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Thermal Resistance of Clothing in Human Biometeorological Models

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Abstract

Three different clothing thermal resistance (r_{cl}) schemes are compared using meteorological and human data collected in Martonvásár. Model 1 is the most complex, it is energy balance based. Model 3 is the simplest, it is the UTCI-clothing model used as submodel in the UTCI (Universal Thermal Climate Index) scheme. It uses air temperature as sole input. Model 2 uses more data than model 3, the data used are the thermal insulation values of the clothing worn. Meteorological data refer to the town Martonvásár. The data were collected in the period August 9, 2016 – May 23, 2018. The main result is that the r_{cl} values obtained by model 1 differ significantly in most of the cases from the results obtained by models 3 or 2. The fact that the results of model 1 rarely match the results of model 3 or model 2 suggests that the energy balance between human body and environment is rarely achieved, merely this is the case in approximately 10 percent of the cases.

Keywords: clothing thermal resistance; energy balance of the human body; clothing ensemble; air temperature; environmental heat deficite; metabolic heat flux density

Introduction

In our day and age, mainly models based on energy balance are used in the human biometeorological investigations (Potchter et al., 2018). It should be emphasized that the human factor can be fully taken into account only in these models. The human factor refers to the activities of people and the clothing they wear. Both factors are decisive in terms of human thermal load and sensation.

Clothing exerts its thermal effect mainly through its thermal insulation. The thermal insulation of clothing (r_{cl}) is mostly an unknown parameter and it varies highly from person to person. It can be both an input and output variable of the energy-balance-based biometeorological models. It is used as an input variable in the vast majority of models, such as in the most commonly used PMV (Predicted Mean Vote), (Fanger, 1970), PET (Physiologically Equivalent Temperature), (Höppe, 1999), or UTCI (Universal Thermal Climate Index), (Fiala et al., 2012) models. In these models, r_{cl} is either constant (e.g. Höppe, 1999) or can be estimated in a very simple way by parametrization (Havenith et al., 2012; Olesen, 1985). In these cases, the personal variability of r_{cl} is not taken into account at all, although this variability can be very large. There are also models (e.g. Auliciems & de Freitas, 1976; Auliciems & Kalma, 1979; Yan, 2005; Yan & Oliver, 1996), in which r_{cl} is an output variable. In these models, r_{cl} is determined on the basis of energy balance of the clothed human body-environment system. These models are a lot less often used compared to the ones, in which r_{cl} is used as input variable.

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As we mentioned, the thermal effect of the individual differences between human characteristics can only be taken into account in models based on energy balance (de Freitas & Grigorieva, 2015). In these models, a person is characterized by his/her activity-related metabolic heat flux density (M), clothing, and thermal sensation. The last factor is the most complex phenomenon, it can only be estimated by asking people; the pioneering work of Fanger (1970, 1973) should be highlighted in this regard, which determined the development of the entire profession. The methodology for estimating M has also improved a lot, among these works we would highlight Weyand et al. (2010), in which M is parameterized for individuals walking at different speed. Clothing is at least as much a variable and individual factor as the previous two due to its thermal insulation. The thermal insulation of clothing can only be accurately determined by measurement. These measurements are time consuming, expensive and individual measurements have no sense due to high interperson variability. Therefore r_{cl} is commonly determined by parameterizations. It is clear that r_{cl} values determined by parameterizations and on the basis of the energy balance of the human body-environment system don't necessarily have to agree. To our knowledge there is no work yet dealing with the comparison of r_{cl} values obtained using different methods.

Based on the aforementioned, the aim of this work is 1) to compare three r_{cl} calculation methods and 2) to test the sensitivity of the energy-balance-based method to variations of wind speed and M. In the following, model 1 is the energy-balance-based method; model 2 is the clothing ensemble model of Olesen (1985), which can be viewed as the most empirical; and model 3 is the wellknown UTCI-clothing model (Havenith et al., 2012). After the presentation of the methods follows a detailed description of the data collected, which is then followed by the presentation and discussion of the results. Eventually, the most important conclusions are drawn at the end.

Clothing thermal resistance models

The basic equations of the models are as follows.

Model 1: Thermal resistance of clothing can be estimated from the energy balance equation of the human body-clothing-environment system (Ács et al., 2021). It can be expressed as follows,

$$r_{cl} = \rho \cdot c_p \cdot \frac{T_S - T_a}{M - \lambda E_{sd} - \lambda E_r - W} - r_{Hr} \cdot \left[\frac{R_{ni}}{M - \lambda E_{sd} - \lambda E_r - W} + 1 \right],$$

where ρ is air density [kgm^{-3}], c_p is specific heat at constant pressure [Jkg^{-1} °C^{-1}], T_a is air temperature [°C], T_S is skin temperature [°C] (a constant, 34 °C), r_{Hr} is the combined resistance for expressing thermal radiative and convective heat exchanges [sm^{-1}], R_{ni} is the isothermal net radiation flux density [Wm^{-2}], M is the metabolic heat flux density [Wm^{-2}], λE_{sd} is the latent heat flux density of dry skin [Wm^{-2}], λE_r is the respiratory latent heat flux density [Wm^{-2}] and W is the mechanical work flux density [Wm^{-2}] referring to each activity, in this case walking. In our model applications, the walking speed is 1.1 ms^{-1}.

The parameterization of environmental and human factors is described in the work of Ács et al. (2019, 2021). The human body is considered as a single node and since T_S is an input variable and r_{cl} is an output variable, this model is the inverse of the common energy-balance-based models (e.g. Fanger, 1970, 1973).

Model 2: Thermal resistance of clothing can also be estimated on the basis of thermal insulation of the garments (Olesen, 1985) that make up the clothing. The expression is as follows,

$$r_{cl} = \sum_{i=1}^{n} r_{cl,i},$$

where r_{cl} is the resulting thermal insulation of total clothes worn, $r_{cl,i}$ is the thermal insulation of the i^{th} garment and i is the number of garments. The r_{cl} value obtained this way can be used as input variable in each model, where T_S is an output variable. The model can be called as clothing ensemble model.

Model 3: Thermal resistance of clothing is estimated in the UTCI model as follows,

$$r_{cl} = 1.372 - 0.01866 \cdot T_a - 0{,}0004849 \cdot T_a^2 - 0.000009333 \cdot T_a^3,$$

where T_a is the air temperature. The model can be referred to as the UTCI-clothing model (Havenith et al., 2012).

Data

Atmospheric and human data are used. They are collected in Martonvásár (geographical latitude 47.31 ^{0}N, geographical longitude 18.79 ^{0}E), more precisely, during running events at the running track surrounding the soccer field in Martonvásár.

occasions. In other occassions, when there was environmental heat surplus, the energy-balance is not met since the process of sweating (evaporation from the wet skin) is not simulated. In these cases, the value of r_{cl} is negative, which cannot be interpreted physically. In the following, we will consider only the applicable cases.

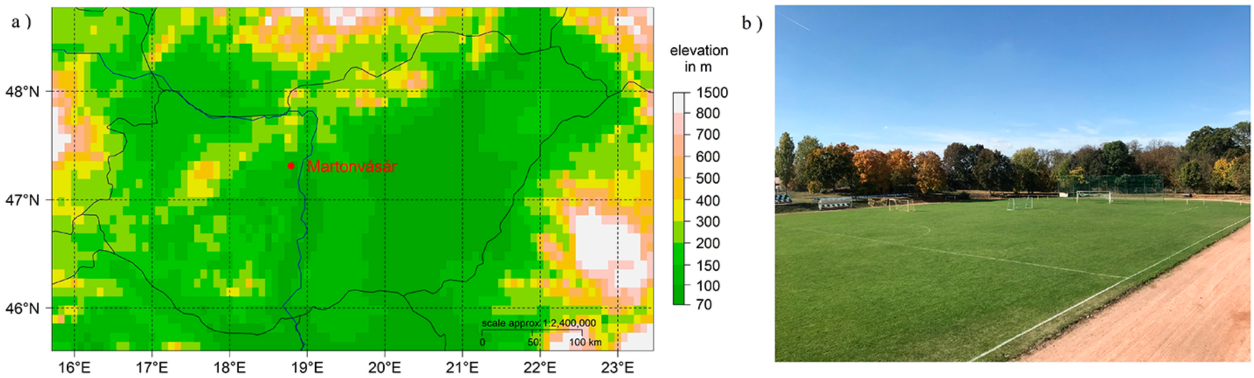

Figure 1. Location of Martonvásár in Hungary and the running track surrounding the soccer field in Martonvásár
Photo by: Ferenc Ács

Atmospheric data

There were in total 112 occasions of running activity (Ács et al., 2019) in the period August 9, 2016 – May 23, 2018. Atmospheric data were collected on each running occasion. Out of these 112 occasions, the energy-balance-based method (method 1) is applicable in 74 the following, we will consider only the applicable cases. Values of air temperature, air humidity, average wind speed, wind gust speed and atmospheric pressure data are taken from the website of Hungarian Meteorological Service (HMS) and refer to Martonvásár. The meteorological station in Martonvásár is one of the stations

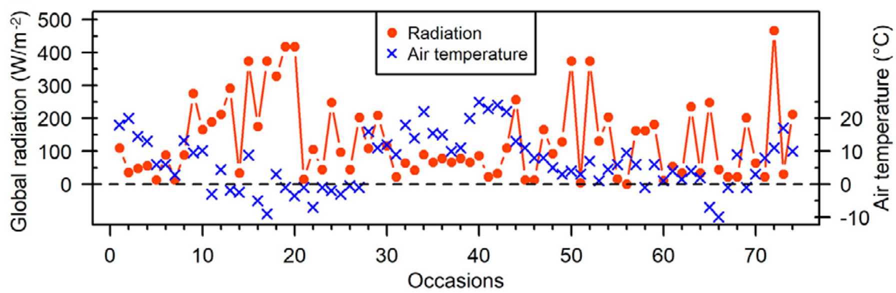

Figure 2. Evolution of air temperature and global radiation values registered during the 74 occasions of running on the Martonvásár athletics track

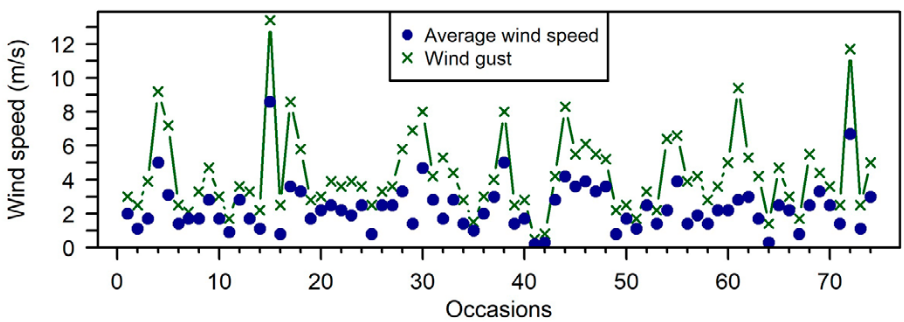

Figure 3. Evolution of average wind speed and wind gust speed values registered during the 74 running occasions on the Martonvásár athletics track

of the Hungarian Meteorological Service from about a thousand stations. The Martonvásár meteorological station - soccer field beeline distance is 100-150 m. Data refer to periods of 10-minutes. The 10-minute period is at the middle of the running activity. The beginning and the end of each running is regularly documented. Relative sunshine duration and cloudiness are visually observed. The referring air temperature and global radiation values as well as wind speed values are presented in Figure 2 and 3, respectively.

Air temperature changed between 10 and 25 °C, whilst global radiation between 0 and 460 Wm^{-2}. There were cases of lower temperatures coupled with higher values of global radiation (e.g. occasion 17 on January 1, 2017; occasion 19 on January 15, 2017; occasion 20 on January 19, 2017), and conversely, higher temperatures coupled with lower global radiation values (e.g. occasion 40 on April 18, 2017; occasion 41 on April 23, 2017 and occasion 42 on April 26, 2017). Average wind speed changed between 0.5 and 8.5 ms^{-1}, but it fluctuated mostly between 2-3 ms^{-1}. Wind gust speed values were mostly between 3 and 6 ms^{-1}, values exceeded 10 ms^{-1} only twice. Note that wind gust speed was lower than 1 ms^{-1} on two occasions.

Human data

There are two types of human data: a) human state variables and the referring basal, walking and total energy flux densities and b) thermal insulation values of garments making up clothing. The anthropometric and energy flux density data of the persons included in the study are presented in Table 1. The heat and energy flux density values shown in Table 1 (the last three columns) were calculated according to Ács et al. (2019) (equations (10)-(14)). Only one person (person 1) undertook the long-term longitudinal experiment – simultaneous and parallel documentation of the weather, activity and the clothing worn. It should be mentioned that such long-term experiments are very rare given the complexity of the work to be performed. The anthropometric data of persons 2 and 3 were used only when the sensitivity of model 1 to changes in metabolic heat flux density was examined (below in chapter: Results, section: Sensitivity of model 1 to metabolic heat flux changes).

Thermal insulation data of the garments making up the clothing of person 1 used during running events are summarized in Table 2.

Table 2. The thermal insulation value of garments worn and the total thermal insulation value of clothing worn in different seasons based on model 2

GARMENTS	
Summer clothes	
Name	Thermal insulation value (clo)
swim briefs	0.04
shorts	0.06
ankle socks	0.05
sneakers	0.08
	in total 0.23
Autumn clothes	
Name	Thermal insulation value (clo)
swim briefs	0.04
sweatpants	0.25
shirt short sleeve	0.1
thin gray sweater	0.2
thick orange sweater	0.3
green vest	0.13
ankle socks	0.05
sneakers	0.08
thick gloves	0.05
black cap	0.05
	in total 1.25
Winter clothes	
autumn attire complete with 1 pair of socks and 1 pantyhose	in total 1.25 + 0.05 + 0.20 = 1.50

The thermal insulation value is expressed in clo unit, which was introduced by Gagge et al. (1941). 1 clo is 0.155 (m^2 · °C)/W. Thermal insulation values expressed in clo for different garments are taken from literature (e.g. Parsons, 2014; Innova, 2002). It is worth mentioning that the same clothes were used during the runs, it is only their combination that may have changed from run to run. As mentioned, the weather, the clothing worn and the activity (duration of the run, weight before and after the run) were documented after each running event. Of course, the wearing of clothes had seasonality. Table 2 also provides information on these possible seasonal thermal insulation values on the basis of model 2.

Table 1. Human characteristics of the persons in the study

Persons	Sex	Age [years]	Body mass [kg]	Body length [cm]	Basal metabolic heat flux density [Wm^{-2}]	Walking energy flux density [Wm^{-2}]	Total energy flux density [Wm^{-2}]
Person 1	male	66	89	190	40.8	94.5	135.3
Person 2	male	53	95	179	42	108	150
Person 3	male	24	120	179	46	124.9	170

Results

Applying the models we a) compared their behavior and b) examined the sensitivity of model 1 to the changes of wind speed and M. The sensitivity of model 1 to changes in wind speed was investigated by comparing r_{cl} values obtained for average wind speed and wind gust speed. The sensitivity of model 1 to changes in M was examined by comparing the r_{cl} values obtained for the M value of person 1 and the r_{cl} values obtained for the M values of persons 2 and 3. We chose wind speed because it is one of the most rapidly changing factors among the meteorological state variables. In model 1, the person is represented by M, so, the variability between people is expressed via variability of M.

Comparison of the models

The comparison of the models can only be done for person 1, since, as mentioned, there is no documented data for the clothes and weather of person 2 and 3. There are three comparisons: results obtained by model 1 are compared by results obtained by model 2 and 3, and lastly, results obtained by model 2 and 3 are also compared. Each comparison contains 74 points, that is, there are exactly as many points in each scatter chart as there are applicable running events. Comparison of r_{cl} values of person 1 obtained by model 1 and 2 is presented in Figure 4.

We can see that for r_{cl} values smaller than 1 clo, most of the points are below the dashed line, that is, model 2 overestimates model 1. For r_{cl} values greater than 1 clo, the scatter of points is much larger and model 1 can overestimate significantly model 2. It seems that the agreement of the models increases as heat deficit increases. Comparison of r_{cl} values of person 1 obtained by model 1 and 3 is presented in Figure 5.

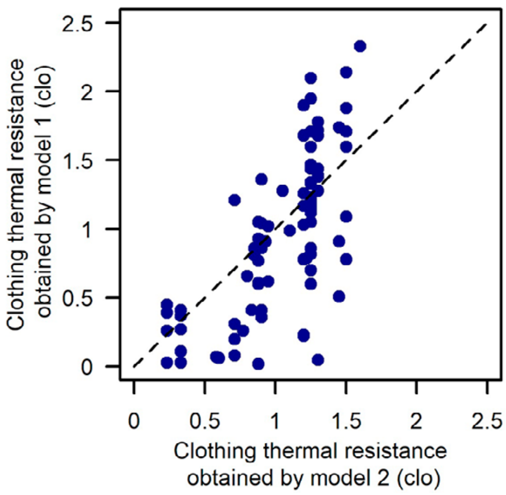

Figure 4. Scatter chart of clothing thermal resistance of person 1 obtained by model 1 (inverse application of the energy-balance-based model) and model 2 (clothing ensemble model)

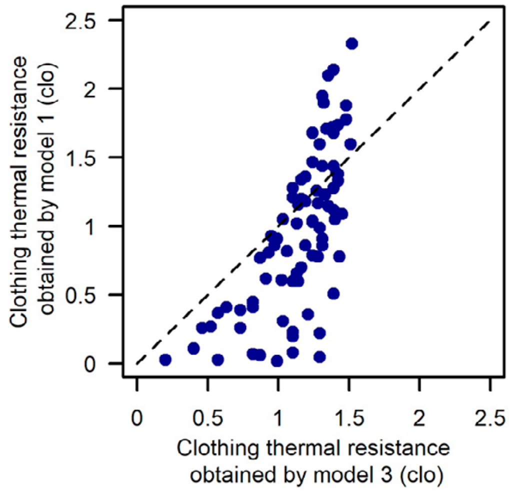

Figure 5. Scatter chart of clothing thermal resistance of person 1 obtained by model 1 (inverse application of the energy-balance-based model) and model 3 (UTCI-clothing model)

Here, the trend observed in Figure 4 is even more pronounced. For r_{cl} values smaller than 1 clo, model 3 overestimates model 1, but for r_{cl} values greater than 1 clo model 1 can significantly overestimate model 3. Note that model 3 cannot produce r_{cl} values greater than 1.7 clo. On the other hand, the r_{cl} values obtained with model 1 became greater than 2 clo in some cases. The biggest differences between the results of model 1 and model 3 are in cases, in which air temperature values are lower (e.g. 4-11 °C) and global radiation values are higher (370-460 Wm^{-2}). These cases can easily be recognized in Figure 2. In these cases, r_{cl} values obtained by model 3 are about 1-1.3 clo, whilst r_{cl} values obtained by model 1 about 0-0.3 clo. The effect of radiation can also be revealed in cases of greater heat deficiency. In these cases, model 1 overestimates (1.7-2.3 clo) model 3 (1.2-1.5 clo), because model 3 is insensitive to the lack of global radiation. Comparison of r_{cl} values of person 1 obtained by model 2 and 3 is presented in Figure 6.

It is noticeable that the results agree much better than previously. In this case, model 3 systematically overestimates model 2. This overestimation is greater in the case of small heat deficits (smaller r_{cl} values), and decreases as heat deficit increases. Based on the results of the scatter charts, differences between the

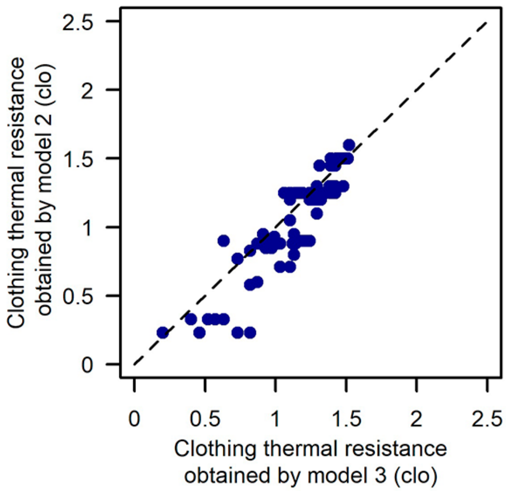

Figure 6. Scatter chart of clothing thermal resistance of person 1 obtained by model 2 (clothing ensemble model) and model 3 (UTCIclothing model)

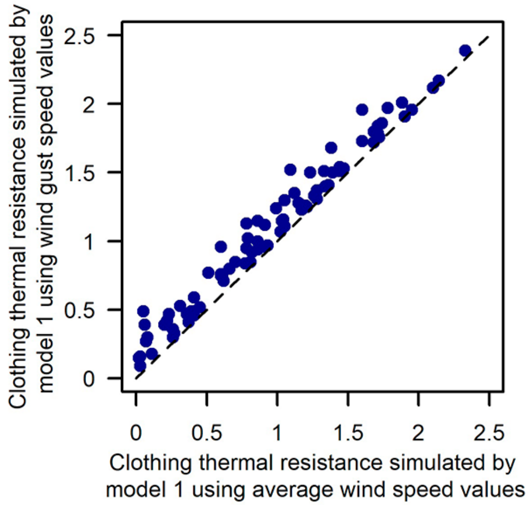

Figure 7. Scatter chart of clothing thermal resistance values obtained by model 1 using wind gust speed and average wind speed values

models are the largest in situations with small heat deficit (r_{cl} less than 0.5 clo).

Sensitivity of model 1 to wind speed changes

Model 1 depends on r_{Hr}, therefore it is sensitive to wind speed changes. Wind speed changes are characterized by comparing average wind speed and wind gust speed values (Figure 3). Comparison of r_{cl} values obtained by model 1 using wind gust speed and average wind speed values is presented in Figure 7.

For these wind speed changes, the maximum value of r_{cl} change is around 0.4 clo. r_{cl} deviations of 0.2-0.4 clo can occur both in case of larger (1.5 clo) and smaller (below 0.5 clo) environmental heat deficits. The determining role of wind can even be seen in cases, where $r_{cl} \leq 0.5$ clo.

Sensitivity of model 1 to metabolic heat flux changes

Model 1 depends on M, therefore it is sensitive to changes of M. M values of persons 1, 2, 3 differ about 15-20 Wm^{-2}. The effect of these constant differences on r_{cl} can be seen in Figure 8.

Since M of person 2 and person 3 is greater than the M of person 1, r_{cl} values obtained for persons 2 and 3 are underestimated with respect to the r_{cl} values obtained for person 1. The bigger the r_{cl} values, the bigger the differences between them. In case of large heat deficits, these differences can reach 0.4-0.7 clo. Note that models 2 and 3 do not explicitly show this dependence.

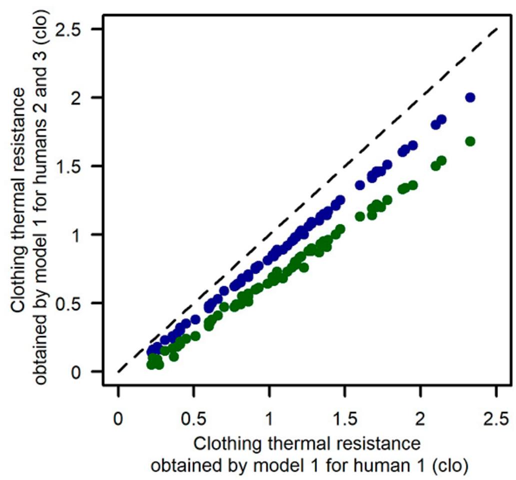

Figure 8. Comparison of clothing thermal resistance values obtained by model 1 for persons 2 and 1 (blue), and for persons 3 and 1 (green)

Discussion

The tested r_{cl} models differ greatly. Each model has its advantages and disadvantages. Model 1 is the most complex because it takes all important environmental and human factors into account. This is both an advantage and a disadvantage. M and r_{cl} are simulated referring to a specific person, whilst thermoregulation processes are not considered at all. In our opinion, thermoregulatory processes (e.g. sweating, shivering) do not need to be simulated if the model is not for testing human comfort, they are rather to be used in simpler tests like climate classification. However, the number of input variables is large. This is a clear disadvantage, especially if we want to use the model for climate classification. Model 2 is much less complex than model 1. Model 2 is simple, but the r_{cl} values of the garments that make up the clothing may differ from the literature values and r_{cl} values may vary from case to case. Model 2 has as many input variables as there are garments that make up the clothing. Model 3 is the most simple since r_{cl} depends only upon air temperature. The human is an imagined average person (Błażejczyk et al., 2010, 2013) with a body weight of 73.5 kg, a body fat content of 14% and of a Dubois area of 1.86 m². Sex is not specified. His/her clothing represents the clothing patterns of European and North American urban populations.

We could see that the r_{cl} values obtained with model 1 and model 3 differed to the greatest extent (Figure 5). These differences were the greatest when heat deficit was small according to model 1, while it was greater according to model 3. These cases were seen when in addition to lower air temperatures (higher heat deficit according to model 3), higher solar insolation values (lower heat deficit according to model 1) occurred. Larger r_{cl} differences obtained by model 1 and model 3 could also be observed in conditions of greater heat deficits ($r_{cl} \geq 1.3$ clo). In these cases, heat deficit was greater ($1.6 \leq r_{cl} \leq 2.2$ clo) according to model 1 and smaller ($1.2 \leq r_{cl} \leq 1.5$ clo) according to model 3. These differences are caused by the fact that model 1 takes the effect of radiation balance on thermal load into account, while model 3 doesn't. These cases show that there can be large differences between the thermal insulation of worn clothing (model 3 or model 2) and the thermal insulation of the clothing providing the energy balance (model 1) in case of either a small or a large heat deficit. It seems that a person's clothing is such that the energy balance of his/her body is rarely completely or approximately fulfilled. More precisely, in 8-10 cases out of 74 cases, the energy balance was fully met (Figure 4, Figure 5). It is most correct to consider each r_{cl} value as an approximate value. Such are the typical seasonal values given in the literature (e.g. Yan, 2005; Yan & Oliver, 1996). The seasonality of the clothing worn can also be seen based on the data presented in this work. According to model 2, the lowest summer r_{cl} values can be around 0.2 clo, the highest winter values are around 1.5 clo, while the autumn and spring values can be often around 0.6-1.0 clo.

Model 1, which is the most complex of the examined models, has highly variable capabilities. It cannot be used in warm climates or in weather situations that provide an excess of ambient heat, in which cases the energy balance equation is not complete, as it does not simulate the process of sweating. However, when it is applicable (cases of lack of heat), it is able to simulate interpersonal variability because of the changes of M. Since the value of M used during walking depends very weakly, that is, to a small extent, on the sex of the person, the difference between the sexes in the variability of the r_{cl} is not noticeable.The interpersonal r_{cl} differences are the smallest in the case of small heat deficits, they increase as heat deficit increases, and they can reach values of 0.4-0.7 clo in cases of large heat deficits. Note that this sensitivity (Figure 8) is comparable with the sensitivity (Figure 7) obtained for wind speed changes. It should be noted that the model is planned to be applied to individuals. The main strength of model 1 is that it eliminates the effect of clothing on the thermal load of human body.

Conclusion

In this work, we compared three different clothing thermal resistance models that can be used either as a stand-alone human biometeorological model (model 1) or as submodels (models 2 and 3). Model 1 is based on energy balance and is therefore the most complex. Model 3 is the simplest one and model 2 is in between the two. To the best of our knowledge, there are no such or similar comparative analyses in the scientific literature. The results obtained show that there is a considerable difference between r_{cl} values obtained by model 1 on one hand and models 2 and 3 on the other. The results suggest that 1) it is hard to achieve a balance of energy between the human body and the environment because in most of the cases it is either of the following: too much or too little clothing is worn. Based on the results obtained in the study, it is approximately in 10% of the cases that an energy balance is met; 2) the impact of individual differences on r_{cl} is greater with increasing environmental heat deficit. Of course, further studies need to be conducted in order to get a better knowledge of the thermal features of the clothing worn by humans.

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