Effect of movement on convection and ventilation in a skin-clothing-environment system

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Abstract

An analytical clothing model is developed to consider the effect of body movement on heat transfer. This model quantifies the impact of forced convection in an enclosed air layer and the effect of ventilation (through fabric pores and ensemble openings) on clothing insulation. The internal air speed (inside an enclosed air layer) caused by human movement is used to calculate the internal forced convective heat transfer coefficient. The model is validated for various combinations of walking speeds, ambient air speeds, and clothing fits. A validation study covering 15 experimental cases compares the local heat transfer coefficients for different parts of the body and for the entire body. These validation cases consist of standing (0 m/s) and two walking speeds (0.27 m/s, and 0.69 m/s), three ambient air speeds: still air (0.17 m/s), 1 m/s and 2 m/s, and three clothing ensembles with different designs. All the experiments were performed on an agile thermal manikin. The average relative error in simulated whole body heat flux was 11%. The presented model has ability to simulate heat transfer with high spatial resolution such as individual body segment, which is the major advantage over existing models..

Keywords:

Dynamic clothing insulation, body movement, pumping effect, ventilation, convective heat transfer

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1. Introduction

The sensible heat transfer from the human body to the environment involves conduction, convection and radiation. The human body-clothing-environment system can be segregated into mainly three layers: (a) Enclosed Air Layers (EAL) (air layer between skin and clothing), (b) Clothing layers, and (c) Boundary Air Layer (BAL) (air layer between clothing and ambient air). Human movements result in variations in the enclosed air volume, which causes an airflow (pumping effect) and increases the forced convective heat transfer in enclosed air layers and around the human body. Human movement reduces the effective total thermal insulation due to the increased convective heat transfer along with ventilation through the fabric and openings [1]. The measurement and theoretical calculation of the forced convective heat transfer coefficient in an enclosed air layer for dynamic conditions is challenging. Human movement not only affects the internal convective heat transfer, but also the convective heat transfer in the boundary air layer due to relative movements between different parts of the body and the ambient air. The ambient air speed, type and intensity of body movement, clothing fit, and body shape affect the heat transfer and consequently the thermal balance of the human body [2-7, 14, 43-46].

The reduction in effective total thermal insulation during human movement has been experimentally investigated by several researchers using agile thermal manikins and human subjects [2-6]. Vogt et al. [6] concluded that a large part of the reduction in the effective total thermal insulation was due to the heat exchange through the openings. However, the experiments of Beldings et al. [2] indicated that the reduction in clothing thermal insulation resulted from the convection (air movement) inside the enclosed air layer, as in their experiment they sealed the openings of the clothing ensembles (i.e. at the ankles, wrists, waist and margins of the face) and an air-impermeable garment was used. These studies have concluded that the reduction in the effective clothing thermal insulation during human movements related to convection and ventilation in an enclosed air layer. However, these studies did not analyse the local effects of forced convection and ventilation on different parts of the body. Nielsen et al. [5] conducted comprehensive research on the effect of physical activity, anatomic body shape, moving patterns for females and males, and ambient air velocity on the thermal insulation of clothing for both male and female clothing ensembles. An important conclusion from their study was that there was a reduction of clothing thermal insulation by 33% for males and 51% for females; this indicates that the garment fit (shape of enclosed air volume) and different moving patterns of females and males has a considerable impact on the pumping effect. Several studies have quantified the effect of body movement, ambient air speed and ventilation on clothing thermal insulation through linear regression [7-9]. A major shortcoming of these regression based models is that they provide correction coefficients for the resultant clothing insulation. This value is applicable for the whole body only and does not provide local heat transfer coefficients for different parts of the body. The details of the heat transfer from different parts of the body is required in many research fields such as physiology models, thermal sensation models, and localised HVAC systems (for energy efficiency) in automobiles and buildings. Furthermore, the correction coefficients from regression based models are applicable to only one particular type of movement (walking).

Theoretical models for the prediction of dynamic clothing insulation have been based mainly on empirical studies and regression analyses and very few models have been developed based on fundamental thermal principles [9-12]. Several theoretical clothing models have been developed and validated based on the assumption of a homogeneous air gap distribution and/or stationary conditions [13-22]. Often, such an assumption leads to an error in computing the conductive, radiative and convective heat transfer [22]. As a consequence, very few studies have investigated the mechanism behind the pumping effect and internal forced convection (convection in an enclosed air layer) by quantifying the air flow regime in an enclosed air layer and considering a realistic air gap/air volume. The model developed by Ismail et al. [21] assumes that the air movement in an enclosed air layer is the result of ventilation either through the fabric due to its air permeability or through openings. However, the findings of an experimental study by Belding et al. [2] showed that there was a significant effect of air movement despite air-tight fabric and sealed openings. Ghali et al. [10] developed and validated their model based on a hot plate and assumed homogenous but temporally varying air gaps, with a relative model error of 31%. As concluded by Nielsen et al. [3], the anatomic shape of the human body, the clothing fit (size and shape of the enclosed air volume) and the way of moving have a major impact on the convective heat transfer coefficient, and heterogeneity in the air gap may affect the heat transfer by up to 30% compared to an equivalent homogenous air gap [22]. Therefore, Ghali's model for clothing research and thermal physiology with an anatomically shaped body and realistic movement may not be applicable. Danielsson [11] investigated in detail the convection coefficient in clothing air layers due to body movement. However, neither the porosity of the fabric nor the heterogeneity of the air layers were considered, and the lack of air gap thickness data led to the inability to validate the model in detail.

The aim of the present study is to develop a clothing model that considers the local convective heat transfer in enclosed and boundary air layers and ventilation resulting from movement of the body. As the developed model is based on fundamental thermal and fluid flow principles, the applicability of the model is not limited to one type of movement and clothing. Technological advances in the field of 3D scanning, garment simulation software from fashion design, and advanced CAD tools have made it possible to analyse the volume and thickness of an enclosed air layer as an essential input to the model. In this study, the volume of the enclosed air layer is analysed using the virtual try-on type of software simulating the draping and movement of the garment fabric around the human body. The detailed and accurate input of the air gap thickness made it possible to develop and validate the model precisely. The developed model is validated for standing still and two walking speeds (0.27m/s and 0.69m/s), three ambient air speeds (0.17m/s, 1m/s and 2m/s) and three different degrees of clothing fit (tight fit, medium fit and loose fit). The developed clothing model is applicable to a wide range of types of human movement and provides detailed information about both global and local thermal insulation, which is very useful in clothing science and simulations of thermal physiology and thermal comfort. The presented model is an extension of the model developed by Joshi et al. [22] which was validated for wide range of ambient temperatures (-10°C to 24°C), ambient air speeds (0.2 m/s and 1 m/s), with a realistic air gap (0 m to more than 50 mm) on an anatomically shaped thermal manikin, but that model was limited to stationary condition (no body movement). In the present study, the extended model simulates the dynamic clothing thermal insulation by considering the forced convection and ventilation resulting from movement of the body.

2. Material and methods

2.1. Modelling concept

This model builds upon model by Joshi et al. [22], which was developed for stationary condition (no human movement) and considered heat transfer mechanisms such as conduction, free convection and radiation. The fundamental reasons behind convective heat transfer resulted from human movement was analysed by quantifying and characterising the air flow in an enclosed air layer. Developed model considers the local convective heat transfer in enclosed and boundary air layers resulting from movement of the body along with ventilation through openings (e.g. ankles, wrists, and waist) and air permeability of clothing as shown in Figure 1(a). The local convective heat transfer in an enclosed air layer was estimated by analysing volume change of the neighbouring body regions, and hence, the likely air flow direction (Figure 1(b)). The volumes were determined based on thickness of enclosed air layer using 3D garment simulation software, which allowed garment draping around body and animation of the human avatar to obtain volumetric data at subsequent stages of body movement. The volume change is analysed for arms, legs and torso regions independently assuming negligible air exchange with outside at the neckline and waistline of trousers as well as between trunk and arms at shoulder joints. The qualitative analysis of enclosed air layer thickness indicated that the air movement caused by change in air volume (or displacement of limbs) was predominant in transverse direction compared to lateral direction, which was later confirmed by results of this study. Finally, the model was validated against data measured with walking thermal manikin for various clothing fit levels, walking and wind speeds forming a basis for systematic validation of the model.

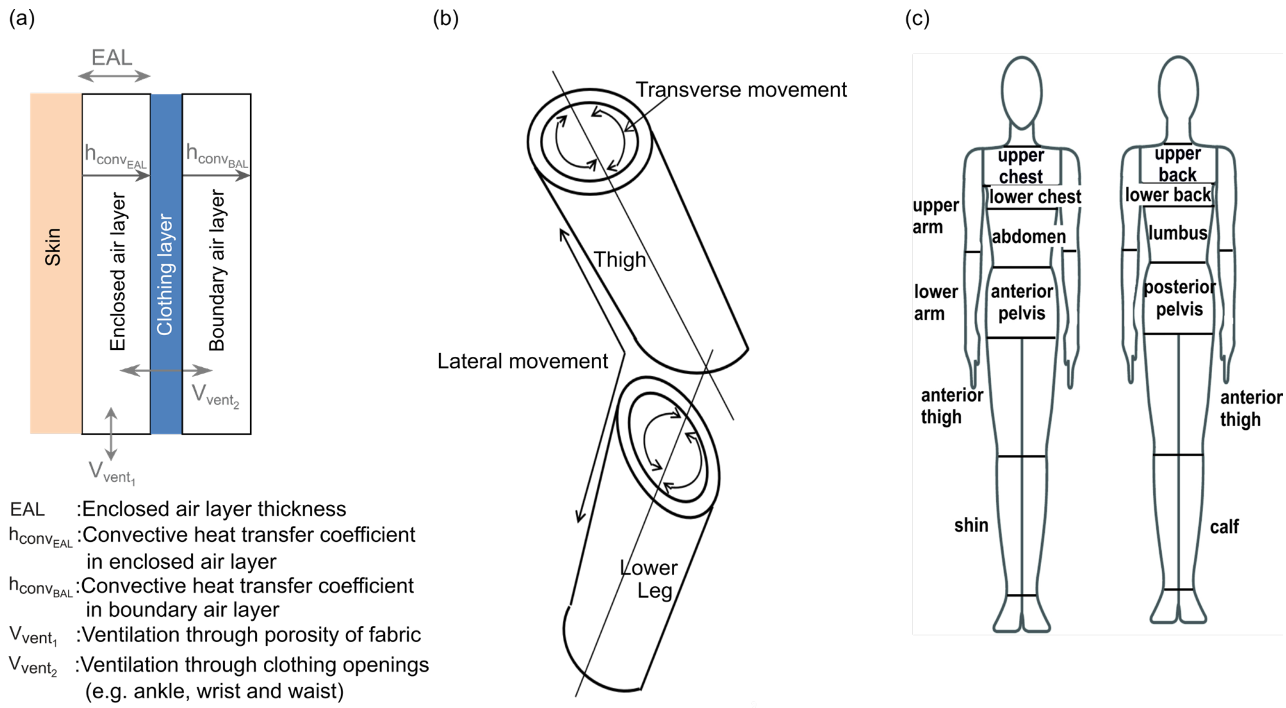


Figure 1 Schematic diagram of (a) convective heat transfer and ventilation from human body (moving) to environment through clothing, (b) air movement between body segments of a limb, and (c) definition of the body regions.

2.2. Model assumptions

The walking movement of the human body is assumed to be recurrent, so air gap thickness/air volumes were analysed for one gait cycle. This model assumes instantaneous thermal equilibrium, as the thermal inertia of air and fabric is low, and therefore, considered as negligible. The assumption of instantaneous thermal equilibrium is valid for wide range of ambient air speed (0.2 m/s to 5 m/s) and semi permeable clothing (air permeability greater than 181.5 l/m2s) [47]. Therefore, for semi permeable to permeable clothing with higher ambient air speed this assumption is appropriate, however, for protective clothing with high specific heat and low air permeability such as fire fighters clothing assumption of instantaneous thermal equilibrium may affect the accuracy of the model. The air flow generated in an enclosed air layer due to human movement is assumed to be incompressible and homogeneous within each individual region of the body implying the average air speed over particular part of body to compute the convective heat transfer coefficients. The shape of the parts of the human body is simplified to a cylinder based on the circumferential area of the actual human body to calculate the average air speed in an enclosed air layer. However, the actual heterogeneous distribution of air gaps is considered for the calculation of conduction and radiation, which was obtained from the garment simulation software. The effect of external wind on the deformation of the garment is not considered due to existing limitation in garment simulation software.

2.3. Mathematical formulation

2.3.1. Convective heat transfer coefficients for the enclosed air layer

Activities like walking, cycling, or skiing induce changes in the distribution of the air gap in clothing, resulting in a forced air flow between the skin and the clothing layer, which causes a forced convective heat transfer. To estimate the effect of this forced convection on the effective thermal insulation, several factors must be considered: the nature and intensity of the activity, the garment fit, and the effective velocity of the ambient air. The shape of the part of the body is simplified to a cylinder and the clothing around it forms an annulus of an enclosed air layer with heterogeneous air gap distribution.

In the first step, the average air speed can be calculated based on change in enclosed air volume over time as shown in equation 1. Subsequently, equation 1 can be further simplified in the form of more basic geometrical parameters such as radius of body segment, radius of surrounded fabric, and height of body segment as described in equations 2&3.

$$v = \frac{\left(\frac{\partial\, Volume}{\partial t}\right)}{Area} \quad \textbf{(1)}$$

$$v = \frac{\left(\frac{\partial\, \pi\, r_{fabric}^2 H}{\partial t}\right)}{\pi\left(r_{fabric}^2 - r_{body}^2\right)} \quad \textbf{(2)}$$

$$v = \frac{2 \cdot r_{fabric} \cdot H}{\left(r_{fabric}^2 - r_{body}^2\right)} \cdot \frac{\partial r_{fabric}}{\partial t} \quad (3)$$

Here, v is the average air speed in the enclosed air layer $\left(\frac{m}{s}\right)$,

r_{fabric} is the radius of fabric (m),

r_{skin} is the radius of the part of the body/cylinder (m),

t is the time (s), and

H is the height of the body part (m).

The convective heat transfer coefficient depends on the type of airflow (laminar or turbulent) and whether the flow is fully developed or developing in terms of its velocity and temperature profiles. The type of air flow in an annulus depends on several parameters, such as the properties of the fluid and the dimensions of the annulus. The classification of flow into laminar or turbulent flow is done based on a non-dimensional number such as the Reynolds number (Re), the Grashof number(Gr), or the Prandtl number (Pr). The transition from laminar to turbulent flow in an enclosed air layer of clothing occurs at a Reynolds number Re>2000 if $GrPr\left(\frac{d_h}{l}\right) < 1000$, where d_h is the thickness of the enclosed air layer and l is the length of the part of the body [11]. The flow can be classified as fully developed if Gz^{-1}(the inverse of Graetz number) is greater than 0.05 [11]. If the flow is fully developed, the Nusselt number for laminar convection will be constant and equal to 4.36 for a constant heat flux and 3.66 for a uniform surface temperature[11, 23]. The convective heat transfer coefficients for laminar and turbulent flow are given in equations (7 to 10) [11, 23, 24].

$$R = \frac{\rho * v * d_h}{\mu} \quad \textbf{(4)}$$

$$d_h = d_{fabric} - d_{skin} \quad \textbf{(5)}$$

$$Gz = \frac{d_h * R * Pr}{l} \quad \textbf{(6)}$$

Here, R is the Reynolds number,$(-)$

Pr is the Prandtl number,$(-)$

Gz is the Graetz number,

d_h is the characteristic length scale, the thickness of the enclosed air layer (m),

d_{fabric} is the outer diameter of the fabric (m),

d_{skin} is the inner diameter of the skin (m),

μ is the dynamic viscosity of air $\left(\frac{kgm^2}{s}\right)$, and

l is the length of the part of the body(m).

For laminar flow with uniform surface temperature, the Nusselt number can be calculated by the following equation [24].

$$Nu = 1.86\left(\frac{\Re Pr}{\frac{l}{d_h}}\right)^{\frac{1}{3}}\left(\frac{\mu}{\mu_s}\right)^{0.14} \quad (7)$$

Here, Nu is the Nusselt number,

μ is the dynamic viscosity of air at the average fluid temperature $\left(\frac{kgm^2}{s}\right)$, and

μ_s is the dynamic viscosity of the air at surface temperature $\left(\frac{kgm^2}{s}\right)$.

For turbulent flow with uniform surface temperature, the Nusselt number can be calculated by [11,23]

$$Nu = 0.024Re^{0.8}Pr^{0.4} \quad , \quad (8)$$

if the air is heated by the surface (surface temperature is above the ambient temperature) and

$$Nu = 0.026Re^{0.8}Pr^{0.3} \quad (9)$$

if the air is cooled by the surface (surface temperature is below the ambient temperature).

The convective heat transfer coefficient of an enclosed layer is

$$h_{conv_{EAL}} = Nu\frac{k_{EAL}}{x_{EAL}}. \quad (10)$$

At low to moderate paces of movement, forced convection also interacts with natural convection and causes a mixed convective heat transfer. At high ambient air speed or intensive movements, natural convection is negligible compared to the prevailing forced convection [11], which can be expressed by the Richardson number (Ri) (the ratio of the buoyancy term to the flow shear term) as expressed in equation 11[25]. If the Richardson number is less than 0.1, the natural convection is negligible; forced convection is negligible for Ri>10; and for 0.1<Ri<10 the heat transfer is due to the mixed convection[26].

$$Ri = \frac{Gr}{Re^2} \tag{11}$$

Here, Ri is the Richardson number,

Gr is the Grashof number, and

R is the Reynolds number

The radiative heat transfer coefficient for different parts of the body depends on the view factor, the temperature difference and the Stefan-Boltzmann constant. It can be obtained by the method described by Joshi et al. [22]. The total heat transfer coefficient of an enclosed air layer can be defined as below.

$$h_{EAL} = h_{conv_{EAL}} + h_{r_{EAL}} \tag{12}$$

Here, $h_{conv_{EAL}}$ is the convective heat transfer coefficient for the enclosed air layer $\left(\frac{W}{m^2K}\right)$,

$h_{r_{EAL}}$ is the radiative heat transfer coefficient for the enclosed air layer $\left(\frac{W}{m^2K}\right)$,

h_{EAL} is the total heat transfer coefficient of the enclosed air layer $\left(\frac{m^2K}{W}\right)$,

x_{EAL} is the thickness of the enclosed air (m), and

k_{EAL} is the thermal conductivity of the enclosed air $\left(\frac{W}{mK}\right)$.

2.3.2. Convective heat transfer coefficients for the boundary air layer:

The walking movement consists of repeated gait cycles. The gait cycle has two main phases: stance phase and swing phase [48]. During stance phase foot stays in contact with ground [48]. While, during swing phase movement of limbs results in relative motion between parts of the body and the ambient air, which affects the convective heat transfer in the boundary air layer. The influence of forced, mixed, and natural convection can be identified by the Richardson number as described in equation 11. The speed of motion for different parts of the body(v_w) can be obtained from the frequency and amplitude of the moving extremity (step length) of human body or thermal manikin. According to Danielson, the convection coefficients of two conditions (walking speed (v_w)and air speed(v_a)) cannot be simply added, but the resultant convective coefficient can be obtained by employing equation 13 [11]. The empirical coefficients x for various movements can be obtained by measuring the local heat flux, temperature, and air velocity at the part of the body in question while performing the activities (walking, resting, bicycling, etc.) [11]. Additionally, the local convective heat transfer coefficient and the value of the empirical coefficient (x) can be obtained using naphthalene sublimation by translating the weight loss resulting from the naphthalene sublimation to the heat transfer coefficient as suggested by Nishi and Gagge [27]. The value of (x) for walking depends on the specific part of the body and is described in **Table 1**.

$$h_{conv_{BAL}} = \left[h_{conv\,BAL}(v_a)^x + h_{conv\,BAL}(v_w)^x\right]^{\frac{1}{x}}. \quad \textbf{(13)}$$

The radiative heat transfer coefficients for different parts of the body can be obtained by the method described by Joshi et al. [22]. The total heat transfer coefficient of an enclosed air layer can be determined by

$$h_{BAL} = h_{conv_{BAL}} + h_{r_{BAL}} \quad \textbf{(14)}$$

where $h_{conv_{BAL}}$ is the total convective heat transfer coefficient for a boundary air layer $\left(\frac{W}{m^2K}\right)$,

$h_{r_{BAL}}$ is the radiative heat transfer coefficient for a boundary air layer $\left(\frac{W}{m^2K}\right)$,

h_{BAL} is the total heat transfer coefficient of a boundary air layer $\left(\frac{m^2K}{W}\right)$,

$h_{conv_{BAL}}(v_a)$ is the convective heat transfer coefficient for a boundary air layer $\left(\frac{W}{m^2K}\right)$ (due to the velocity of the ambient air), and

$h_{conv_{BAL}}(v_w)$ is the convective heat transfer coefficient for a boundary air layer $\left(\frac{W}{m^2K}\right)$ (due to walking or other bodily movement).

x empirical coefficient defined in table 1

Table 1. The values of x for different parts of the body for walking [11].

Part of the body	x (Clothed body)	x (Nude body)
Leg	2.7	2.1
Trunk	1.8	1.0
Arm	2.4	1.9
Whole body	2.4	1.5

2.3.3. Ventilation

The exchange of air between the enclosed air layer and the environment through the opening of the clothing ensemble or fabric pores can affect the air temperature of the enclosed air layer and the heat flux from the skin. The ventilation rate (air exchange between the enclosed air layer and environment) through garment opening can be approximated through the internal air speed (equation 3), and thickness of enclosed air layer (3D scanning or garment simulation software) as follows [11]:

$$V_{vent_1} = v * AGT * p \quad \textbf{(15)}$$

where V_{vent_1} is the exchange of air between microclimate and ambient through the openings in clothing ensembles $\left(\frac{m^3}{s}\right)$,

v is the air speed in an enclosed air layer$\left(\frac{m}{s}\right)$,

AGT is the thickness of the enclosed air layer (m), and

p is the the circumference of the enclosed part of the body(m).

As fabrics are porous, a difference in air pressure can also result in an exchange of air through the fabric. The ventilation through the pores of the fabric depends on the air permeability of the fabric and the pressure difference. The resulting ventilation can be calculated as follows [10].

$$V_{vent_2} = \frac{AP*(P-P_{env})}{\Delta P_m} * A \quad \textbf{(16)}$$

Here, V_{vemt_2} is the ventilation through the pores of the fabric$\left(\frac{m^3}{s}\right)$,

AP is the air permeability of the fabric $\left(\frac{l}{m^2 s}\right)$,

P is the pressure of the enclosed air layer (Pa),

P_{env} is the environmental air pressure (Pa),

ΔP_m is the standard pressure difference for air permeability measurement (Pa), and

A is the surface area of the clothing (m^2).

Where, pressure can be calculated based on following ideal gas and Bernoulli's equations:

$$P = \rho R T \quad (17)$$

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2 \quad (18)$$

Where, P is the pressure of air layer (Pa),

ρ is the density of air layer $\left(\frac{kg}{m^3}\right)$,

R is the gas constant $\left(\frac{J}{kg\ K}\right)$ = 286.9 $\frac{J}{kg\ K}$,

T is the temperature of air layer (K)

v is the velocity of air $\left(\frac{m}{s}\right)$,

The effective ventilation depends on the specific part of the body and the design of the clothing. Those parts of the body with openings (such as the lower leg and the lower arm) are affected by ventilation through both pathways: through the garment openings and also through the pores of the fabric ($V_{vent} = V_{vent_1} + V_{vent_2}$). Other parts of the body (such as the thigh and the upper arm) are affected by ventilation through the pores of the fabric only ($V_{vent} = V_{vent_2}$).

The ventilation in an enclosed air layer affects the air temperature of the enclosed air and the heat flux. The temperature of the enclosed air T_f is reduced to (T_{f_v}) due to ventilation. This reduction can be calculated as follows [11]:

$$T_{f_v} = \frac{h_{EAL} T_s A_s + h_{BAL} T_{cl} A_{cl} + V_{vent} c_p \rho T_a}{h_{EAL} A_s + h_{BAL} A_{cl} + V_{vent} C_p \rho} \quad \textbf{(19)}$$

$$q_v = \frac{\left(V_{vent}\ c_p\ rho\left(T_f - T_{f_v}\right)\right)}{A_s} \quad \textbf{(20)}$$

where T_f is the temperature of the enclosed air (K),

T_{f_v} is the reduced temperature of the enclosed air due to ventilation (K),

h_{EAL} is the total heat transfer coefficient of the enclosed air layer $\left(\frac{W}{m^2 K}\right)$,

h_{BAL} is the total heat transfer coefficient of the boundary air layer $\left(\frac{W}{m^2 K}\right)$,

A_s is the surface area of the skin (m^2)

A_{cl} is the surface area of the clothing (m^2),

C_p is the specific heat of air $\left(\frac{J}{kgK}\right)$, and

T_a is the temperature of the ambient air (K)

2.4. Validation and Experimental setup

2.4.1. Validation strategy

The validation of the model was performed using an agile thermal manikin, which can perform the walking movement at various speeds (maximum walking speed 0.69 m/s [38, 39]. The manikin consists of 30 separate uniformly heated sectors of the body that can be heated to maintain a predefined constant temperature of 34°C. The experiments were performed in a climatic chamber under controlled ambient conditions, such as an ambient temperature of 21°C (±1°C) and relative humidity of 50% (±5%).

The details of the motion of the parts of the thermal manikin are as follows:

- Step rates of 0.37 Hz and 0.92 Hz for the walking speeds of thermal manikin of 0.28 m/s and 0.69 m/s, respectively;
- The velocity of the moving arm was (v_w) 0.15 m/s (at walking speed of 0.28 m/s) and 0.40 m/s (at walking speed of 0.69 m/s) as measured at the wrist.
- The velocity of the moving leg was (v_w) 0.28 m/s (at walking speed of 0.28 m/s) and 0.67 m/s (at walking speed of 0.69 m/s) as measured at the ankle.
- During the walking movement of the manikin, the torso and head remained stationary and only the limbs were in motion.

The experimental design for the validation was a combination of conditions with three clothing ensembles (Table 2), three walking speeds (standing and walking at 0.27 and 0.69 m/s) and three ambient air speeds (still air of 0.17 m/s and two ambient air speeds of 1 and 2 m/s) giving in total 15 validation cases. The garments used for experimental setup were described in section 2.3.2. The methodology to calculate the change in enclosed air volume during human movement was described in section 2.3.3. To consider the effect of speed and direction of ambient air on local convective heat transfer and ventilation, parts of body divided into front and back and at joints (e.g. upper arm and lower arm) to address the volume change. The heat transfer coefficient was measured and analysed for local body and whole-body values for 12 individual parts of the body (chest, back, abdomen, buttocks, upper arm front, upper arm back, lower arm front, lower arm back, thigh front, thigh back, shin, calf). Since thermal manikin had lower body part resolution than the simulated data, some body regions needed to be lumped together for validation comparisons (upper and lower chest and back correspond to chest and back of the manikin, respectively, abdomen and anterior pelvis and lumbus and posterior pelvis correspond to abdomen and buttocks of the manikin, respectively, figure 1(c)).

The output of the presented model was also compared to the computed correction coefficient for walking speed and ambient air speed provided in the ISO 9920:2007 standard, which is based on a large database of clothing ensembles measured with thermal manikins. The experimentally measured whole-body thermal insulation (under steady-state condition) in ambient calm and stationary conditions is considered as a reference and the correction coefficient represents the fraction by which this reference value decreases due to movement and ambient air speed.

The quality of experimental data were quantified based on the standard deviation (SD) and the coefficient of variation (CV). The comparison of simulated and measured data was done based on the relative error (RE) by the following equations:

$$\%Relative\ error(\mathrm{RE}) = \frac{Experimentaldata - Modellingdata}{Experimentaldata} \times 100\%$$

$$StandardDeviation(SD) = \sqrt{\frac{\sum(x-\bar{x})^2}{(j-1)}}$$

$$Coefficientofvariation(CV) = \frac{SD}{\bar{x}} \times 100\%$$

Where, $\bar{x}$ is the mean value of the sample data,

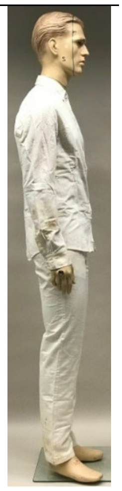
x is the observed value of the sample data, and

j is the number of samples.

2.4.2. Garments

Three clothing ensembles with different degrees of ease allowance (ease allowance is the difference between the girth of the body and the girth of the garment girth at a given body landmark) were selected for the present study, as shown in Table 2. The ease allowances and properties of the fabric for the clothing ensembles are described in Table 3.

Table 2. Ease allowances and material properties of three different ensembles with different clothing were used for validation

		Clothing ensemble 1 (Regular fit)		Clothing ensemble 2 (Loose fit)		Clothing ensemble 3 (Tight fit)	
		Front	Side	Front	Side	Front	side
	View						
	Garment	T-shirt	Trou-sers	T-shirt	Trousers	T-shirt	Trou-sers
Ease allowance	Chest	13	n/a	14	n/a	6	n/a
	Waist	25	n/a	35	n/a	20	n/a
	Biceps	9	n/a	13	n/a	10	n/a
	Hip	7	n/a	22	n/a	12	n/a
	Thigh	n/a	4	n/a	5	n/a	1
	Calf	n/a	7	n/a	9	n/a	4
	Thickness[1] (mm)	0.5	0.8	0.65	0.65	0.65	0.65
	Air perme-ability (l/m^2s)	239.4	46.1	229.7	229.7	229.7	229.7
	Thermal resistance (m^2K/W)	0.012	0.020	0.017	0.017	0.017	0.017

	Fibre content	95% cotton 5% elastane	100% cotton	100% cotton	100% cotton	100% cotton	100% cotton
	Fabric	Knitted single jersey	3/1 twill woven	Plain weave	3/1 twill woven	Plain weave	3/1 twill woven
	Weight[2], g/m²	339.7	188.3	137	179	137	179

1. Frank thickness tester, according to ISO 5084:1996
2. Precision scale, according to ISO 9073-1:1989

2.4.3. Quantification of the volume of the enclosed air layers

To simulate dynamic clothing insulation, it is necessary to have accurate input regarding the thickness of the enclosed air layer during body movement. The precise measurement of an enclosed air layer thickness can be made using garment simulation software or a 3D scanning method [28-37]. In this study, the thickness of an enclosed air layer is analysed using a fashion design software, CLO version 4.2 (CLO VIRTUAL FASHION, South Korea) for one gait cycle. The coordinates of the movement trajectory for the human body are as described in Figure 2, which was obtained from the movement mechanisms of an agile thermal manikin (SAM). The same coordinates were used in both simulation and validation cases using a thermal walking manikin.

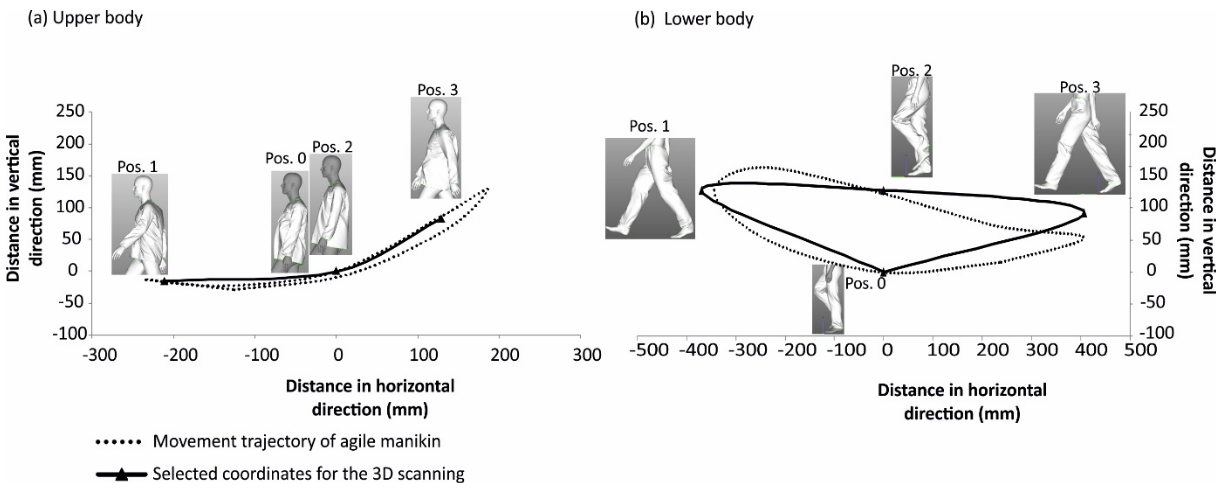
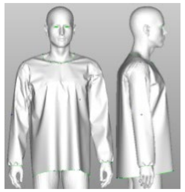
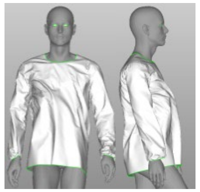
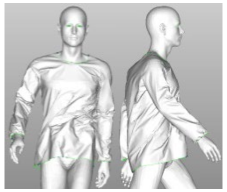
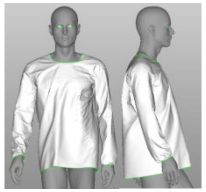
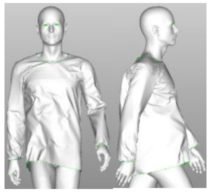
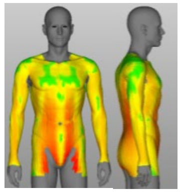
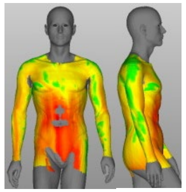
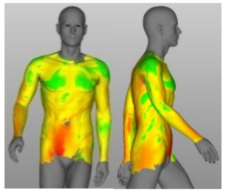
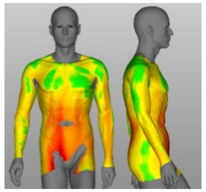
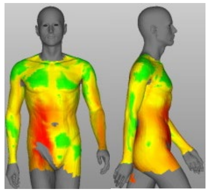
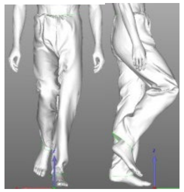
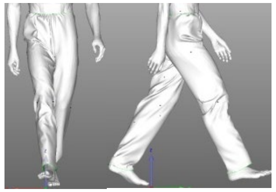
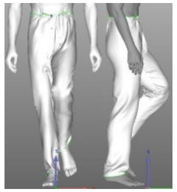
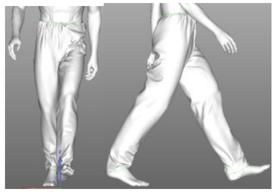
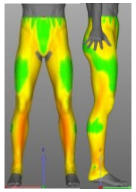
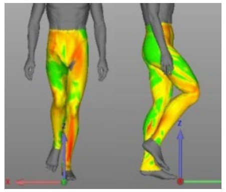
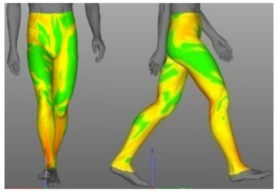
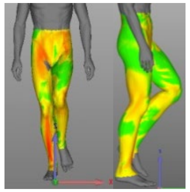
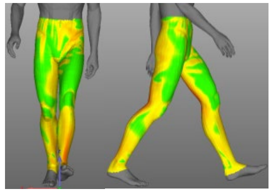


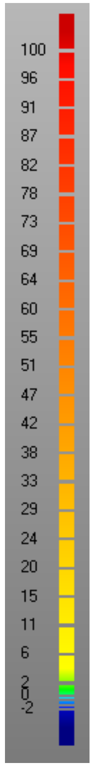
Figure 2 Movement trajectory of the agile thermal manikin and selected positions for the 3D scanning (a) upper body, (b) lower body

The dressed avatar body from CLO version 4.2 (CLO VIRTUAL FASHION, South Korea) was divided into several parts to describe the local draping behaviour of the garment [32] (Figure 1c). The virtual garment patterns and characterised fabric properties were imported to the garment simulation software CLO version 4.2. The virtual garment patterns were placed around the avatar body to drape around it. Finally, the avatar body with draped garment around it was exported to Geomagic Control 2015 (3D systems, USA) for the calculation of the contact area and average air gap thickness [32]. Table 3 presents the distribution of the thickness of the air gap during body movement for the upper and lower parts of the body. The average air gap thickness and contact area for the individual parts are required as an input to the model for the computation of the forced convective heat transfer coefficient, as shown in Figures 3 and 4. The contact area and average air gap thickness is used for the calculation of the conductive and convective heat transfer in an enclosed air layer [22].

Table 3. Variation in air gap thickness during walking movement

	Standing	Position 0	Position 1	Position 2	Position 3
Upper body					
					
Lower body					
					

AGT [mm]



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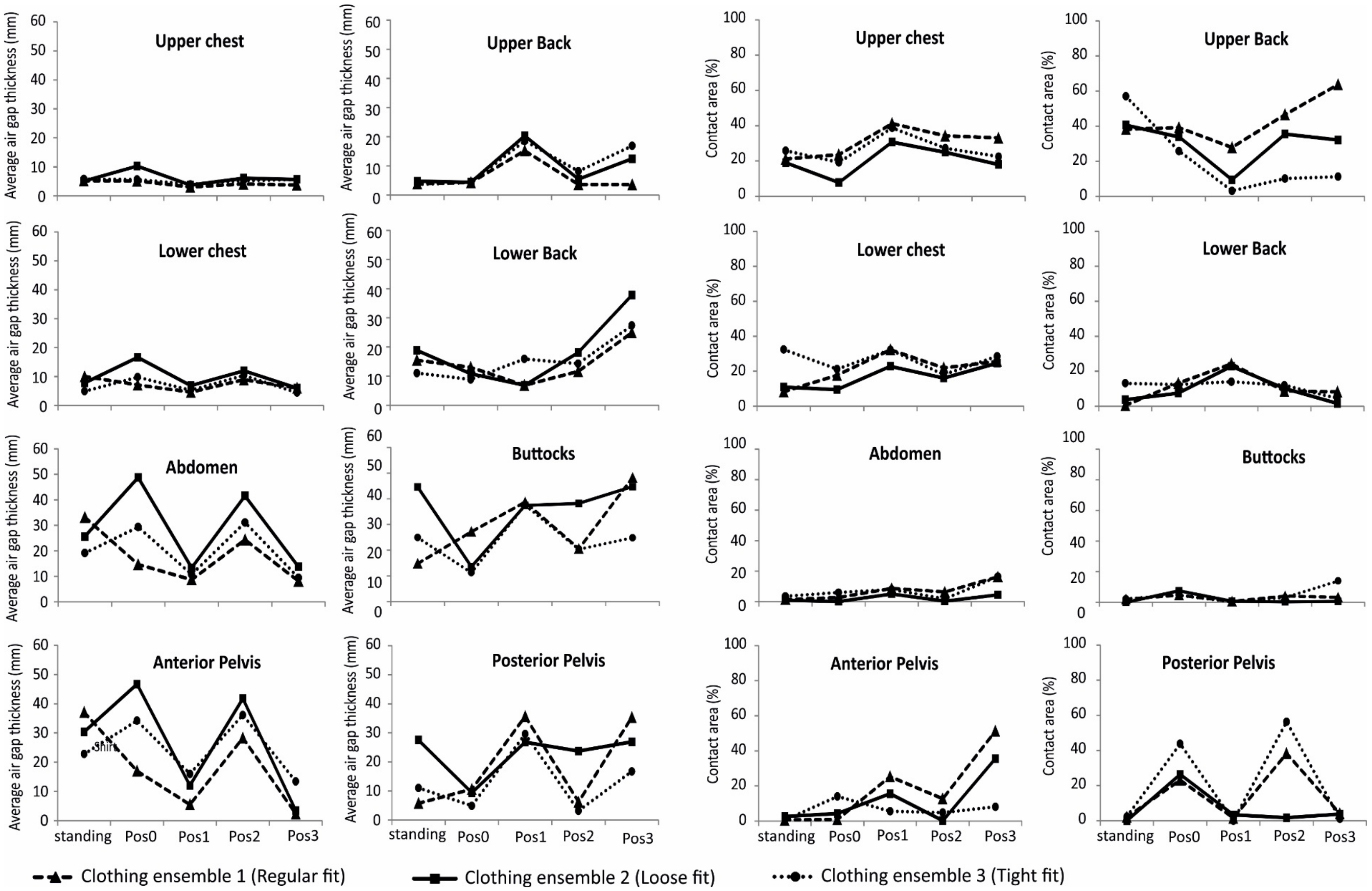


Figure 3 Variation in average air gap thickness and contact area over upper body during body movement

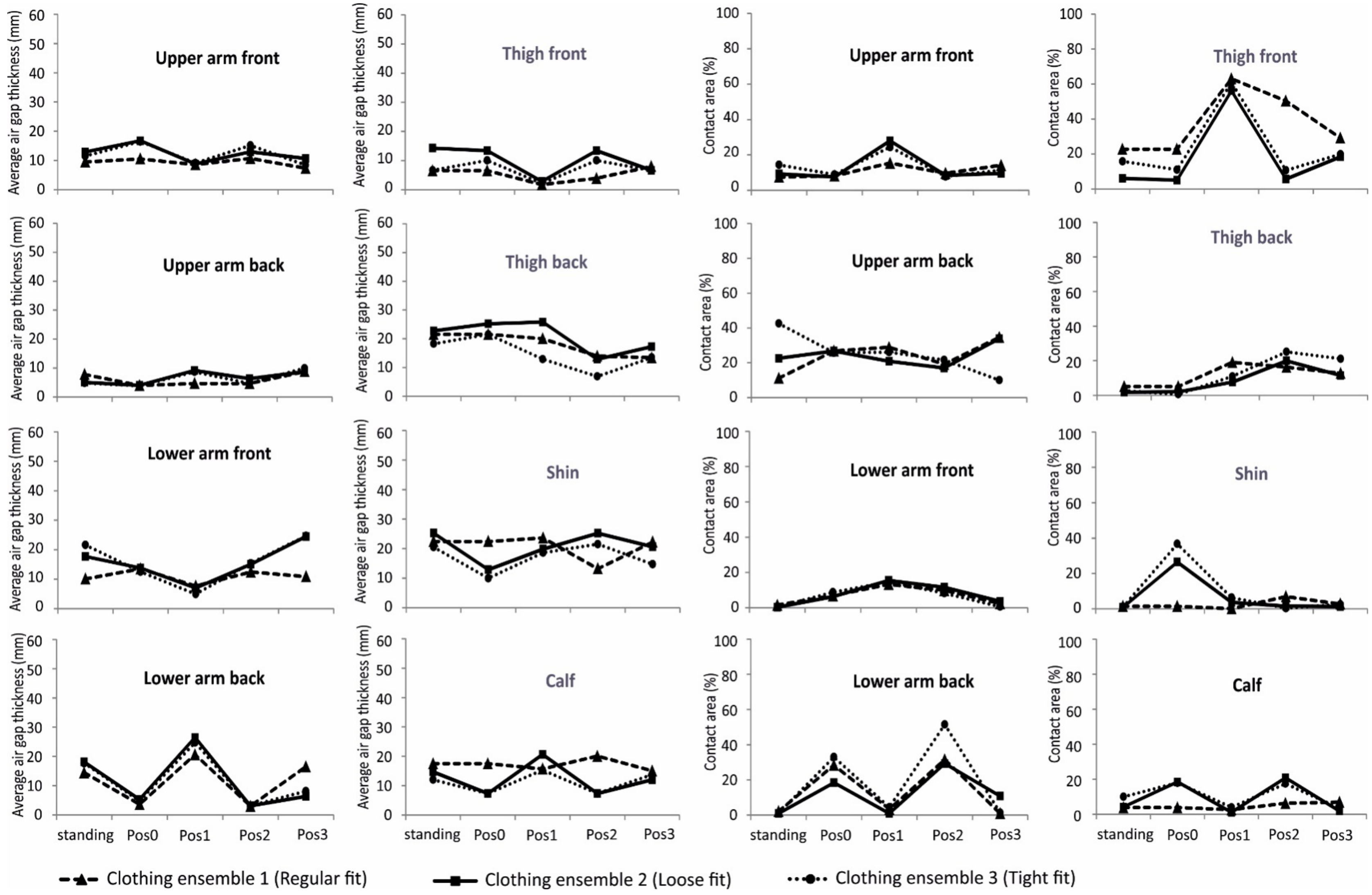


Figure 4 Variation in average air gap thickness and contact area of limbs during body movement

3. Results

3.1. Effect of walking speed, ambient air speed and clothing fit on overall and local total heat transfer coefficients

Figure 5 presents the measured and simulated whole-body heat transfer coefficients along with the corrected values according to the ISO 9920:2007 standard for three different walking and wind speeds in clothing ensemble 1 (Table 2).

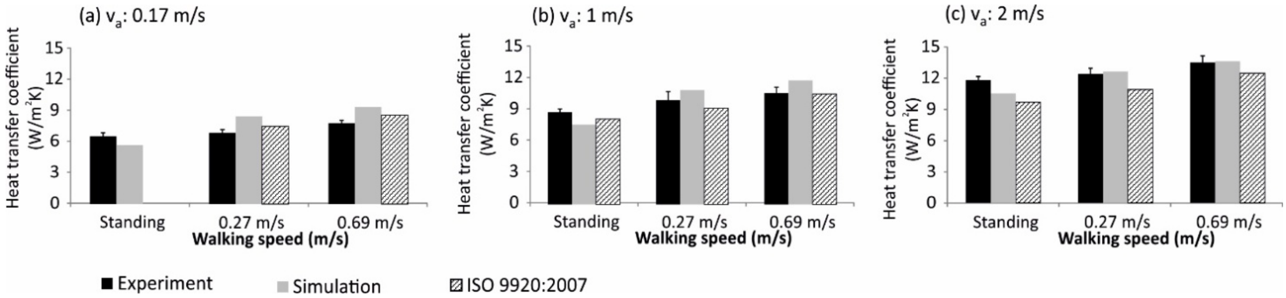


Figure 5 Whole-body heat transfer coefficients from the human body at different walking and wind speeds in clothing ensemble 1

Figure 6 presents the measured and simulated whole-body heat transfer coefficients along with corrected values from the ISO 9920:2007 standard for three different walking speeds and various clothing fits at ambient calm conditions (0.17 m/s).

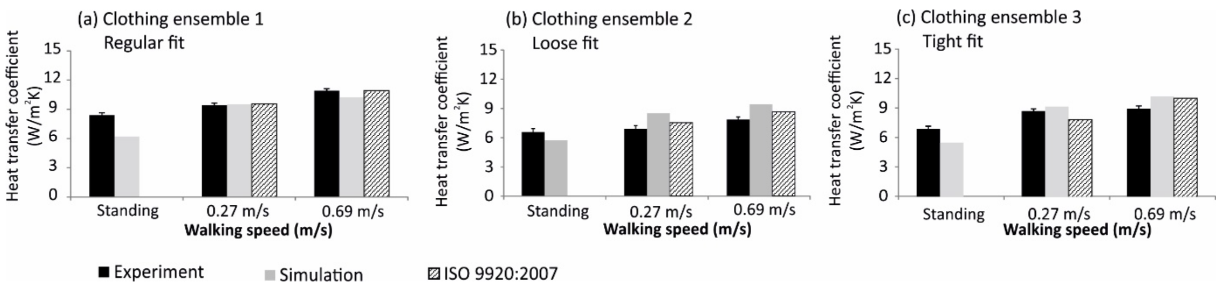


Figure 6 Whole-body heat transfer coefficients from the human body at different walking speeds and for different clothing ensemble fits (Table 2) at ambient calm conditions (0.17 m/s)

Figures 7 and 8 present the comparison of simulated local body heat transfer coefficients along with measured and corrected heat transfer coefficients according to ISO 9920:2007. The correction coefficient provided by ISO 9920:2007 is applicable to whole body only for various walking speeds, wind speeds and clothing fits. The standard deviation (SD) of the measured heat transfer coefficients in most cases was very low (below 0.27 $\frac{W}{m^2 K}$ except for those parts of the body that move at higher speeds and have openings, such as the lower arm, shin and calf (below 0.48 $\frac{W}{m^2 K}$).

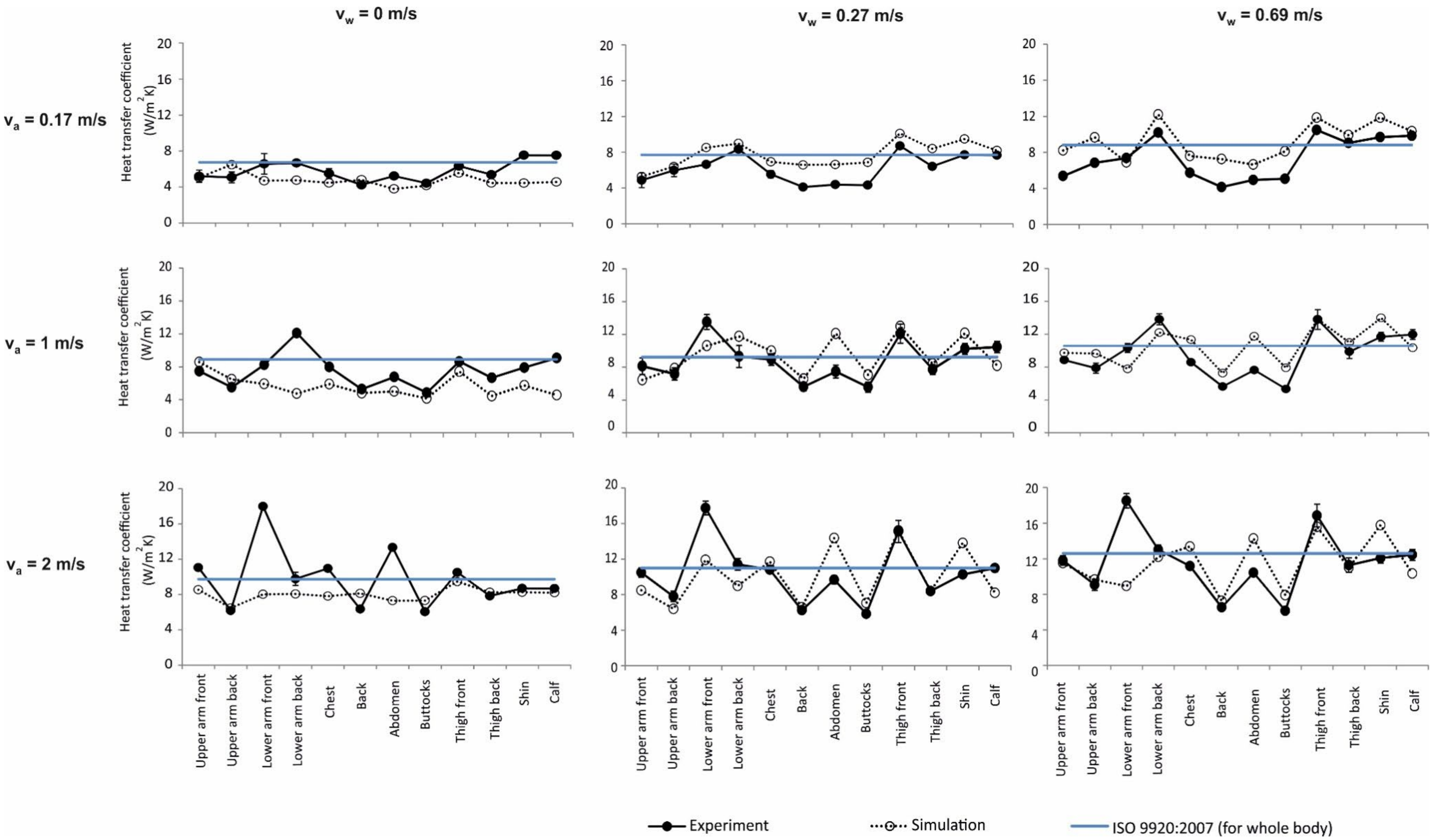
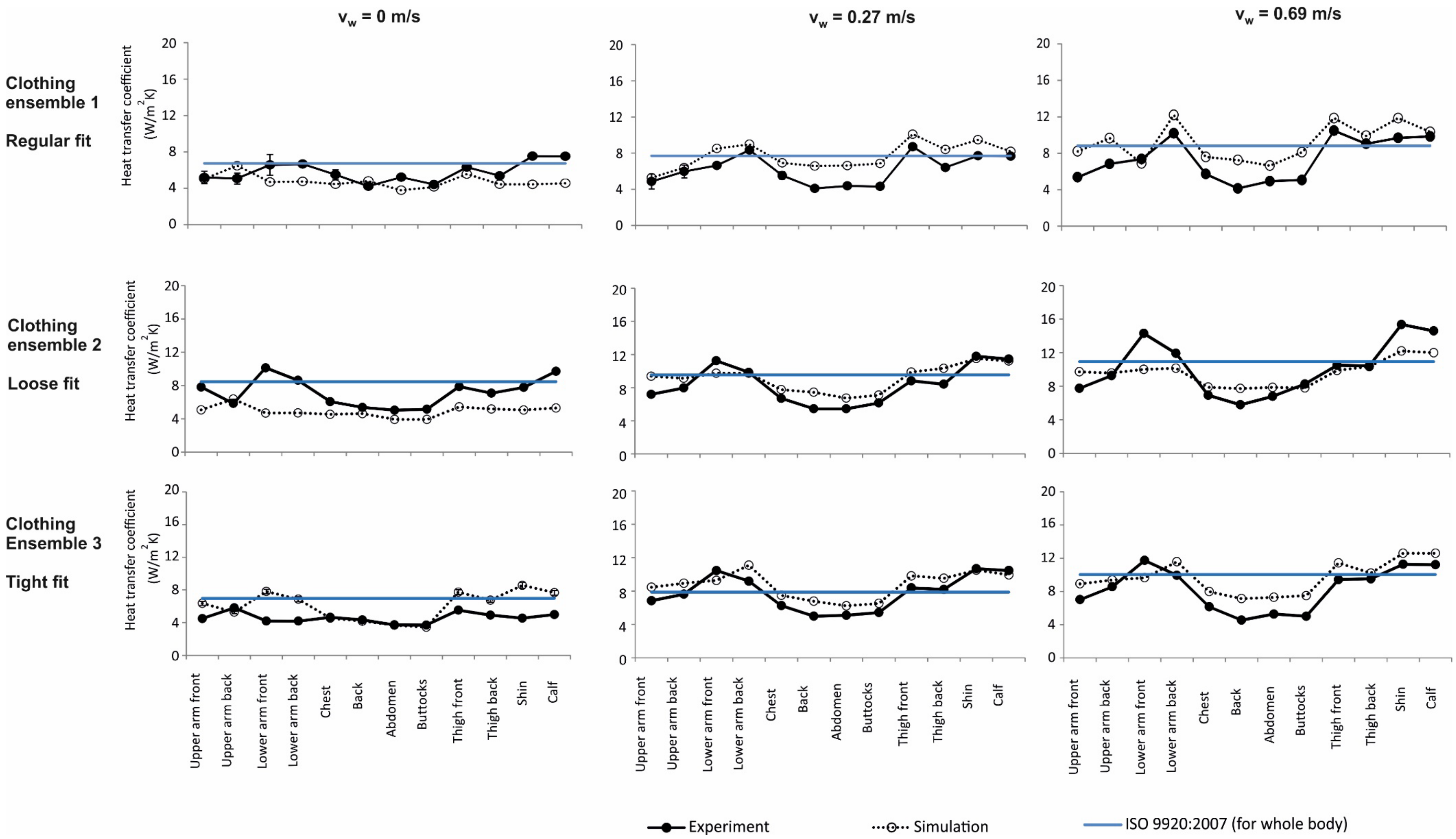


Figure 7 Local body heat transfer coefficients at different walking and wind speeds for clothing ensemble 1 (regular fit), average SD for trunk (chest, abdomen, back, and buttocks) was 0.27 $\frac{W}{m^2K}$ and for limbs (arms and legs) was 0.48 $\frac{W}{m^2K}$



1

2 **Figure 8 Local body heat transfer coefficients at different walking speeds and for different clothing fits at ambient calm conditions (0.17 $\mathrm{m/s}$), average SD for trunk**

3 **(chest, abdomen, back, and buttocks) was 0.18 $\frac{W}{m^2K}$ and for limbs (arms and legs) was 0.28 $\frac{W}{m^2K}$**

3.2. Average air speed and convective heat transfer coefficient in an enclosed air layer

The modelling approach presented in this study provides detailed information about the increased forced convection in enclosed air layers, as well as the fundamental processes behind it. The simulated average internal air speeds and corresponding local convective heat transfer coefficients in the enclosed air layers of parts of the body resulting from different walking speeds and clothing fits are presented in Figure 9 and 10, which is very challenging to measure experimentally without affecting the air layers and fluid flow. The presented data is provided for clothing ensemble 1.

With the increase in walking speed, Reynolds number (Re) also increase for all body parts because Re is function of internal air speed and air gap thickness (equation 4). The Reynolds number (Re=60) was lowest for upper arm where internal air speed is relatively low (Figure 9a) while back and buttocks had highest Reynolds number (RE = 3113). For majority of body parts the Reynolds number was below 2000, which indicates that the air flow inside an enclosed air layer was laminar. For the majority of body parts Richardson number was well below 0.1 (average Ri for whole body is 0.042) that indicates the natural convection was negligible compared to forced convection. However, some body parts with very low internal air speed (and low Re) and high air gap thickness (e.g. upper arm) shows possibility of mixed convection (natural convection along with forced convection). The Nusselt number was observed in the range of 3.7 (upper arm) to 16.5 (buttocks) which further leads to the convective heat transfer coefficient.

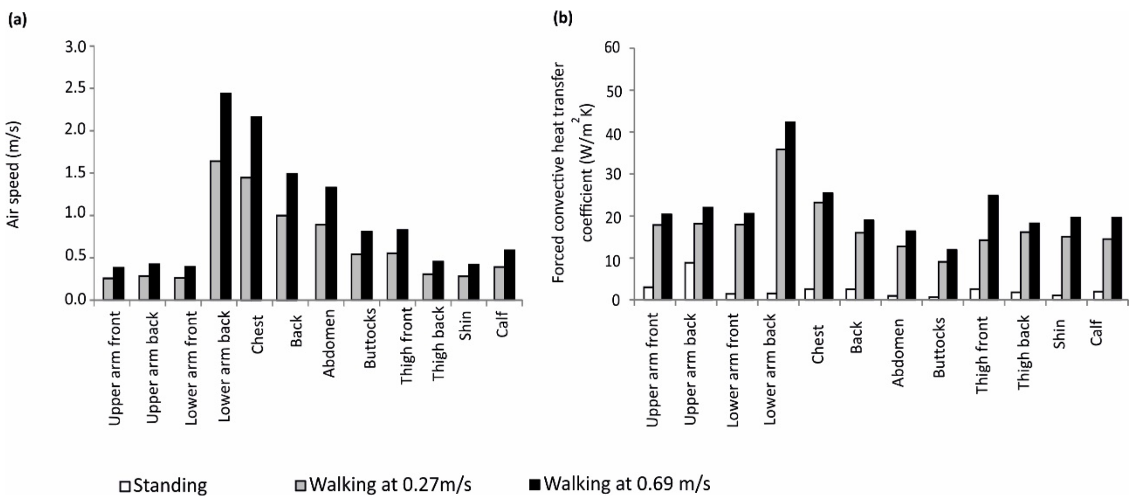


Figure 9 Simulated average internal (in an enclosed air layer) air speed and forced convective heat transfer coefficient (in an enclosed air layer) due to human movement in clothing ensemble 1 (regular fit)

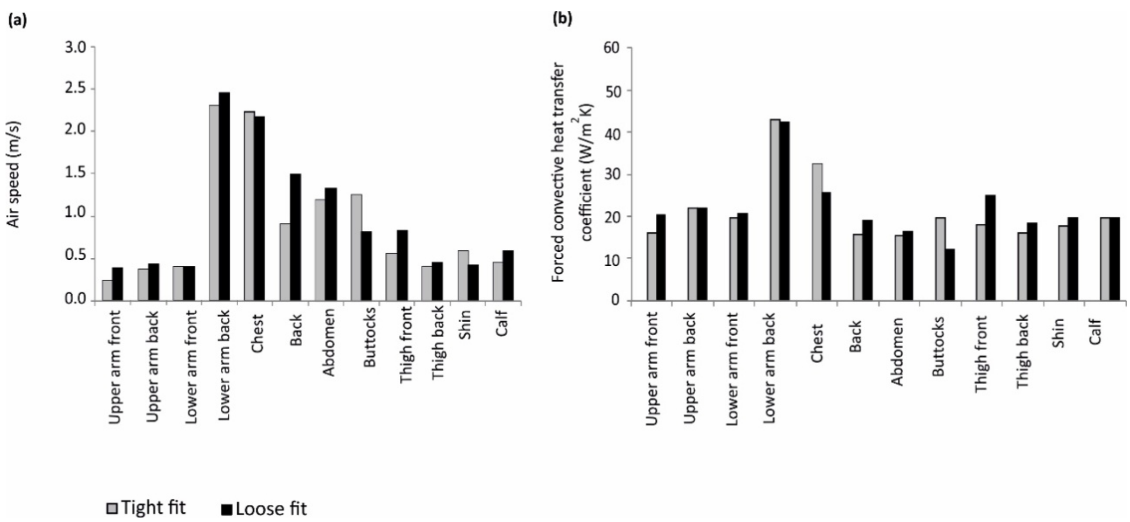


Figure 10 Average internal (in an enclosed air layer) air speed and forced convective heat transfer coefficient (in an enclosed air layer) due to human movement at walking speed 0.69m/s and ambient air speed 0.17 m/s

3.3. Effect of clothing ventilation

The heat transfer resulting from ventilation is affected by several parameters, such as clothing design, ambient air speed, and human movement. The effect of clothing ventilation due to fabric air permeability, human movement, and clothing openings on the total heat transfer was simulated at the local parts of the body for various conditions in clothing ensemble 1 will now be presented as shown in Figure 11.

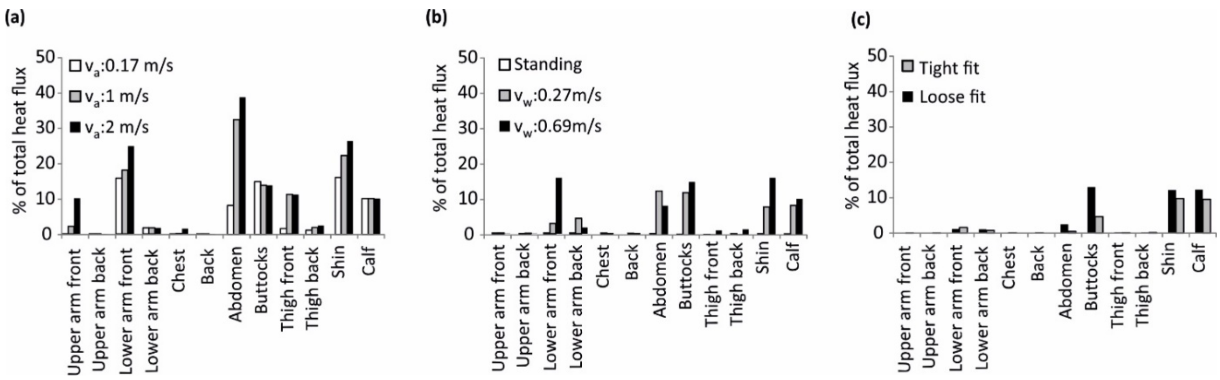


Figure 11 The contribution of clothing ventilation to the total heat flux for the various conditions were simulated including effect of body movement at ambient calm condition (0.17 m/s) (a), effect of ambient air speed at walking speed of 0.69 m/s (b), and effect of clothing fit at walking speed of 0.69 m/s (c).

4. Discussion

The developed model provides detailed and accurate insights about the effect of human movement on heat transfer pathways such as conduction, radiation, forced convection due to internal air flow in the enclosed air layer and ventilation through the fabric and garment openings [22]. The change in the thickness of the enclosed air gaps and the consequent changes in their volumes due to human movement was quantified using validated 3D simulation technology. Based on this data, the internal air flow and forced convective heat transfer coefficients were derived for the different parts of the body. The simulated and experimental data indicate that the air exchange through clothing openings and fabric due to its air permeability was significant and can contribute up to 40% of the total heat flux from local parts of the body (abdomen at wind speed 2m/s Figure 11). The importance of considering separately the different parts of the body was emphasized as oscillating parts (lower and upper limbs) can have a forced convective heat transfer two to three times higher than stationary parts of the body (chest, back, abdomen, and buttocks), as shown in Figure 7 . A high spatial resolution in terms of parts of the body was achieved with the developed modelling approach, which is its major advantage compared to existing regression-based models such as ISO 9920:2007 [8] and the model by Ghaddar et al. [40].

The whole body heat transfer coefficient for three different walking speeds (standing still, 0.27m/s, and 0.69 m/s), three ambient air speeds (0.17 m/s, 1m/s, and 2 m/s), and three different clothing fits (regular, loose, and tight fit) increases with an increase in walking speed for all three clothing fits and wind speeds, as shown in Figures 5 and 6. The average relative error in the simulated whole-body heat transfer coefficient was 11% compared to the average coefficient of variation in the measured data of 5%. The average relative error in the simulated heat transfer coefficient remained constant for different walking speeds, i.e. for standing still, walking at 0.27 m/s and 0.69 m/s the average relative error was 10%, 9%, and 11%, respectively. On the other hand, the average relative error in the simulated heat transfer coefficient reduces with an increase in ambient air speed, i.e. for the ambient air speeds of 0.17m/s, 1m/s, and 2ms the average relative error was 12%, 11%, and 2%, respectively. The reduction in relative error with increase in ambient air speed is due to the higher magnitude of the ambient air speed, which results in a higher contribution of convective heat transfer in the boundary air layer: 46%, 71%, and 79% for ambient air speeds of 0.17 m/s, 1 m/s and 2 m/s, respectively. The convective heat transfer coefficient in the boundary air layer is well defined and validated in existing studies [22, 41]. In enclosed air layer, the Richardson number indicated the dominance of forced convection during movement, while natural convection was predominant in stationary state (no human movement) and ambient calm condition. In boundary air layer, mixed convection was present in ambient calm conditions (stationary state and presence of movement) because Richardson number was observed between 0.1 and 10, therefore, both natural and forced convection had significant effect on heat transfer.

The developed model was further validated with regard to the heat transfer coefficients at parts of the body (Figures 7 and 8) through comparison to measured data with an agile walking thermal manikin. The parts of the body with higher moving frequency relative to the whole body, such as the upper arm, lower arm, thigh, and lower leg, presented higher heat transfer coefficients compared to those parts of the body that moved less with only an overall progressive speed of walking, such as the chest, abdomen, back, and buttocks. The higher moving frequency induced higher air speeds in the enclosed air layer since the change in the enclosed air volume occurred during a shorter period of time, which resulted in a higher forced convective heat transfer coefficient. The data also indicates that the whole-body heat transfer coefficients differ from the local heat transfer coefficients of parts of the body. Based on the analysis of enclosed air volume for all body parts (Figure 3 and 4), major air exchange was between the front and back body parts (e.g. upper arm front and upper arm back) and air exchange due to movement between laterally neighbouring body parts (e.g. upper arm and lower arm) was negligible. Therefore, the body parts were assumed as independent segments without any lateral exchange of air between them. However, according to Ismail et al. and Joshi et al. [42, 22], the intersegmental air exchange due to air permeability and natural convection under stationary state (no human movement) affected the heat loss from individual body parts and the accuracy of model by up to 6% [20].

For many applications, such as modelling of thermal physiology and thermal comfort, clothing research requires the local heat transfer coefficients of the parts of the body. Up to now, existing regression models of clothing ventilation that provide the heat transfer coefficient for only the whole body have been frequently used due to the lack of local models. If the whole body heat transfer coefficient values (for example, obtained by using ISO 9920:2007 [8] or other regression based models [7,8]) were used for the local parts of the body, these heat transfer coefficients would have a large error for stationary parts of the body (head, chest, back, abdomen, and buttocks) compared to moving body parts (lower and upper limbs) (Figure 7 & 8). The values of the heat transfer coefficient obtained from the presented model are more accurate for individual parts of the body, as seen by the comparison of the experimental and simulation data in Figure 7 & 8. For example, for those parts of the body which are relatively stationary while walking, the presented model shows an average relative error in predicted heat transfer coefficient of 15%, whereas the average relative error of the whole body heat transfer coefficient based on ISO 9920:2007 is inaccurate for the same region by 24%. The average relative error in predicted heat transfer coefficient for moving parts of the body parts was 11% for both the presented model and ISO 9920:2007.

The presented model is based on fundamental principles of fluid flow, and heat and mass transfer. Therefore, it provides much more detailed insight into heat and mass transfer processes such as air flow in an enclosed air layer and ventilation compared to other models which are based on empirical data [7, 8]. The model calculates the internal air speed based on the pump rate (equation 3), which depends on the change in air gap thickness (air volume) and intensity of movement. As shown in Figure 7 (a) and (b), the internal air speed and forced convective heat transfer coefficient vary significantly among the parts of the body. The internal air speed increases with an increase in walking speed (Figure 9(a)) and change in air volume, because changes in the air volume due to walking take place during a shorter time period at higher walking speed. For example, the change in air volume (compression/expansion) is highest for region in lower arm, shin and calf (36%) compared to upper arm which has lowest (4%). There could be several reason for the differences in measured compression/expansion of air volume in present study and the reported value of Danielsson (between 10% to 65%) [11]. For example, variation in moving patterns (e.g. stride length) in human avatar (simulation) and human subject, clothing design (trouser and t-shirt/shirt in present study while whole body coverall in Danielsson's study), ease allowances for given clothing fit in both the studies, and different methods such as tracer gas method and garment simulation software. Due to variation in all these parameters one to one comparison of compression/expansion of air volume between present study and Danielsson's study was not possible.. The internal air speed is corelated to change in air volume and duration of change. Human movement causes changes in an enclosed air volume, at a given walking speed (0.69m/s) the time required to change the enclosed air volume is the same (for different clothing fit and between different phases of the gait cycle). For different clothing fit levels, the change in an enclosed air volume is also similar (Figures 3 and 4) for the majority parts of the body, except the back and buttocks where ease allowances have a pronounced effect on the air gap due to the concavity of the shoulder blades. Therefore, as shown in Figure 10(a and b), the clothing fit has a negligible effect on the internal air speed and forced convective heat transfer coefficient in the enclosed air layers.

The presented model also considers the ventilation of air resulting from the fabric air permeability and clothing openings. The ventilation of air due to this air permeability is influenced by the ambient air speed and direction of air flow, as shown in Figure 11(a). At higher wind speeds, wind-facing parts of the body show a higher share of convective heat transfer in the total heat transfer coefficient than the rear parts of the body. With an increase of wind speed the penetration of air through the porous fabric also increases due to the increased pressure difference (equation 16), which also results in increased heat transfer by ventilation. Consequently, the wind facing parts of the body have 40% to 63% higher heat transfer coefficients for wind speeds of 1m/s and 2 m/s, respectively, compared to the rear parts of the body. Besides, the clothing openings play a major role in ventilation as those parts of the body with clothing openings, such as at the shin, calf, lower arm, abdomen and buttocks, demonstrate a higher share of ventilation in the total heat transfer coefficient. This effect results from the infiltration of ventilated ambient air with lower temperature contributing to additional heat loss. As shown in Figure 11 (b), with an increase of walking speed the heat transfer due to ventilation increases in those parts of the body with openings, because a higher walking speed represents a high rate of oscillation and frequent air exchange through the openings. The ventilative heat transfer is also affected by the size of the clothing openings, and loosely fitting clothing has relatively larger openings (the difference between the circumference of the clothing and of the part of the body at the opening) at the lower leg (24cm) and waist (23cm) compared to tightly fitting clothing (18cm and 10cm for lower leg and waist, respectively) because bigger clothing openings will allow more ventilation of air compared to smaller clothing openings. Therefore, the ventilative heat transfer is slightly higher for loosely fitting clothing compared to tightly fitting clothing at the buttocks and the region of the lower leg. The openings at the lower arms were closed (cuffs with buttons) in both the loosely fitting and tightly fitting clothing, and had similar opening sizes (11cm), and hence, no noticeable difference was observed at the lower arms. This implies that ventilative heat transfer depends more on the size of the clothing openings than on the fit of the clothing (ease allowance) of a part of the body with an opening.

There are very few analytical models that consider the fundamental reasons of forced convection in air layers due to human movement [10, 11]. They however typically oversimplify the skin-clothing-environment system and neglect the factors that affect the forced convective heat transfer due to human movement (anatomic shape of human body, change in enclosed air gap thickness). The model developed by Ghali et al. [10] for the simulation of a homogeneously varying air gap and periodic ventilation was validated on a flat plate with a relative error of 31%. The assumption of a flat plate and homogenous air gaps does not represent the actual spatial complexity of skin-clothing-environment system. The present study and previous experimental studies have emphasized the pumping effect and various parameters affecting it, such as a change in enclosed air volume and anatomic shape of human body, and clothing fit [2, 3, and 11]. Therefore, these parameters should be considered during the modelling and validation of the effect of human movement on the heat transfer coefficient. Another model, developed by Ismail et al. [21], has considered the local heat transfer coefficients for parts of the body, but neglected the effect of internal air speed resulting from the compression and expansion of the enclosed air layer due to the deformation of the clothing layer during movement. Ismail et al. [21] assumed that the only air movement inside of the enclosed air layer is due to the ventilation either through the clothing's air permeability or clothing openings. The experimental data of Belding et al. [2] and of the present study suggest that the air speed in an enclosed air layer (mixing of air) resulting from body movement has a significant effect on the convective heat transfer coefficient, which contradicts the assumptions made by Ismail et al. [21]. The forced convection in enclosed and boundary air layers, and ventilation are mainly responsible for the reduced thermal insulation during body movement, as shown in Figures 9 and 10. The mathematical modelling of such an effect requires an accurate input for the change in enclosed air gap thickness and consequently air volume, which is possible with 3D scanning or garment simulation on a human avatar in dedicated software. The methods to obtain air gap data using these methods are nowadays well established and validated [37][32][40][41]. Obtaining the air gap data using garment simulation on a human avatar consists of several steps, such as preparing a garment 2D pattern, draping the garment around the human avatar, applying human movement simulation, and post processing the air gap thickness in CAD software. This process is very time- and cost-efficient as well as accurate as compared to 3D scanning or experimental methods.

The forced convection in an enclosed air layer for human movements other than walking, such as crawling during firefighting, skiing, and biking can also be addressed by the methods of the present study. However, analysing such complex movements using experimental methods such as measurement on a thermal manikin or human subjects can be very cumbersome process. The convective heat transfer coefficient in the boundary air layer is the combined effect of the motion of the parts of the body and the ambient air speed. As suggested by Danielsson [11], both these components cannot be simply added to have an equivalent convective heat transfer coefficient. The correction coefficients used in this study (Table 1) [11] are limited to walking, and should be developed individually for other types of movement. This can be done empirically as suggested by Danielson [11] and Nishi and Gagge [27], either by measuring the local heat flux, temperature, and air velocity at different parts of the body during movement, or using naphthalene sublimation and translating the weight loss resulting from the naphthalene sublimation to the heat transfer coefficient.

5. Conclusion

The presented model provides detailed insight into the forced convective heat transfer mechanism as affected by human movement along with ambient air speed and clothing fit. It provides much detailed information about individual heat and mass transfer mechanisms such as conduction, radiation, convection including the air flow in an enclosed air layer, and ventilation. The results from presented model systematically compared against the experimentally measured data on an agile thermal manikin for wide range of conditions such as standing still and two walking speeds (0.27m/s and 0.69m/s), three ambient air speeds (0.17m/s, 1m/s and 2m/s) and three different degrees of clothing fit (tight fit, medium fit and loose fit). The average relative error in simulated whole body heat flux was 11%. The presented model has ability to simulate heat transfer with high spatial resolution such as individual body segment, which is the major advantage over existing models. The developed model can be extended to other movement types as well because it employs the fundamental factors behind the pumping effect. The ability of the presented model to simulate the forced convection in an enclosed air layer, and ventilation of an enclosed air layer for different parts of the body, makes it ideal for optimization and parametric studies, which can be very useful as a research and design tool in many fields, such as clothing research, thermal physiology modelling, energy efficiency in automotive and building sectors, and occupational safety.

Acknowledgements

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