havenith [3], who developed the individualized physiological model based on the model described by Lotens [4]. In this study, Havenith extended model inputs by individual anthropometric data (weight, body fat, body area), by the value of $\dot{V}_{O2max}$ and by acclimatization data.

Zhang et al. [5] developed a model which translates descriptive data about an individual (height, weight, gender, body fat, skin colour and others) into a set of physiological parameters which can be used in thermal models. These parameters were incorporated into a model of human thermoregulation by the *body builder* module. Van Marken Lichtenbelt et al. [6] introduced a multi-segmental mathematical model of the human thermoregulation, which was tested for its capability to predict individualized human responses. In this article, there was incorporated body composition data into the model, the value of resting metabolic rate and the actual measured metabolic rate during the tests which were realized for mild cold conditions. Another study by Takada et al. [7] is focused on identifying the coefficients that represent the thermoregulatory responses in the two-node model for individuals. In this article six coefficients related to the regulation of the sweating and skin blood flow are determined by the experiments turned for the individuals. Some models are also focused on the influence of different ethnicity on the human thermoregulation, for example, Zhou et al. [8] created a model for prediction of skin temperature for Chinese adults.

Fiala based thermophysiological model FMTK (as a direct translation from Czech language - Physiological Model of Thermal Comfort) [9] was developed at the Department of Thermodynamics and Environmental Engineering and was verifying for a wide range of ambient temperature and used for testing of protective and military clothing, such as Tychem-F and FOP M2000, see [9].

The aim of this study is to build the individualized model of the passive system and to employ FMTK for prediction of thermophysiological responses of four different individual persons, see *Table 1*. Afterward, there is presented the relevance study of model individualization for different ambient temperatures.

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2. METHODS

As mentioned above this article is focused on the individualization of FMTK model [9], which was validated for ambient temperatures from 5 °C to 48 °C and metabolic rates from 0.8 met to 9 met. Simultaneously the model was applicated for prediction of human thermal stress in protective clothing, where the error of prediction of the mean skin temperature was 0.78 °C, the error of rectal temperature 0.2 °C.

In order to be able to enter individual characteristics as input into the model, the module named "Bodybuilder" was created. Due to the incorporation of this module to the passive system of the FMTK model, the individual anthropometric data (mass, skin area, body fat) can be considered in the prediction of the physiological response of the human body. In *Table 1* the anthropometric data for four individual people (average, lean, thin muscular, fat person) are described. These four different settings of the human body are used for prediction of the human thermal stress in protective clothing at different ambient temperatures.

Table 1: Individual characteristics of four different individual persons

Type	Mass [kg]	Skin area [m^2]	Body fat [%]
Average person	73.5	1.86	14.4
Lean person	68.4	1.78	14
Fat person	86.3	2.04	26.7
Thin muscular person	69.3	1.78	9.4

2.1 Simulated scenarios

Four types of ensembles were simulated as follows: Shorts, Klimatex underwear, military NBC suit FOP M2000 (FOP) and chemical-protective clothing Tychem-F (during preconditioning only shorts), for exact clothing parameters see [9]. The range of temperature for cold tests was from 10 °C to 15 °C and for neutral and hot conditions all tests was from 25 °C to 40 °C. The time of every test was from 55 to 300 min, see *Table 2*.

Table 2: Test scenarios

Scenario	Number of tests	Ambient and radiant temperature $T_a = T_r$ [°C]	Metabolic production M [met]	time t [min]
Shorts	2	10, 15	0.8, 0.9	150, 300
Klimatex underwear	4	25, 30, 35, 40	3.2	125, 95, 95, 65
FOP	2	35, 40	3.7	83, 125
Tychem-F	3	30, 35, 40	4.3	75, 60, 55

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The test procedure had the following steps. For cold conditions, preconditioned phase took 25 minutes in ambient temperature 30 °C and activity level 0.8, respectively 60 minutes in 20 °C and 1.5 met. For neutral and hot conditions, firstly, the preconditioned phase was 10 minutes at the room temperature 23 °C and only shorts were dressed up, followed by the entry into the climate chamber and 5 min rest, then the test procedure started: 20 min exercise and then 5 min rest. Metabolic activity during the whole tests is described in *Figure 1, 2*. Detailed settings of each study are listed in [9].

Figure 1: Metabolic activity during the cold tests

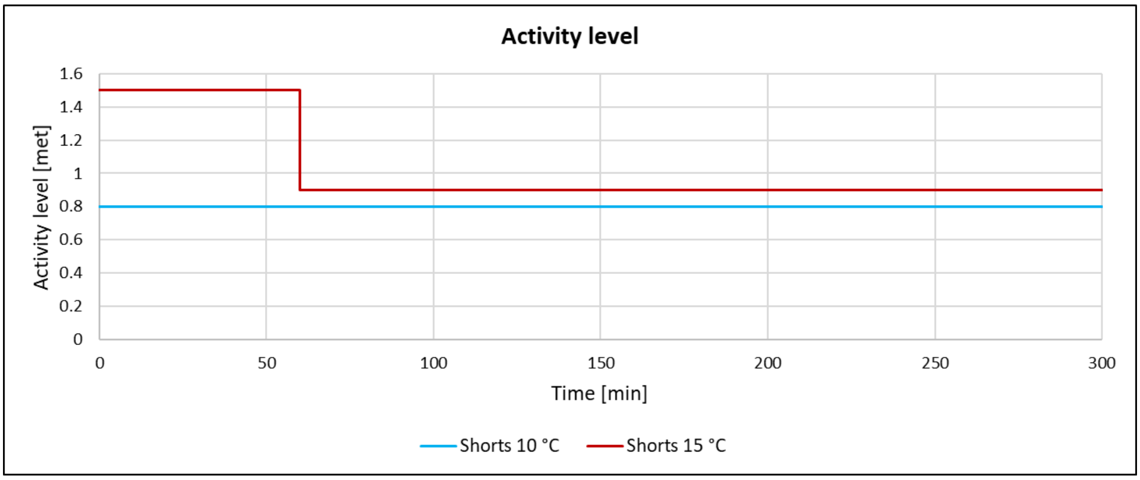
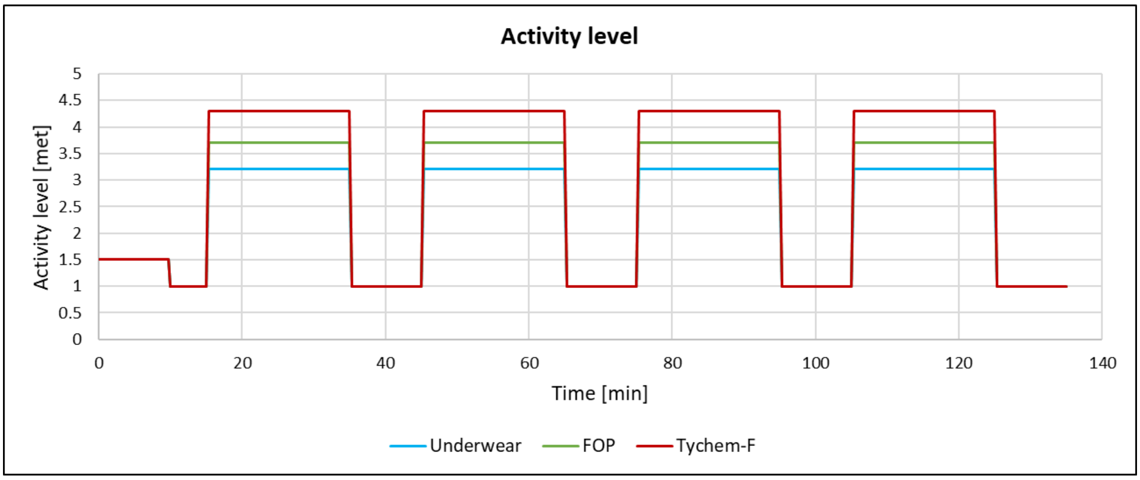


Figure 2: Metabolic activity during the neutral and hot tests



2.2 Statistical testing

The relevance study of individualization for different ambient temperatures is performed by statistical testing. Statistical significance of individual setting of the human body was tested using Kruskal-Wallis statistic test, carried out in the program MINITAB. The test was selected

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because each scenario was performed under dynamic conditions. Unlike parametric tests, the K-W test does not require normal distribution as a prerequisite, which is very difficult to meet in dynamic conditions.

As a null hypothesis is used the assumption that there are no differences between predicted temperatures for each case. The value of significance level α is set as 0.05 and results are evaluated from p-value for each test.

3. RESULTS

Results are presented separately for each individual clothing set. Following graphs show results for individual scenarios (clothing and ambient temperature). But, it is necessary to consider that it was assumed that the thermoregulatory system works for all simulated people in the same way.

3.1 Shorts

The graphs in *Figure 3* represent the results of the simulated case with Shorts for temperatures of 10 °C and 15 °C. It is possible to see, that fat person in comparison to the other simulated body composition (average, lean, thin muscular) has a higher temperature of the hypothalamus and lower mean skin temperature.

Table 3: p – values for individual cold cases and settings of the human body

	Temperature of the hypothalamus			Mean skin temperature		
	F vs. A	L vs. A	M vs. A	F vs. A	L vs. A	M vs. A
Case 10 °C	p = 0	p =0	p = 0	p = 0	p = 0.382	p = 0
Case 15 °C	p = 0	p =0	p = 0	p = 0	p = 0.413	p = 0

Statistical testing using the nonparametric Kruskal-Wallis test demonstrated that for the prediction of the temperature of the hypothalamus the differences between all three simulated persons (fat (F), lean (L), thin muscular (M)) and average (A) person are statistically significant for both ambient temperatures 10 °C and 15 °C (p – values are lower than 0.05), see *Table 3*. For prediction of the mean skin temperature of both cases the differences are statistically significant except the differences between Lean person and Average person (p – value = 0.382 and 0.413), where it is possible to see, that mean skin temperature has practically the same values for both settings of the human body.

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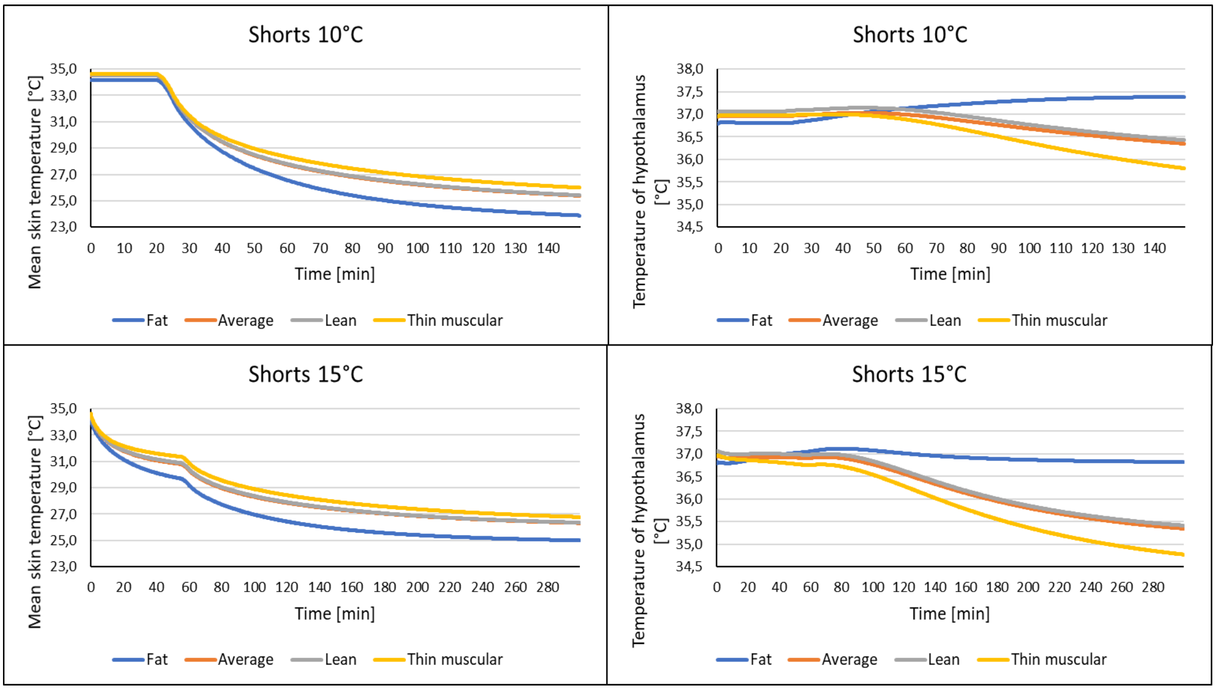
Figure 3: Simulated mean skin temperature and temperature of the hypothalamus (shorts)



3.2 Klimatex underwear

The graphs in *Figure 4* represent the results of the simulated case with Underwear for temperatures of 25 °C, 30 °C, 35 °C and 40 °C. It is possible to see, that with increasing ambient temperature the fat person has the lower temperature of the hypothalamus in comparison to the other simulated body composition (average, thin, thin muscular). The mean skin temperature of the fat person is lower than for others typified persons for all ambient temperatures.

Table 4: p – values for individual Klimatex cases and settings of the human body

	Temperature of the hypothalamus			Mean skin temperature		
	F vs. A	L vs. A	M vs. A	F vs. A	L vs. A	M vs. A
Underwear 25 °C	p = 0.596	p = 0	p = 0	p = 0	p = 0	p = 0
Underwear 30 °C	p = 0	p = 0	p = 0.406	p = 0	p = 0	p = 0
Underwear 35 °C	p = 0	p = 0	p = 0.872	p = 0	p = 0	p = 0
Underwear 40 °C	p = 0	p = 0	p = 0.763	p = 0	p = 0	p = 0

Statistical testing using the nonparametric Kruskal-Wallis test demonstrated that for the prediction of the temperature of the hypothalamus for case Underwear 25 °C the differences between fat and average person are statistically insignificant, statistically significant become with increasing ambient temperature, where as mentioned temperature of the hypothalamus of the fat person is lower in comparison to other simulated persons. From p-values can be seen

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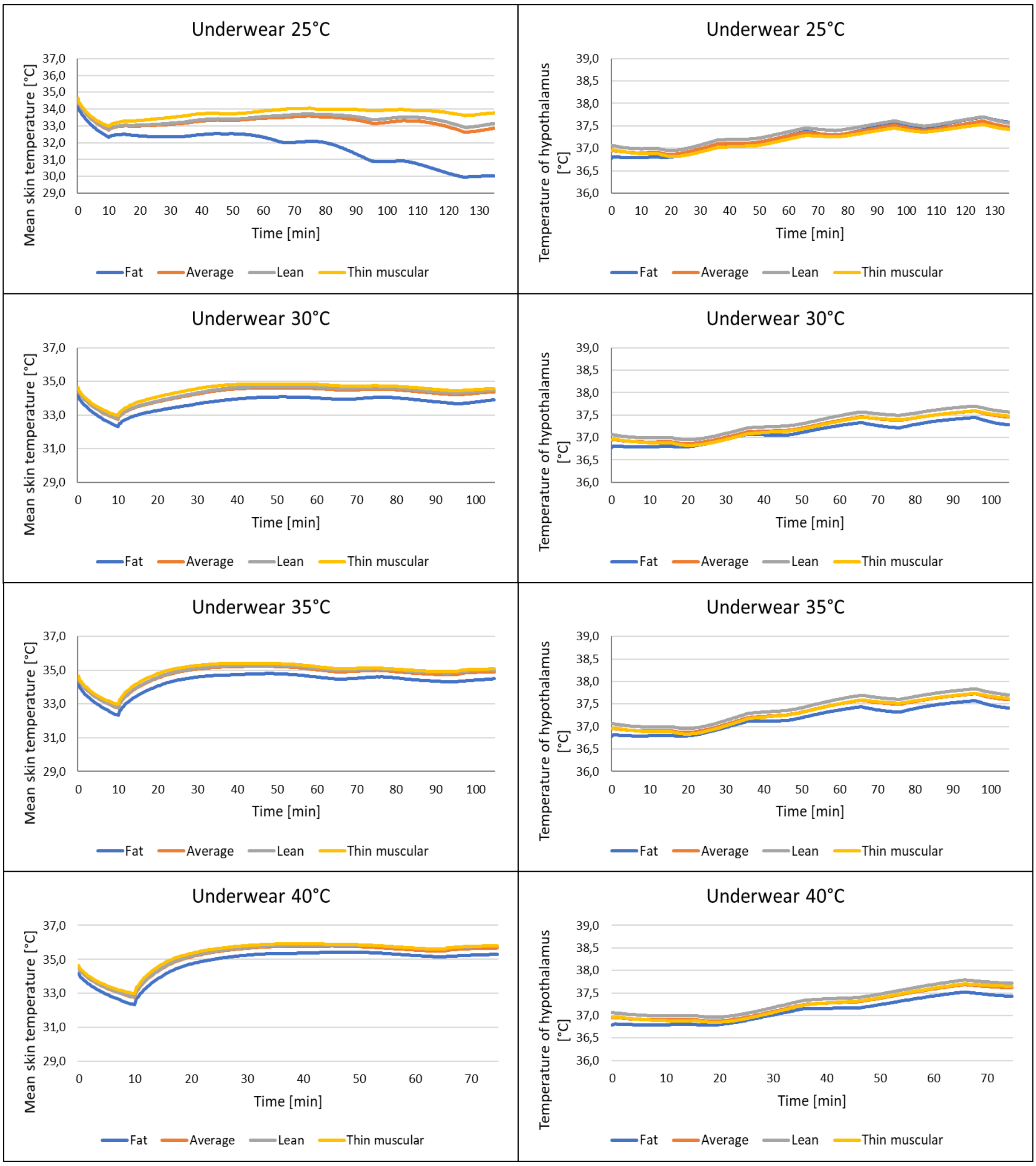
that there is practically no difference between prediction of the temperature of the hypothalamus between muscular and average person for higher ambient temperatures. Differences for other comparisons appear to be statistically significant (p – value = 0 < 0.05). The same applies to the differences between the prediction of the mean skin temperature for all simulated persons during the different ambient conditions, for all cases the p – value was equal to zero.

Figure 4: Simulated mean skin temperature and temperature of hypothalamus (underwear)



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3.3 Tychem-F

The graphs in *Figure 5* represent the results of the simulated case with Tychem-F for temperatures of 30 °C, 35 °C and 40 °C. It is interesting to see that temperature of the hypothalamus of the fat person is still lower in comparison to other persons even in such hot conditions of 40 °C, the same goes for the mean skin temperature.

Table 5: p – values for individual Tychem – F cases and settings of the human body

	Temperature of the hypothalamus			Mean skin temperature		
	F vs. A	L vs. A	M vs. A	F vs. A	L vs. A	M vs. A
Tychem - F 30 °C	p = 0	p =0.001	p = 0.757	p = 0	p = 0.227	p = 0.059
Tychem - F 35 °C	p = 0	p =0	p = 0.903	p = 0.001	p = 0.359	p = 0.131
Tychem - F 40 °C	p = 0	p =0.001	p = 0.907	p = 0.004	p = 0.348	p = 0.234

Table 5 is possible to see, that with increasing ambient temperature the differences between the prediction of the mean skin temperature for comparison between lean and average, resp. muscular and average human become insignificant. In terms of the temperature of the hypothalamus differences between muscular and average human are insignificant (p – value > 0 for all ambient temperatures), but the other differences stay significant.

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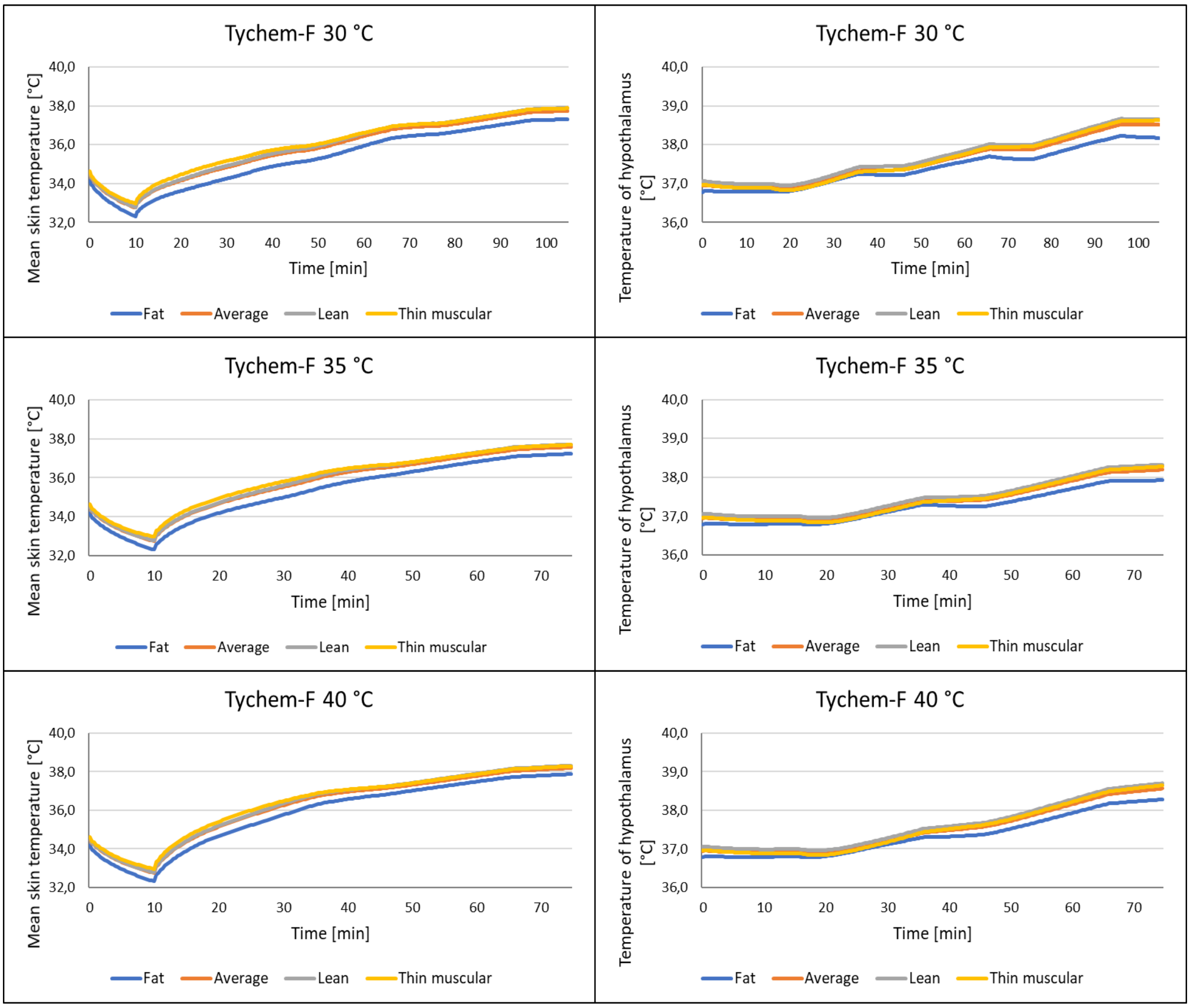
Figure 5: Simulated mean skin temperature and temperature of the hypothalamus (Tychem-F)



3.4 FOP M2000

The graphs in *Figure 6* represent the results of the simulated case with FOP for temperatures of 35 °C and 40 °C. Again it could be observed similar behaviour as before cases in protective clothing Tychem – F. The predicted temperature of the hypothalamus and mean skin temperature of the fat person is still lower in comparison to the other typified persons. Results of the statistical tests are similar to the previous one with simulations in protective clothing Tychem – F.

Table 6: p – values for individual FOP cases and settings of the human body

	Temperature of the hypothalamus			Mean skin temperature		
	F vs. A	L vs. A	M vs. A	F vs. A	L vs. A	M vs. A
FOP 35 °C	p = 0	p =0.005	p = 0.498	p = 0	p = 0.144	p = 0.098
FOP 40 °C	p = 0	p =0.009	p = 0.526	p = 0	p = 0.167	p = 0.166

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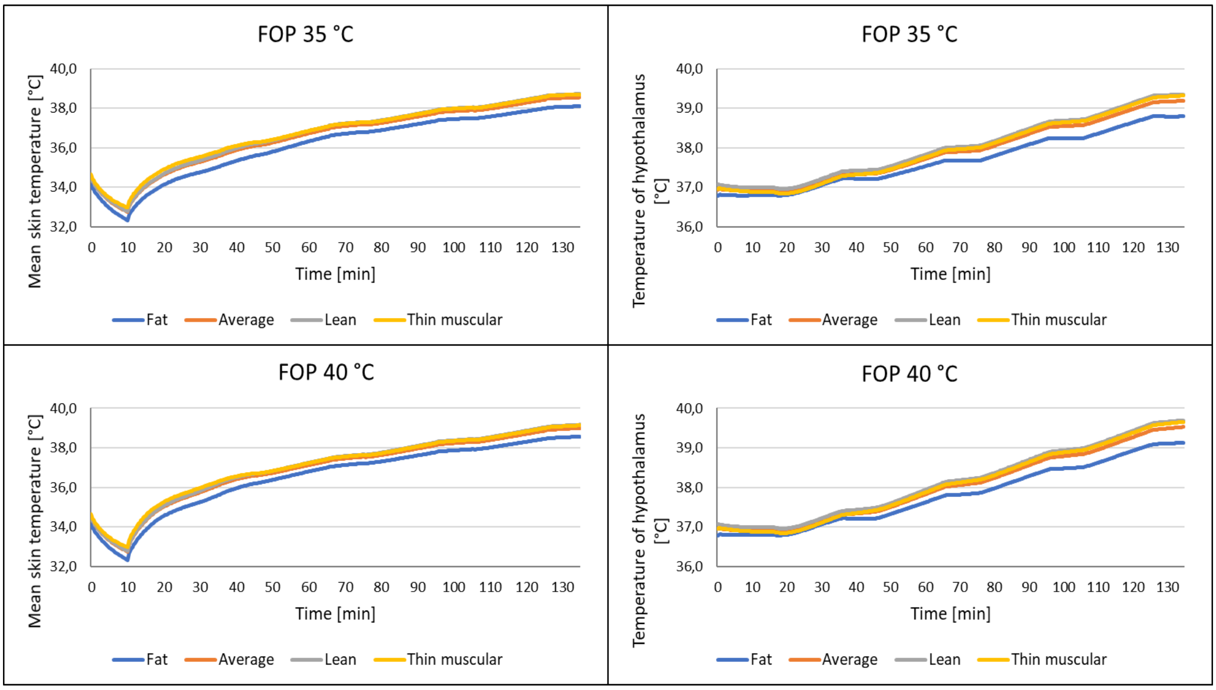
Figure 6: Simulated mean skin temperature and temperature of the hypothalamus (FOP)



4. DISCUSSION

The results showed that fat person in comparison for example to the average person is much more resistant to the cold conditions (higher temperature of the hypothalamus) due to the higher percent of the body fat that acts as an insulation in these conditions. This thermal behaviour is mainly visible in lower ambient temperatures, such as simulated cases in 10 °C and 15 °C.

With increasing ambient temperature, the differences between the prediction of the temperature of the hypothalamus for every simulated person are not too pronounced, but for comparison between fat and average person are still statistically significant. The decreasing of differences between predicted value of temperature of the hypothalamus for fat an average person is caused by the fact, that skin blood flow in cold conditions is not too strong to offset the resistance by peripheral adipose tissue, unlike in warm conditions when it already has enough strength to overcome this insulation caused by fat layer. Similar behaviour is already mentioned in the article [10].

For neutral and hot conditions is possible to observe that fat person has the lower temperature of the hypothalamus in comparison to the other simulated persons. This behaviour is more expressive in cases with protective clothing. Hypothetically it means that fat person is possible to stay in these extreme conditions and in protective clothing for the longer time than for example average person. But it could be explained by the fact, that for simulations there was used the same metabolic rates for every simulated person, but in reality, when for example fat person and average person perform the same activity, the fat person has higher production of the metabolic rate in comparison to the average person. Because of it, when it is used the same

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metabolic rate for fat and the average person the same heat is generated but the fat person has the larger amount of body tissue and because of it, he heats up slowly [10].

Similar behaviour is possible to see in the prediction of the mean skin temperature, where the differences between fat and average person are decreasing from increasing temperature. However, in this case, the results from statistical tests show, that these differences are still statistically significant (p-value < 0.05). As an explanation for this phenomenon appears to be a larger skin area of the fat person against average person, which can cause the lower mean skin temperature of the fat person.

Thanks to these results it is possible to say, that above-described individualization of the model for prediction thermophysiological behaviour is meaningful rather for lower ambient temperatures than for higher temperatures, where results for predictive temperatures are almost the same and the presence of the body fat layer is not too significant. Nevertheless, in this article only passive system was individualized mainly through the percentage of body fat and furthermore the same value of the metabolic rate was used as boundary conditions for individual typified persons, because of it, it is necessary to pay attention to the individualization of the active system in order to take into account, for example, physical condition or acclimatization which affect the thermophysiological behaviour of every human.

5. CONCLUSION

This article shows the preliminary results of the ongoing study related to the individualization of FMTK model. In the first step, some anthropometric characteristics of person were individualized by the created module called “Bodybuilder”. Results show that the upgraded model reacts to the individualized inputs. The sensitivity study shows that differences between predictions of temperatures (mean skin temperature, the temperature of the hypothalamus) for each individual setting of the human body are more significant in case of lower ambient temperatures. Furthermore, the results show the need to enter the different values of the metabolic rates as boundary conditions for individual typified persons, because of the different heat production at the same activities. The study will continue by improving the “Bodybuilder” and incorporation of individual characteristics into the active system of FMTK model.

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