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Common clothing area factor estimation equations are inaccurate for highly insulating (I_{cl}>2 clo) and non-western loose-fitting clothing ensembles

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Abstract: The aim of this study was to evaluate the equations for calculating the clothing area factor (f_{cl}) used in the standards based on data sets of clothing ensembles, that are meant to provide thermal comfort over a wide range of climatic conditions from hot summer days to extremely cold winter. Over 10 equations for f_{cl} calculations were selected from the international standards and the literature. At first a theoretical comparison based on a range of insulation values was performed. Then the data sets were used to compare the equations and measurements on real clothing systems. Most of the f_{cl} calculation equations do give reasonably good results for western type and industrial clothing with basic insulation (I_{cl}) up to 1.5 clo. Above the I_{cl} of 2 clo, the error in the calculations based on traditional equations increases considerably and they overestimate f_{cl}. Some new equations were suggested for modern clothing systems. Oppositely, for non-western clothing (for hot climate), the available equations did give good match only for very light clothing sets and commonly underestimated the real f_{cl}. For such sets and and fashion clothes their own equations maybe needed, that count for various design aspects, e.g. fit, draping etc.

Key words: Standards, Calculation method, Clothing systems, Clothing basic insulation, Comparative evaluation

Introduction

Besides climate factors (air temperature, mean radiant temperature, air velocity, humidity) and activity level / metabolic heat production, many standards for evaluating human exposure to thermal environments, e.g. ISO 7933[1] (heat), ISO 7730[2] (indoor climate), ISO 11079[3] (cold) use basic clothing insulation (I_{cl}) as one of the input variables. Clothing ensemble insulation can be measured on a thermal manikin[4, 5] or estimated based on available literature or databases where other, similar clothing items and ensembles have been measured[6–11]. Manikin measurements do provide directly the total (I_T) or resultant total ($I_{T,r}$) insulation. In order to calculate I_{cl} from I_T an air layer insulation (I_a) and clothing area factor (f_{cl}) are needed:

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \quad (1)$$

f_{cl} is the ratio of the outer surface area of the clothed body to the surface area of the nude body, and it counts for the increase in the surface, that is in contact with surrounding air where the heat exchange occurs. I_a can be

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measured on a nude manikin and is commonly an essential part of manikin testing as one of the solid reference values, while f_{cl} can be estimated by photographic method, 3D scanning etc.[7, 11–16] or calculating based on the variety of equations in the literature and standards[3, 8, 17]. However, as the equations commonly are based on databases, that to a large extent are based on indoor and moderate climate clothing, then it can be assumed, that for heavy protective clothing, the equations are not valid. ISO 9920[8] also defines the application range of the equations between 0.2 and 1.7 clo. In this large database, there are seldom occurring any combinations that have f_{cl} over 1.5, while the calculations according to the most equations exceed 1.5 when I_{cl} reaches above 1.5–2 clo. An exception from the other equations is one developed during Subzero project[18] that focused especially on measurements of cold protective clothing on thermal manikins[6, 17].

The aim of this study was to evaluate the equations for calculating the clothing area factor used in the standards based on professional modular clothing system offered for ambulance personnel, that is meant to provide thermal comfort over a wide range of climatic conditions from hot summer days to extremely cold Nordic winter[19]. In addition, some other databases, including the one of non-western clothing[7], were utilized for comparison in order to widen the scope of this work.

Materials and Methods

Clothing

The clothing elements were acquired from a Swedish manufacturer Taiga AB and were selected based on assumptions, that the various layers were designed to work together in any of the possible combinations. 27 items were selected and tested on a thermal manikin Tore at Lund University thermal environment laboratory in stationary mode in wind still conditions. Based on the ISO 9920 summation method over 100 realistic clothing ensemble insulation values were calculated, and finally, 14 sets (Fig. 1) were selected to cover as evenly as possible the estimated basic insulation range from 0.63 (T1) to 3.33 (T14) clo. The insulation of the selected sets was measured on a thermal manikin and clothing area factor was estimated with the photographic method based on 2 pictures: a side and a front view, following the recommendations of Havenith *et al*[7]. The measured insulation of selected sets ranged from 0.53 (T1) to 3.19 (T13) clo. Table 1 shows the total and basic insulation[19] and total and clothing evaporative resistance[20] of selected clothing combinations, and the measured f_{cl}. The full details of the measurements, and description of the clothing items and the ensembles is available in Kuklane and Toma[19].

Additionally, some datasets, e.g. Subzero[18] and database for non-western clothing[7] etc., were utilized in the analysis to avoid one-sided discussion on the topic.

Calculation of clothing area factor (f_{cl})

According to ISO 11079[3] and ISO 7933[1] (based on McCullough *et al.*[9]) f_{cl} shall be calculated by equation:

f_{cl}=1.0+1.97×I_{cl} (2)

where I_{cl} is expressed in m^{2}K/W.

However, in the algorithm available in the official IREQ

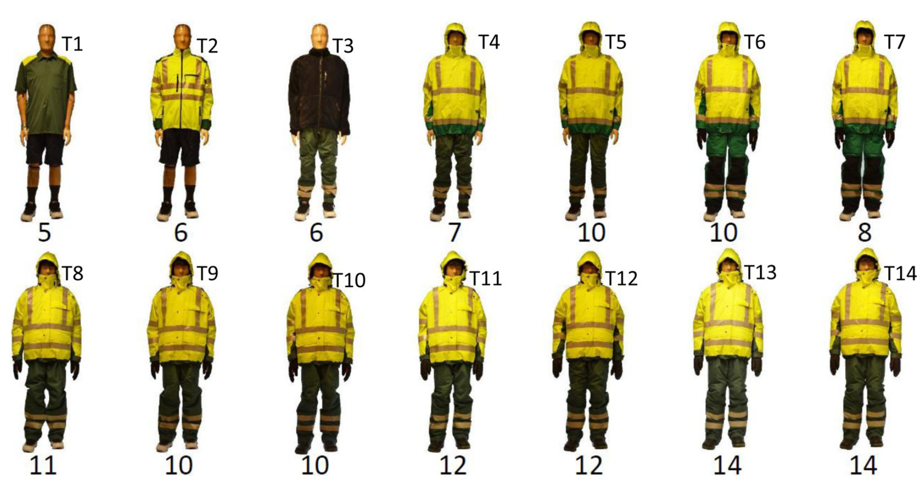

Fig. 1. 14 sets consisting of items from the Taiga AB ambulance system. Number under each figure defines number of items in the set. Details of the items are available in Kuklane and Toma[19].

Table 1. f_{cl} from photographic method, total and basic clothing insulation, and total evaporative resistance and clothing evaporative resistance of selected clothing combinations (for methodological background see Kuklane *et al.*[29], Toma *et al.*[20], Toma *et al.*[30]).

	f_{cl}	I_T (m^2K/W)	I_{cl} (m^2K/W)	R_{et} (m^2Pa/W)	R_{ecl} (m^2Pa/W)
AL*	1.00	0.094			
SK**	1.03	0.131	0.040	9.1	
T1	1.15	0.164	0.082	17.1	8.9
T2	1.18	0.197	0.118	22.2	14.3
T3	1.27	0.277	0.204	30.9	23.5
T4	1.29	0.290	0.218	39.2	31.9
T5	1.39	0.336	0.269	66.9	60.1
T6	1.38	0.380	0.312	68.3	61.5
T7	1.28	0.298	0.226	47.4	40.1
T8	1.44	0.431	0.366	92.2	85.6
T9	1.40	0.386	0.319	88.4	81.6
T10	1.44	0.430	0.365	96.6	90.0
T11	1.41	0.440	0.373	95.7	89.0
T12	1.49	0.546	0.484	114.9	108.6
T13	1.49	0.557	0.495	121.9	115.6
T14	1.45	0.525	0.460	112.9	106.4

***AL is air layer insulation measured on nude manikin.**
****SK is the textile skin that was used only during evaporative resisitance measurements.**

webpage[3] (http://www.eat.lth.se/fileadmin/eat/Termisk_miljoe/IREQ2009ver4_2.html) the equation is used in the form of

f_{cl}=1.0+1.197×I_{clr} (3)

where I_{clr} is resultant basic clothing insulation in m^2K/W (row 100, for duration limited exposure calculation) while also

f_{cl}=1.0+1.97×I_{clr} (4)

is also available (row 195, in heat storage estimation where I_{clr} is taken equal to I_{cl}) and

f_{cl}=1.0+1.197×$IREQ$ (5)

is used in IREQ related calculations (row 74, for IREQ iteration).

Also, a different version of this equation is published in Patty's Industrial Hygiene chapter on cold stress[21]:

f_{cl}=1.0+0.97×I_{cl} (6)

It is a question why the equations in the standards differ. It is even more unclear why the standard on cold protection[3] and related publications[21] present different equations with similar digits in the used numbers.

According to ISO 9920[8], the clothing area factor is calculated according to the following equations:

f_{cl}=1.00+1.81×I_{cl} (7)

if I_{cl} is expressed in m^2K/W, or

f_{cl}=1.00+0.28×I_{cl} (8)

if I_{cl} is expressed in clo.

According to ISO 7730[2] if clothing insulation is above 0.078 m^2K/W then

f_{cl}=1.05+1.645×I_{cl} (9)

As mentioned in the *Introduction* there are two other ways available to calculate f_{cl}, that have been developed especially for cold protective clothing in the course of the Subzero project[17, 18]. They are based on total clothing insulation (I_T) measured by parallel method (I_T)[22] and on I_{cl}:

f_{cl}=1.00+0.85×I_T (10)

f_{cl}=1.05+0.645×I_{cl} (11)

The equation with I_T is valid if it is measured at low air velocity where natural convection dominates. It may be very convenient to use, as I_T is the value that we acquire directly from the manikin test.

In a recent publication on modern western clothing database Smallcombe *et al.*[10] suggest new equations:

f_{cl}=1.01+1.599×I_{cl} (12)

or

f_{cl}=1.0+1.697×I_{cl} (13)

if with fixed constant. These last equations were tested by Smallcombe *et al.*[10] for basic clothing insulation less than 1 clo, i.e. the range covered also by the standards.

Equations 2, 3, 6, 7, 9, 10, 11, 12 and 13 were used in comparison. In order to evaluate and compare the equations various steps were performed. In order to study the differences systematically, a theoretical list of the insulation was created (0–5 clo with steps of 0.25 until 2 clo and further by 0.5 clo) and the equations were compared. However, as some equations utilized different insulation than basic clothing insulation in calculations, then also several databases were used, e.g. non-western clothing[7], Subzero project[17, 18], separate unpublished data sets etc., were scanned for measured f_{cl} and relevant insulation values. The data was used to compare the equations and measurements on real clothing. Thereafter, the combinations of the ambulance clothing were utilized to picture the differences within the same clothing system.

Results and Discussion

Comparison based on theoretical clothing basic insulation

Comparison of the theoretical list (Fig. 2) showed that equation 2 gave the highest values followed by ISO 9920[8] equations (Eq. 7; Eq. 8 is identical but adapted for different insulation unit (clo)), and Eq. 9 from ISO 7730[2]. However, the results did not differ considerably and stayed in the same range being reasonable up to about 2 clo, but reaching to 2.32 to 2.53 for 5 clo. The equation used for f_{cl} calculation in ISO 11079 algorithm (Eq. 3) provided considerably lower values even when similar I_{cl} was used in the equation instead of I_{clr} (1.93 for 5 clo). If all theoretical insulation values were reduced by 20% to simulate corresponding I_{clr}, then the difference with the results by standard equations was even larger (1.74 for 5 clo). If to look in ISO 9920[8] tables with clothing ensembles' I_{cl} and f_{cl}, then of those many combination only very few reach f_{cl} of 1.5 or above, and none is above 2. The range and values for the higher insulation values from 1.5–2 clo are much more similar to the ones acquired by Eq. 3.

Smallcombe *et al.*[10] did check f_{cl} and I_{cl} relationship with modern western indoor clothing and suggested new equations (equations 12 and 13) that give somewhat lower f_{cl} than the original equations, while the calculations for higher insulation values still stay in the same range as the standard equations (equations 2, 7–9) provide, i.e. far above 1.5. The difference may have been caused by modern clothing being in general more tight fitting than the ones from the previous decades.

Non-western clothing

When comparing measured and estimated f_{cl} of non-western clothing[7] (Fig. 3) then it can be seen that instead of over-estimating the f_{cl}, the calculations underestimated them. Many of these clothes were traditional, 1–2 layer thin clothing sets for hot climates with loose fit and covering large body areas for being able to ventilate well during motion and to protect skin from solar (UV) radiation, i.e. in opposite to the modern western clothing trends. The measured f_{cl} was commonly higher than the estimated one. Very light clothing (full body not covered, sets with several layers (for cold season in warm countries) or the ones influenced by western style were often the closest points to the line of identity and for the standard calculations. Although, for these type of clothes (wide, loose fitting) a separate equation with fixed constant can be suggested:

f_{cl}=1.0+0.4366×I_{cl} (14)

then due to relatively high variation (R^2=0.601, Fig. 3), the adjustments may be required based on specific clothing (design) parameters, e.g. fit, draping, layering etc. On the other hand, this equation may make a reasonably correct estimation of f_{cl} for some specific fashion styles. The equation is very close to the one developed by Havenith *et al.*[7] (as based on practically the same dataset). The equation is also close to an equation suggested by Ke and Wang[23] for Chinese traditional minority groups' clothing that also represent relatively loose-fitting garments. In that study f_{cl} was derived with a 3D scanning methodology instead of the photographic method.

Cold protective clothing

Completely opposite trend was observed for the cold protective clothing (I_{cl}>1.5clo, Fig. 4). Only the lower end (for 1.5–2 clo) of the standard calculations stayed reasonably close to the line of identity. At the same time, modifi-

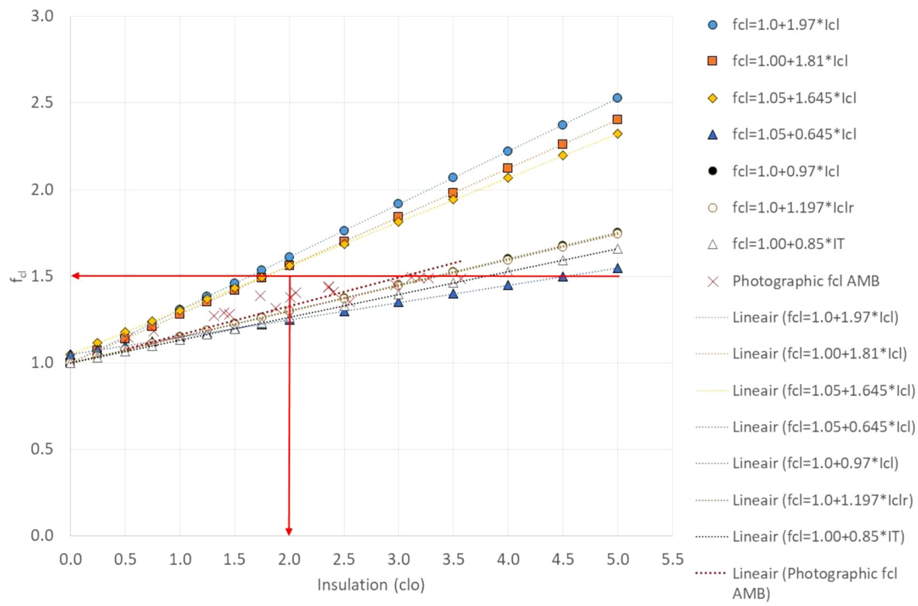

Fig. 2. Theoretical f_{cl} calculation results with measured f_{cl} from Taiga ambulance (AMB) system for reference. Red lines with arrows mark f_{cl} of 1.5 and insulation of 2.0 clo.

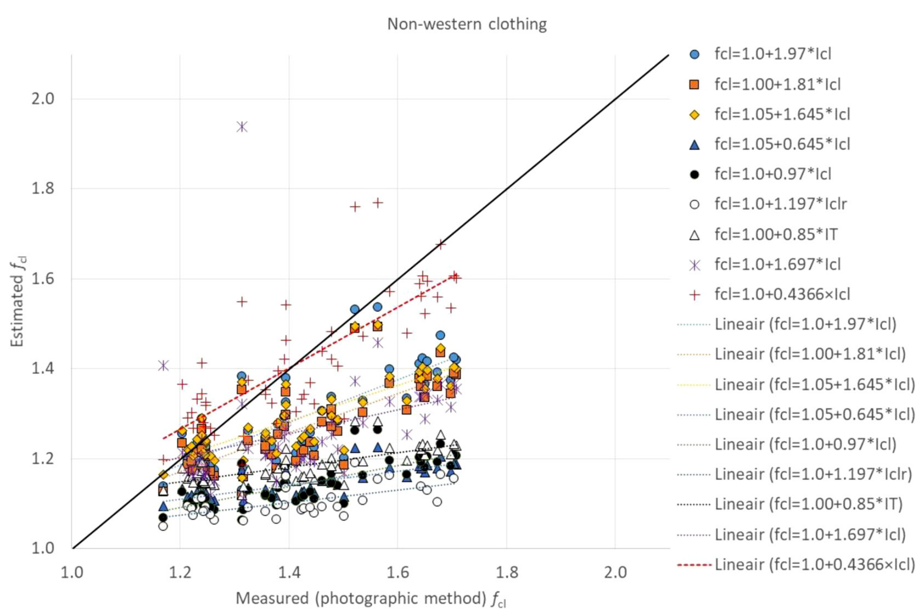

Fig. 3. Comparison of estimated and measured f_{cl} of non-western clothing based on Havenith *et al*[7].

cations of Eq. 2, the Eqs. 3, 5 and 6[3, 21] and the equations from Subzero project, Eqs. 10 and 11[17] provided reasonably close measured and estimated f_{cl} values. It allows to assume that the possible suspected errors in IREQ algorithms[3] and in Holmér[21], all addressing cold protection, have been intentional adjustments. The closest to the line of identity for this small set of protective clothing were Eqs. 6 and 10. It would be positive to use Eq. 10 as the manikin measurements provide total clothing insulation and if measured according to ISO 9920[8] suggestions in static and low wind conditions (<0.2 m/s) then f_{cl} of heavy protective clothing could be estimated directly.

Ambulance clothing system

The same trend as for cold protective clothing was observed also for the ambulance clothing system that in-

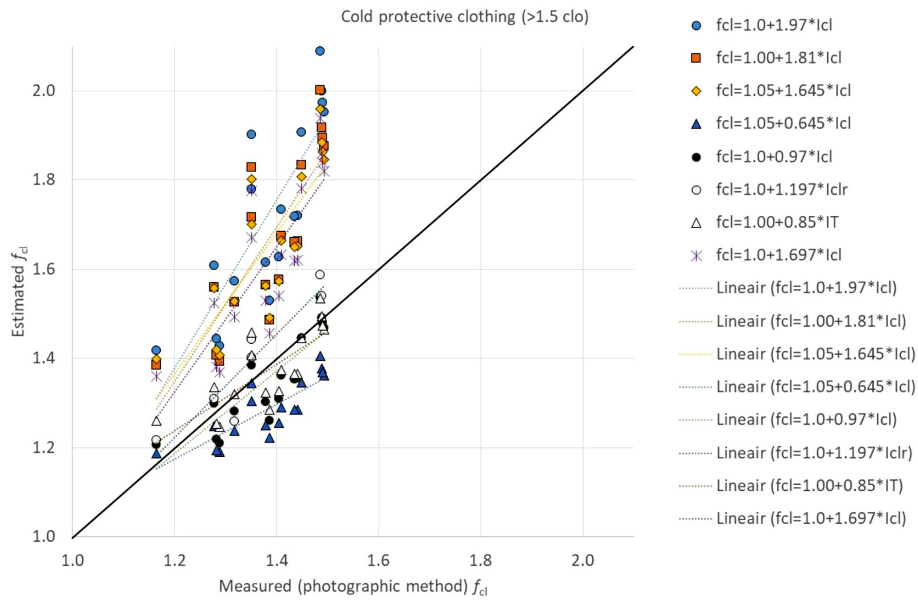

Fig. 4. Comparison of estimated and measured f_{cl} of cold protective clothing from various published studies where f_{cl} by photographic method was available[6, 19] and from some unpublished data sets.

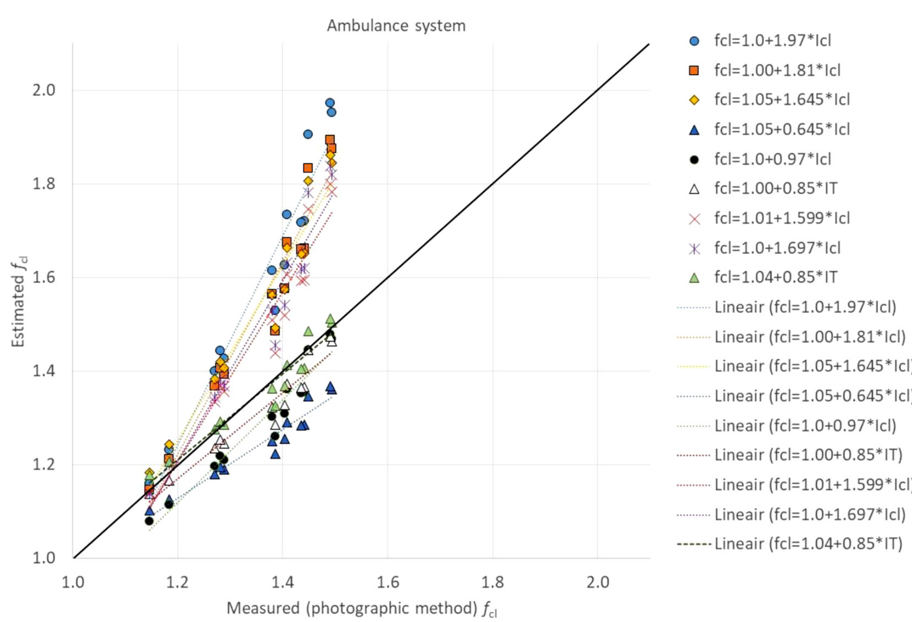

Fig. 5. Measured vs estimated f_{cl} of Taiga AB ambulance clothing system.

cluded a sequence from light clothing to heavy protective ensembles (Fig. 5).

If now the specific clothing sets were compared, then the outcome differed depending on the set. Subzero equations (Eqs. 10 and 11)[17] and ISO 11079[3] equation (Eq. 3) provided very similar results that did fit well not only with Subzero sets, but also with other modern professional clothing and sets with high insulation. In some cases, these clothing sets could be with quite low insulation while the calculated f_{cl} was in a reasonable range compared to the measurements by photographic method. Subzero results were available for ISO 11079[3] developers and thus Eqs. 3 and 6 may have got inspiration from Eqs. 10 and 11.

Protective clothing against extreme heat, i.e. with insulation layers, would most probably act as cold protective clothing, and thus, Eqs. 3, 6, 10 and 11 are expected to be more relevant in those cases. Based on ambulance system the Subzero Eq. 10 could be modified by changing intercept and then the closest results to the line of identity can be acquired (Fig. 5):

f_{cl}=1.04+0.85×I_T (15)

Simultaneously, creating trendlines for the whole ambulance system separately, it can be seen that the best fit is given by a curvilinear line (Fig. 6). The suggested equation in this case is:

f_{cl}=1.2424×$I_{cl}^{0.1546}$ (16)

The general curvilinear (parabolic) relationship between f_{cl} and I_{cl} was recently also suggested by Ke and Wang[23]. Although they showed linear relationships between local intrinsic clothing insulation and local f_{cl}, they demonstrated a curvilinear relationship between local intrinsic clothing insulation and local clothing air gap size[23]. Thus, considering special clothing systems and advanced thermo-physiological predictions, then it might be useful to create such clothing system specific relationships for these, too.

Expected impact of using f_{cl} on I_{cl} calculation and physiological responses

Although nowadays it is possible to measure clothing area by 3D scanning, then photographic method is still widely used[7, 10]. A reason for that may be that photographic method is a cost-effective and simple method that has been validated in numerous studies and backed up by international standards. There are some studies that allow comparison of photographic and 3D scanning methods for f_{cl} calculation[12, 14]. The study by McCullough *et al.*[14] showed that the 3D method gave in average somewhat higher f_{cl} than the photographic method. Their study covered a range of protective clothing and they recommended the use of the photographic method. Another, a recent study[12], provided basic parameters for advanced modelling and compared mainly local values and different postures, but also a variety of evaluation methods on 2 indoor garment ensembles. This thorough study provided the 3D scanning accuracy values, too. However, as the focus of that study was on individual body areas and body postures, then it was not possible to utilize it directly for comparing 3D scanning with the commonly used whole body f_{cl} estimation in standing posture by the photographic method. The difference for various body areas differed and was not always in the same direction even for the used 2 types of the indoor clothing ensembles. In spite of the higher claimed accuracy of 3D scanning method, this method is not easily available for occupational health and safety specialists in the field because of the cost, and following the standards allows a more simple approach. For wider use of 3D scanning method it needs to be standardized and interlaboratory round robin testing is needed together with the comparison of the other available methods. Furthermore, the new f_{cl} algorithms for wide range of clothing insulation have to be developed based on 3D scanning. Until then the suggested improvement of the f_{cl} calculation provided in this paper is still useful.

A separate question is how much f_{cl} affects insulation calculation and any predictions' outcome. For example, EN 342[24] omits f_{cl} in I_{cl} calculations (there is $I_{cl} = I_{tot}-I_a$). The motivation has been that in the case of cold protec-

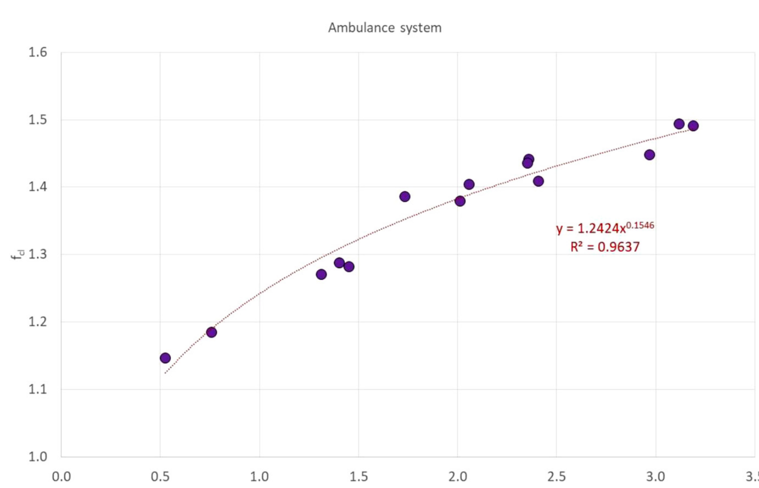

Fig. 6. Clothing area factor (f_{cl}) relation with basic insulation (I_{cl}) for Taiga AB ambulance clothing system.

tive clothing the subtracted part would be up to about 0.1/1.5=0.07 m^2K/W and skipping f_{cl} in the calculation would put the worker on more safe side in relation to cold. If the purpose of the testing is plain certification and comparison of clothing ensembles, then it does not really matter very much if f_{cl} is used. However, if the aim is to use the measured values for modelling and prediction, then the use of f_{cl} is justified. If to count maximal f_{cl} of a clothing ensemble being 1.5 by measurements and 2.0 by calculations, then the difference in I_{cl} estimation could be 0.02 m^2K/W. This is around the insulation difference where human start feeling the difference between various ensembles. Brady *et al.*[25] stated that the influence of f_{cl} on I_{cl} is generally small. However, the subjective feeling or an objective measure, e.g. skin temperature change will also depend on total insulation of clothing ensemble itself. In a way, depending on cooling/heating speed and local sensitivity of skin, this outcome of the discussion would match with the predictions by Fojtlín *et al*[12]. In their study based on physiological model predictions the mean skin temperature differed 0.4 °C and local skin temperatures up to 0.6 °C due to differences in local f_{cl} values.

General discussion

Equations 2, 7–9 did fit best with insulations <1.5 clo, and for non-western clothing[7] even above 2 clo. It seems that the number of the layers, fit (tight or loose), the presence of thermal liners/layers that fill the air gaps between textile layers and possibly the flexibility of the textiles plays role in the outcome[7, 11, 13, 23, 26].

The modern professional clothing, especially for cold conditions contain tight fitting underwear and thermal liners that fill open space between different garments, while non-western and other traditional and warm weather clothes are loose fitting and adding an additional layer increases the outer surface relatively more compared to increase in insulation. For cold protective garments, it is probably not the case—relatively rigid outer layer's outer surface is not able to expand too much and defines the surface area and it can't be expanded much. Instead large air gaps between garments are filled with insulation materials of the thermally protective middle layers.

For improving ISO 11079[3] (see also the critical review by d'Ambrosio Alfano *et al.*[27]) and any predictions for highly protective clothing the relationships between the listed factors and f_{cl} need to be studied, developed and validated. Until then equations from ISO 11079 algorithms (Eq. 3)[3] and Holmér (Eq. 6)[21] or from Subzero project (Eqs. 10 and 11)[17] could be used for basic clothing insulation above 1.5 clo but should certainly be used if above 2 clo. With relatively light clothes in warm climates (>+10 °C) and for estimated basic insulation less than 1.5–2 clo ISO 9920[8] equations (Eqs. 7, 8) should be used. In the range of 1.5 to 2 clo the equation choice could be decided depending on the fact, if prediction models for warm or cold climate are used (above or below 10°C).

A separate question is, if and how much different approaches of f_{cl} calculation affect IREQ prediction outcome. In order to be sure of proper predictions, the changes in the model must be investigated and tested against available databases of human exposures to cold and actual physiological responses while based on other studies[12, 25] there can be expected a small but observable difference.

Any mobile decision-making tools using physiological and clothing models for thermo physiological evaluation of the environment and personal or professional advice, e.g. ClimApp[28], should count with the deviations created in the calculations from f_{cl} estimations. The range of using the equations should be limited by the range of clothing insulation, but even better if design factors could be considered. The latter may be difficult in practice while modern technology could provide a solution, e.g. by taking a picture of the clothing ensemble and feeding it to a specific algorithm.

Conclusion

Most of the clothing area factor (f_{cl}) calculation equations do give reasonably good results for western type and industrial clothing with basic insulation (I_{cl}) up to 1.5 clo. Above the basic clothing insulation of 2 clo, the error in the calculations based on traditional equations (2, 7–9) and the ones suggested by Smallcombe *et al.* (Eqs. 12 and 13)[10] increases considerably and they overestimate f_{cl}. The calculation accuracy by these equations in the range of 1.5–2 clo may still be acceptable, while it can be strongly recommended to use equations developed during Subzero project and related equations instead. These equations (10, 11 and 15) should be used for clothing with basic insulation above 2 clo.

For modern clothing systems based on western industrial clothing a curvilinear relationship between I_{cl} and f_{cl} gives the best fit over the wide range of insulation values. However, this relationship may be related only to this system and must be validated on other clothing ensembles. Considering that often very similar materials and close design is utilized for modern industrial clothing, then it can be expected, that the generalization is possible and the use of Eq. 16 can be widened.

For non-western clothing (for hot climate), that with their variety may also represent the wide variation in fashion the available equations do give good match only for very light clothing and commonly underestimate the real f_{cl}. For such sets their own equation is needed, but as the variety is large then for reasonable accuracy various design aspects, e.g. fit, draping etc., should be included in the calculations.

Disclaimer

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of their respective organizations.

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References

1) ISO 7933:2004 (2004) Ergonomics of the thermal environment—analytical determination and interpretation of heat stress using calculation of the predicted heat strain. International Organisation for Standardisation, Geneva.
2) ISO 7730:2005 (2005) Ergonomics of the thermal environment—analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Organisation for Standardisation, Geneva.
3) ISO 11079:2007 (2007) Ergonomics of the thermal environment—determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects. International Organisation for Standardisation, Geneva.
4) ASTM F1291-16 (2016) Standard test method for measuring the thermal insulation of clothing using a heated manikin. American Society of Testing and Materials International (ASTM), Philadelphia.
5) ISO 15831:2004 (2004) Clothing—physiological effects—measurement of thermal insulation by means of a thermal manikin. International Organisation for Standardisation, Geneva.
6) Anttonen H, Niskanen J, Meinander H, Bartels V, Kuklane K, Reinertsen RE, Varieras S, Sołtyński K (2004) Thermal manikin measurements—exact or not? Int J Occup Saf Ergon **10**, 291–300 (JOSE). [Medline] [CrossRef]
7) Havenith G, Kuklane K, Fan J, Hodder S, Ouzzahra Y, Lundgren K, Au Y, Loveday D (2015) A database of static clothing thermal insulation and vapor permeability values of non-western ensembles for use in ASHRAE standard 55, ISO 7730, and ISO 9920. ASHRAE Trans **121**, 197–215.
8) ISO 9920:2009 (2009) Ergonomics of the thermal environment—estimation of the thermal insulation and evaporative resistance of a clothing ensemble. International Standards Organisation, Geneva.
9) McCullough EA, Jones BW, Huck J (1985) A comprehensive data base for estimating clothing insulation. ASHRAE Trans **91**, 29–47.
10) Smallcombe J, Hodder S, Loveday D, Kuklane K, Mlynarczyk M, Halder A, Petersson J, Havenith G (2021) Updated database of clothing thermal insulation and vapor permeability values of western ensembles for use in ASHRAE standard 55, ISO 7730 and ISO 9920; Results of ASHRAE RP-1760. ASHRAE Trans.
11) Veselá S, Psikuta A, Frijns AJH (2018) Local clothing thermal properties of typical office ensembles under realistic static and dynamic conditions. Int J Biometeorol **62**, 2215–29. [Medline] [CrossRef]
12) Fojtlín M, Psikuta A, Fišer J, Toma R, Annaheim S, Jícha M (2019) Local clothing properties for thermo-physiological modelling: comparison of methods and body positions. Build Environ **155**, 376–88. [CrossRef]
13) Kakitsuba N (2004) Investigation into clothing area factors for tight and loose fitting clothing in three different body positions. J Hum Environ Syst **7**, 75–81. [CrossRef]
14) McCullough EA, Huang J, Deaton S (2005) Methods for measuring the clothing area factor. Environmental Ergonomics XI (Proceedings of the 11th International Conference on Environmental Ergonomics). Holmér I, Kuklane K and Gao C (Eds.) 433–436, Lund University, Lund.
15) McCullough EA, Jones BW (1983) Measuring and estimating the clothing area factor. Technical report 83–02. Manhattan K.S. Institute for Environmental Research, Kansas State University.
16) Psikuta A, Mert E, Annaheim S, Rossi RM (2019) 3D body scanning technology and applications in protective clothing. In: Firefighters' Clothing and Equipment: Performance, Protection, and Comfort. Song G, Wang F (Eds.) 269–284, CRC Press, Boca Raton.

17) Anttonen H, Hellsten M, Bartels V, Kuklane K, Niskanen J (2002) Report of the manikin measurements with analysis of the test results. SUBZERO project, D2. Oulu, Finland: Oulu Regional Institute of Occupational Health (ORIOH); December 2002.
18) Meinander H, Anttonen H, Bartels V, Holmér I, Reinertsen RE, Soltynski K, Varieras S (2003) Thermal insulation measurements of cold protective clothing using thermal manikins. SUBZERO project, final report (Report No. 4). Tampere, Finland: Fibre Materials Science, Tampere University of Technology.
19) Kuklane K, Toma R (2020) Validation of ISO 9920 clothing item insulation summation method based on an ambulance personnel clothing system. Ind Health **59**, 27–33.[Medline] [CrossRef]
20) Toma R, Kuklane K, Fišer J, Jícha M (2019) Evaporative resistance calculations analysis based on prewetted thermal manikin measurements. ICEE2019, Environmental Ergonomics XVIII. Local Organising Committee (Eds.), International Society for Environmental Ergonomics, July 7–12, 2019, Amsterdam.
21) Holmér I (2011) Cold stress. Patty's Industrial Hygiene and Toxicology, 6th. 1639–1683, Rose VE and Cohrsen B (Eds.), John Wiley & Sons, Hoboken.
22) Kuklane K, Gao C, Wang F, Holmér I (2012) Parallel and serial methods of calculating thermal insulation in European manikin standards. Int J Occup Saf Ergon **18**, 171–9. [Medline] [CrossRef]
23) Ke Y, Wang F (2020) An exploration of relationships among thermal insulation, area factor and air gap of male Chinese ethnic costumes. Polymers (Basel) **12**, 1302. [Medline] [CrossRef]
24) EN 342:2017 (2017) Protective clothing—ensembles and garments for protection against cold. European Committee for Standardisation, Brussels.
25) Brady JL, Rao NZ, Rioux T, Winterhalter C (2009) Comparison of thermal resistance between two garment designs driven by material characteristics using a thermal heated manikin. Environmental Ergonomics XIII (Proceedings of the 13th International Conference on Environmental Ergonomics). Castellani JW and Endrusick TL (Eds.), 300–303, Boston.
26) Kuklane K, Havenith G (2017) Clothing design parameters that affect estimation of clothing insulation change due to posture and motion. ICEE2017, Environmental Ergonomics XVII. Local Organising Committee (Eds.), International Society for Environmental Ergonomics, November 12−18, 2017, Kobe.
27) d' Ambrosio Alfano FR, Palella BI, Riccio G (2013) Notes on the implementation of the IREQ model for the assessment of extreme cold environments. Ergonomics **56**, 707–24. [Medline] [CrossRef].
28) Petersson J, Kuklane K, Gao C (2019) Is there a need to integrate human thermal models with weather forecasts to predict thermal stress? Int J Environ Res Public Health **16**, 4586. [Medline] [CrossRef]
29) Kuklane K, Toma R, Lucas RAI (2020) Insulation and evaporative resistance of clothing for sugarcane harvesters and chemical sprayers, and their application in PHS model-based exposure predictions. Int J Environ Res Public Health **17**, 3074. [Medline] [CrossRef]
30) Toma R, Kuklane K, Fojtlín M, Fišer J, Jícha M (2020) Using a thermal manikin to determine evaporative resistance and thermal insulation—a comparison of methods. Journal of Industrial Textiles (Epub ahead of print). [CrossRef].