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Human body area factors for radiation exchange analysis: standing and walking postures

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Abstract Effective radiation area factors (f_{eff}) and projected area factors (f_p) of unclothed Caucasians' standing and walking postures used in estimating human radiation exchange with the surrounding environment were determined from a sample of adults in Canada. Several three-dimensional (3D) computer body models were created for standing and walking postures. Only small differences in f_{eff} and f_p values for standing posture were found between gender (male or female) and body type (normal- or overweight). Differences between this study and previous studies were much larger: ≤0.173 in f_p and ≤0.101 in f_{eff}. Directionless f_p values for walking posture also had only minor differences between genders and positions in a stride. However, the differences of mean directional f_p values of the positions dependent on azimuth angles were large enough, ≤0.072, to create important differences in modeled radiation receipt. Differences in f_{eff} values were small: 0.02 between the normal-weight male and female models and up to 0.033 between positions in a stride. Variations of directional f_p values depending on solar altitudes for walking posture were narrower than those for standing posture. When both standing and walking postures are considered, the mean f_{eff} value, 0.836, of standing (0.826) and walking (0.846) could be used. However, f_p values should be selected carefully because differences between directional and directionless f_p values were large enough that they could influence the estimated level of human thermal sensation.

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Keywords Effective radiation area · Projected area · Solar radiation · Longwave radiation · Standing posture · Walking posture

List of symbols

A_1 (A_{eff})	Effective radiation area (m^2)
A_2	Spherical surface area (m^2)
A_{3DS}	Total body surface area obtained from 3DS Max computer software program (m^2)
A_D	Total body surface area (m^2)
A_{Du}	Total body surface area calculated using DuBois and DuBois (1916) formula (m^2)
A_P	Projected area (m^2)
dA_1	A small portion of the human body surface area (m^2)
dA_2	A small portion of the entire surrounding spherical surface area (m^2)
F	Angle factor
f_{eff}	Effective radiation area factor (= A_{eff} / A_D)
f_p	Projected area factor per unit of effective radiation area (= A_p / A_{eff})
f_p^*	Projected area factor per unit of total body surface area $\left(= A_p/A_D = f_p \times f_{eff}\right)$
K_b	Direct beam solar radiation on the human body surface (Wm^{-2})
K_d	Diffuse beam solar radiation from the sky (Wm^{-2})
K_r	Total reflected solar radiation by objects and ground (Wm^{-2})
L	Terrestrial (longwave) radiation on the human body surface (Wm^{-2})
$n_{1/4}$	Number of observations over one-quarter of the entire surrounding spherical surface area
$n_{1/2}$	Number of observations over one-half of the entire surrounding spherical surface area

R	Incoming solar radiation on the human body surface (Wm^{-2})
r	A distance between the human body surface and a surrounding spherical surface area (m)
T_a	Air temperature (°C)
T_{mrt}	Mean radiant temperature (°C)
α	Azimuth angle (°)
β	Altitude (elevation) angle (°)
β_1	An incident angle between dA_1 and central point line of dA_1 and dA_2 (°)
β_2	An incident angle between dA_2 and central point line of dA_1 and dA_2 (°)
ψ_{sky}	Sky view factor (1.0=100%)

Introduction

Radiation exchange plays a significant role in the human energy budget. Steadman (1971) estimated that the apparent temperature was raised by nearly 14°C under calm conditions and by 7°C in a strong wind by the effect of solar radiation. Hodder and Parsons (2007) stated that each increase of direct beam solar radiation of around 200 Wm^{-2} increased predicted mean vote (PMV; Fanger 1972) by one sensation scale unit. Also, radiation exchange was revealed as the largest component of total body energy loss for people in a normal environment (Landsberg 1969) and on clear winter nights in New Zealand (Tuller 1980).

Human receipt and emission of radiation are affected by body shape, posture and clothing. Body shape and posture control the body surface area exposed to direct beam solar or other point-source radiation (projected area, A_p) and the proportion of the total body surface area exposed to the surrounding radiant environment rather than to other body parts (effective radiation area, A_{eff}). Often, factors that represent proportions of the body surface area are utilized. The projected area factor is A_p /A_{eff} (f_p) or A_p /A_D (f_p^*) when A_D is total body surface area. The effective radiation area factor (f_{eff}) is A_{eff} /A_D.

Many human thermal exchange models have employed f_{eff} and/or $f_p(f_p^*)$ directly [e.g. Burt model (Burt 1979, modified by Tuller 1990), COMFA (comfort formula; Brown and Gillespie 1986, 1995), MENEX (Man-environment heat exchange; Blazejczyk 1994, 2004, 2005), OUT_SET* (Pickup and de Dear 2000), RayMan (Matzarakis et al. 2000, 2007, 2009), PT (perceived temperature; http://www.utci.org/isb/documents/perceived_temperature.pdf)] or mean radiant temperature (T_{mrt}), which uses f_{eff} and f_p in its formula [e.g., PMV, PET (physiological equivalent temperature; Höppe 1999), UTCI (universal thermal climate index; http://www.utci.org)].

A number of studies estimating human body radiation area factors are available. However, each of these employs somewhat different methods, subjects and sample sizes. No study has f_p^* or f_{eff} values that are applicable to the entire population. Our purpose is to extend the investigation of human body radiation area factors to body shapes and postures that have received only limited attention. We begin with a review of the methods and subjects of major human body radiation area studies.

Clothing styles, color and insulation values are quite variable and will not be addressed in this study. The effect of clothing can be considered by utilizing clothing area factors dependent on various clothing types and ensembles employing information found in sources such as McCullough et al. (1985, 1989), ASHRAE (1997) and ISO9920 (2007).

The age composition of the population and human body shape in developed countries are changing. There is increasing concern about implications of the trend toward more overweight people. The mean contemporary Canadian adult population is already considered to belong to the overweight body mass index (BMI) category (CHS 1978; CHHS 1992; CCHS 2004). The population is aging. However, many reported f_p and f_{eff} values have been determined from samples of young, normal-weight adults, idealized human body shapes or cylinders.

The widely used f_{eff} and f_p results of Underwood and Ward (1966) and Fanger (1972) were determined by photographing a limited sample of standing and sitting people from a variety of angles. Steinman et al. (1988) modified Fanger's model making it applicable to the complex enclosures found in modern architecture using mean f_p values. Jones et al. (1998) applied the photographic method to a mannequin in clothed and unclothed standing postures. They studied both the whole body and individual body parts. Tanabe et al. (2000) and Kubaha et al. (2004) used three-dimensional, computerized human body models in unclothed sitting and standing postures.

Studies that have investigated the effects of gender (male or female) and body type (under-, normal-, overweight or obese) on body area factors have usually relied on small samples. Results are not wholly consistent between studies. Bandow and Bohnenkamp (1935) used an electrical capacity technique and found that f_{eff} slightly decreased with increasing body size for males but increased for females. However, Guibert and Taylor (1952) noted these results suffered from problems of accuracy and consistency (9% difference in f_{eff} when the measurement was repeated). Guibert and Taylor (1952) showed 3% and 1% decreases of f_{eff} from medium to heavy and light standing male body types, respectively. However, they studied only one male subject in each or the light, medium and heavy body type categories. Horikoshi et al. (1990) also tested only three male subjects and found a 1% difference in f_{eff} between two under-weight subjects and no difference in f_{eff} between under-weight and over-weight subjects. Underwood and Ward (1966) originally used 25 male and 25 female subjects 14–59 years old and found less than 1.0% difference in f_{p}^{*} between genders. Hence, they focused on males only and gave no data for females. They also found less than 2.5% between body sizes (largest and smallest A_{D} subjects). Though they compared f_{p}^{*} between genders and body sizes, they did not compare f_{p}^{*} between different body types. They also measured at only five different azimuth angles (0, 45, 90, 135 and 180°) and four different altitude angles (0, 30, 63 and 90°). Fanger (1972) reported no gender- and body type-related differences in f_{eff} and no gender-, body type- and clothing-related differences in f_{p}. His ten male and ten female college students belonged to only one body type category, the normal-weight BMI class, so his results did not confirm similarity or difference of body area factors (f_{eff} and f_{p}) between various body types. Therefore, the similarity or variation of body area factors among the combination of gender and body type has not yet been clearly proved.

Currently available body models consider only sitting and standing postures. In outdoor areas and many indoor situations, walking is another common posture. Standing and sitting postures have the arms and legs in consistent positions. Walking is a series with different positions of each arm and leg in relation to other parts of the body. PET and UTCI are based on an adult's walking posture. However, no detailed study of actual walking posture has been published. Only one study, Ward and Underwood (1967), modeled one position of a walking stride among three male subjects using a photographic method. However, measured angle variation was too limited, and the results seem unrealistically high. Also, they did not define the effective radiation area factor (f_{eff}). Roller and Goldman (1968) measured a projected area factor (f_{p}^{*}) of 0.24 at only one solar altitude, 60°, which was 0.02 greater than standing posture. Steadman (1979) assumed 0.80 as a walking subject's f_{eff} and presented a formula for estimating f_{p}^{*} as a function of altitude angle adding 0.02 to the mean f_{p} values of Fanger's (1972) standing posture. de Freitas et al. (1985) modelled moving people (runners). They estimated runners' f_{eff} as 0.82, from Fanger's (1972) f_{p} values, and f_{p}^{*} values from Taylor's (1956) formula. Their estimate of f_{eff} has not been tested, and Taylor's formula is not for a moving body posture but for a cylindrical standing posture (Pugh and Chrenko 1966).

The purpose of this study is to fill some of the gaps in currently available human body radiation area factors, f_{eff} and f_{p}, and expand their application to a wider range of body shapes and postures. Many of the studies noted above were done several years ago on a very limited number of subjects. Our study sampled a relatively larger number of present-day adults. This is the first detailed investigation of walking posture to include the complete stride cycle. The study includes both genders and investigates whether there are any radiation area factor differences between normal- and over-weight people. Comparisons with body area factors given in previous studies are included. Examples of possible effects of differences in radiation area factors on modelled human absorbed solar and longwave radiation are given.

Methods

Analytical theory

According to the reciprocity theorem (Fanger 1972),

$$A_1 F_{A1-A2} = A_2 F_{A2-A1} \tag{1}$$

A_1 is the effective radiation area of the human body surface (A_{eff}), $F_{\mathrm{A1\text{-}A2}}$ is the angle factor between the person and the sphere (A_2), $A_2=4\pi r^2$ is the spherical surface area and $F_{\mathrm{A2\text{-}A1}}$ is the angle factor between the sphere and the person.

For a small part of the spherical surface area, dA_2, Eq. 1 will be (ASHRAE 1997),

$$dF_{A1-dA2} = dF_{A1-\cos\beta 2dA2} \tag{2}$$

$$A_1 dF_{A1-\cos\beta 2dA2} = \cos\beta_2 dA_2 F_{\cos\beta 2dA2-A1} \tag{3}$$

Therefore, the angle factor between A_1 and A_2 would be (Oguro et al. 2001),

$$F_{A1-A2} = \int_{A2} dF_{A1-dA2} = \int_{A2} dF_{A1-\cos\beta 2dA2} = \int_{A2} \left(\frac{F_{\cos\beta 2dA_2-A_1}}{A_1}\right)\cos\beta_2 dA_2 \tag{4}$$

From the definition of angle factor (ASHRAE 1997),

$$F_{\cos\beta 2dA_2-A_1} = \int_{A1} \frac{\cos\beta_1 \cos\beta_2 dA_1}{\pi r^2} \tag{5}$$

β_1 and β_2 are incident angles between central points of dA_1 and dA_2. If the size of the body part dA_1 and the portion dA_2 is very small compared to the distance r between dA_1 and dA_2, it could be considered that $cos\beta_2 \approx 1.0$. Then Eq. 5 can be written as,

$$F_{\cos\beta 2dA2-A1} = \int_{A1} \frac{\cos\beta_1 dA_1}{\pi r^2} = \frac{A_p}{\pi r^2} \tag{6}$$

$$A_p = \int_{A1} \cos\beta_1 dA_1 \tag{7}$$

By combining Eqs. 4 and 6,

$$F_{A_1-A_2} = \frac{1}{\pi}\int_{A_2} \frac{f_p}{r^2}\cos\beta_2 dA_2 = \frac{1}{\pi}\sum_{i=1}^{n}\frac{f_{pi}}{r^2}\cos\beta_2 dA_2 \quad (8)$$

(Kubaha et al. 2003)

$$f_p = \frac{A_p}{A_1} = \frac{A_p}{A_{eff}} \quad (9)$$

n is the number of equal areas dA_2 comprising the entire spherical surface area.

As the angle factor $F_{A1\text{-}A2}$ should be 1.0, the effective radiation area of the body A_1 (=A_{eff}) can be estimated from Eq. 10 by combining Eqs. 8 and 9,

$$A_{eff} = \frac{1}{\pi}\int_{A_2} \frac{A_p}{r^2}\cos\beta_2 dA_2 = \frac{1}{\pi}\sum_{i=1}^{n}\frac{A_{pi}}{r^2}\cos\beta_2 dA_2 \quad (10)$$

$$f_{eff} = \frac{A_{eff}}{A_D} \quad (11)$$

The following sections describe the method used to obtain the information needed to compute f_{p} and f_{eff} from a sample of adults.

Subjects

Body data were collected for a sample of both normal- (male, n=31; female, n=40) and over-weight (male, n=48; female, n=20) adults (age 18–65 years) at Saanich Commonwealth Place recreation center in Victoria, BC, Canada (Table 1). This study was approved by the University of Victoria ethics committee. Informed consent was obtained from all subjects. The mean BMI, 24.8, of this study was at the border between the normal-weight category, 18.5–24.9, and over-weight category, 25.0–29.9.

All subjects wore swim suits (male: triangle or box style, female: one piece or bikini style). They were instructed to stand and walk naturally. Their age and height data were collected using a survey. Heights (m) were confirmed using photometric comparison with several reference heights. Weights (kg) for all subjects were measured with a digital electronic scale manufactured by Taylor (http://www.taylorusa.com) and calibrated with several reference weights. Standing posture was obtained by taking pictures with Sony Cybershot 3.2 and Nikon Coolpix 8700 cameras, and walking posture by recording videos with Sony DCR-TRV22 and Canon ZR45 camcorders. Pictures and videos of each person were taken one each from the front and side (Fig. 1a). The pictures were taken at the median height of the torso (chest and abdomen), 1.2 m, instead of using the weighting height of human body, 1.1 m, because the torso has the largest body surface area among all body parts. All photos were taken at a distance of 10 m to reduce image distortion.

Total body surface area

Two methods were used for determining total body surface area (A_{D}, m^2): the DuBois and DuBois (1916) formula (A_{Du}) and 3DS Max 9.0 software (A_{3DS}; Autodesk®, http://www.autodesk.com). The DuBois and DuBois (1916) formula overestimated A_{D} in both male and female models compared with the 3DS Max method. The overestimation was less than 1% in male models but reached 7.4% in female models. Also, the overestimation in overweight models was almost twice that in normal weight models (Table 1).

Table 1 Subjects' mean basic body data categorized by body mass index (BMI) class. *NW_M* Normal-weight male, *NW_F* normal-weight female, *OW_M* over-weight male, *OW_F* over-weight female. *SD* standard deviation

Category	n	Height (m)		Weight (kg)		BMI[a]		Total body surface (m^2)	
		Mean	SD	Mean	SD	Mean	SD	Mean	
								A_{3DS}[b]	A_{Du}[c]
NW_M	31	1.81	0.06	75.6	6.5	23.0	1.4	1.95	1.96
NW_F	40	1.69	0.05	62.5	6.4	22.0	1.8	1.65	1.71
OW_M	48	1.81	0.05	88.0	5.8	26.9	1.4	2.07	2.08
OW_F	20	1.66	0.05	75.2	6.4	27.2	1.6	1.71	1.84
Mean of all four categories		1.74		75.3		24.8		1.85	1.90

[a] BMI = weight(kg)/height(m)^2. BMI classes are: under-weight (<18.5), normal-weight (18.5–24.9), over-weight (25.0–29.9), obese class 1 (30.0–34.9), obese class 2 (35.0–39.9) and obese class 3 (≥ 40.0)

[b] A_{3DS} obtained from 3DS Max computer software program

[c] DuBois and DuBois's (1916) formula $A_{\mathrm{Du}}=0.007184\cdot(\mathrm{H}\times 100)^{0.725}\cdot \mathrm{W}^{0.425}$ (m^2), H: height (m), W: weight (kg)

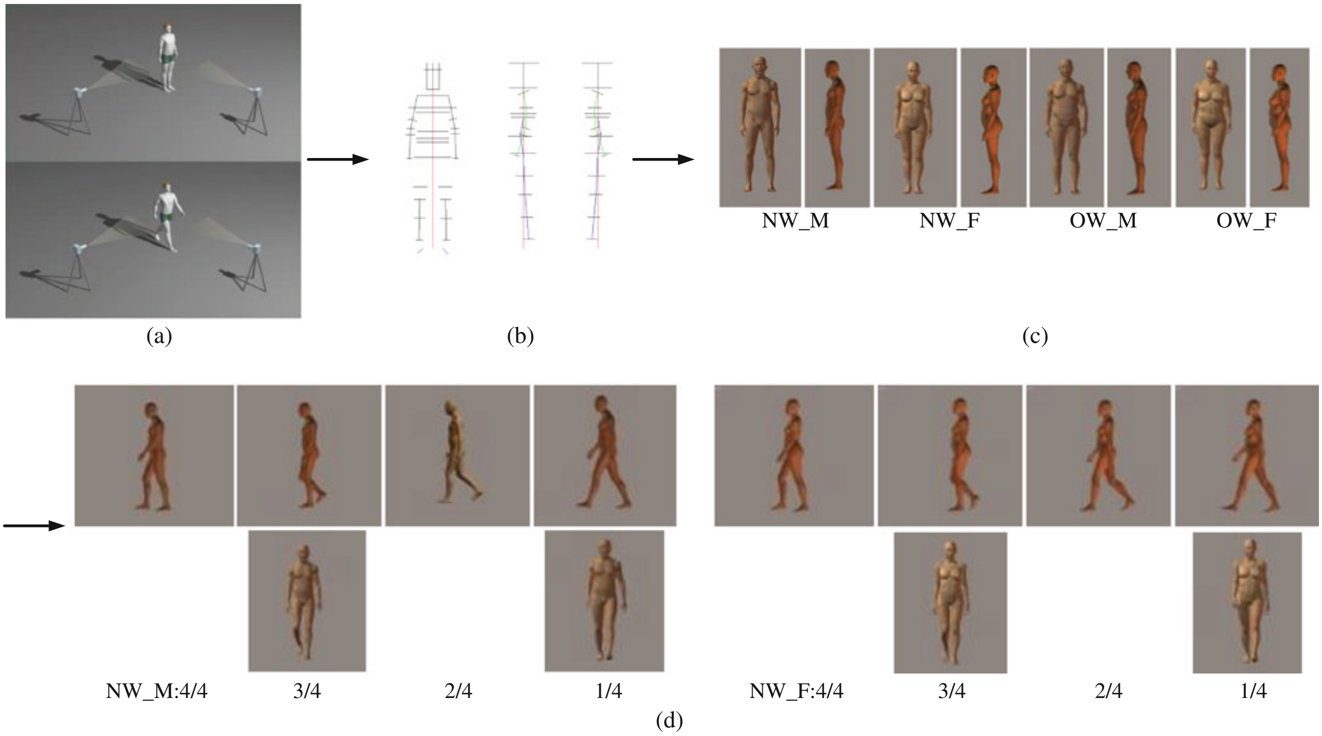

Fig. 1 The process for creating three-dimensional (3D) computer body models of standing and walking postures. **a** Taking pictures and videos, created in Vectorworks 2008 (Nemetschek Vectorworks®, http://www.nemetschek.net). **b** Creating body frames. **c** Front and side views of 3D computer standing models. **d** Positions of a stride for 3D computer walking models

DuBois and DuBois (1916) noted their formula could produce maximum ±5% errors. Many other researchers have also found some errors in the formula and modified it (e.g., Mosteller 1987; Mattar 1989; Livingston and Lee 2001). Recently, 3D scanning technology was adopted in this field (Tikuisis et al. 2001; Yu et al. 2003). The formula estimates of Tikuisis et al. (2001) were within 0.3% of our A_{3DS} values for both of the normal- and overweight male models. The formula results of Yu et al. (2003) were within 0.9% for the normal-weight female model and 4.1% for the overweight female model. The measured values of A_{3DS} were used as A_D in this study.

Data processing

Before analyzing collected data, image distortion was tested with reference images from pictures and videos in AutoCad 2002 (Autodesk®, http://www.autodesk.com). It was found that there was no centroid distortion (i.e., between two same size objects, an object located on the center is bigger than an object located on the edge in photographs). Only horizontal/vertical rotation correction was required.

The digital body shape images were imported into AutoCad 2002 after rotation correction using ACDSee Pro. 1.5 (ACDSee®, http://www.acdsee.com). Edge-of-body lines were digitized. Widths and lengths of important body parts (m) and the angles between them (°) were measured (e.g., width: neck, shoulder, chest, abdomen, hip; length: between neck and shoulder, between shoulder and chest, upper and lower arm, between hip and knee, between knee and ankle; angle: between shoulder and elbow, between elbow and wrist, between hip and knee, between knee and ankle). The mean values of body parts were used to make front and side body frames (Fig. 1b). Four 3D computerized standing body models (normal- and overweight male and female models) were created in Poser 6 & 7 (SmithMicro®, http://www.smithmicro.com) using the frames (Fig. 1c). Using existing body models in the Poser program, each body part's width and angles were adjusted with measured side and front body frames. More details on these adjustments can be found in the Poser program tutorials (http://poser.smithmicro.com/tutorials.html). The two male models consisted of 62,298 small surface elements and female models 194,206 as the female models were created in the advanced version, Poser 7. This would yield greater micro-details for females. However, our study is concerned with more general body images and thus additional micro-details are not important (see Fig. 1c, d).

The mean durations of walking strides of normal-weight male and female models were 0.62 [standard deviation (SD)=0.07)]and 0.57 (SD=0.05) seconds, respectively. Four images within a complete walking stride, the 1/4, 2/4,

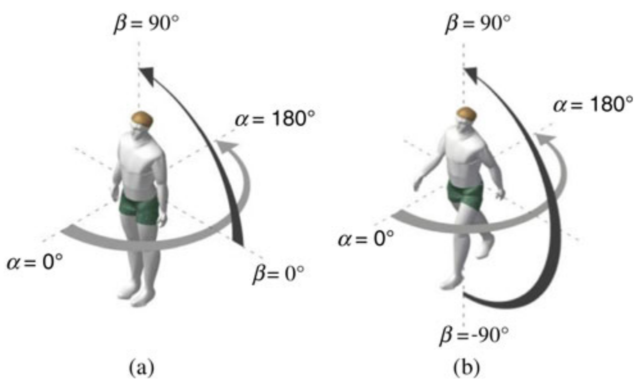

Fig. 2 Variation of azimuth (α) and altitude (β) angles for f_p values. **a** A quarter sphere (0°≤α≤180°, 0°≤β≤90°) for f_p values of standing posture since the body shape is symmetrical in the posture, **b** Half a sphere (0°≤α≤180°, −90°≤β≤90°) for walking posture because of asymmetrical body shape (created in Vectorworks 2008; http://www.nemetschek.net)

3/4 and 4/4 positions, of normal-weight male and female models were extracted from the videos using Adobe Premiere Pro 1.5 (Adobe®, http://www.adobe.com). Angles among upper body, arms and legs were measured in AutoCad 2002. The mean angles were used to construct walking body models in Poser 7 (Fig. 1d). The 1/4 starting position of a stride had the right arm and left leg located in front of the torso in this study. The opposite walking positions (e.g., 1/4 position: the left arm and right leg in front) were assumed to have the same A_p and f_p values in the opposite azimuth angles. Angles of 2/4 and 4/4_Front used mean values of 1/4 and 3/4_Front because their positions were transitional between the latter two.

The 3D models were imported into AutoCad and rotated regularly as shown in Fig. 2. The more frequent the measurements, the more detailed the representation of the human body and the more accurate the determination of A_p and A_{eff}. The initial investigation started with standing posture, normal-weight male and female models. Four different angle increments; 5°, 10°, 15° and 30°; were compared to assess the effects of number of observations on estimated A_{eff} and f_{eff}. The number of observations are $36 \times 18 = 648$ (per 5°), $18 \times 9 = 162$ (per 10°), $12 \times 6 = 72$ (per 15°) and $6 \times 3 = 18$ (per 30°), respectively. Also, the 1/4 spherical surface area was taken at the mid-point of the angle measurement, e.g., for every 5° at azimuth angle (α): 2.5, 7.5······172.5, 177.5°; altitude angle (β): 2.5, 7.5······82.5, 87.5°. The number of per 5° measurements, 648, was almost 4 times the number of per 10° measurements, 162, but the f_{eff} differences were small, 0.005. Per 15° and 30° measurements created greater differences, 0.016 and 0.067, respectively. Because of the small differences, further analyses employed measurements taken every 10°. Further testing for walking posture and over-weight subjects is recommended for further studies.

Rotated images were exported to Photoshop 7.0 (Adobe®, http://www.adobe.com). To keep the same scale for exporting the images, the same scale value in the zoom function was used during the entire process in each category in the AutoCad program. The pixel values (1 pixel≈0.056 cm^2) in Photoshop were converted to the real A_p values.

A_p data were measured from only 1/4 of the entire spherical surface area (α: 0–180°, β: 0–90°) for standing posture (Fig. 2a) and from half a spherical surface area (α: 0–180°, β: -90–90°) for walking posture (Fig. 2b) in this study. Therefore, A_{eff} can be calculated with:

$$A_{eff} = 4 \times \frac{1}{\pi} \sum_{i=1}^{n_{1/4}} \frac{A_{pi}}{r^2} \cos\beta_2 dA_2 \quad \text{for standing posture} \qquad (12)$$

$$A_{eff} = 2 \times \frac{1}{\pi} \sum_{i=1}^{n_{1/2}} \frac{A_{pi}}{r^2} \cos\beta_2 dA_2 \quad \text{for walking posture} \qquad (13)$$

when A_p data are collected at a variety of α and β angle increments in 1/4 ($n_{1/4}$) and 1/2 ($n_{1/2}$) of the spherical surface area. β_2 and r are an incident angle and distance between a human body surface and a small portion dA_2 of the entire surrounding spherical surface area, respectively.

Results

Standing posture

Projected area factor

Projected area factor can be presented in two ways. The first expresses projected area as the proportion of effective radiation area, $f_p = A_p/A_{eff}$. This is then used in a formula to find the mean radiant temperature (T_{mrt}) in PMV (Fanger

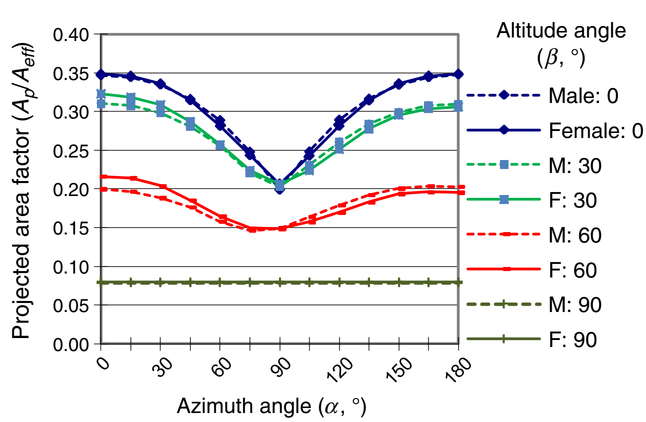

Fig. 3 Comparison of projected area factors (f_p) of normal-weight male and female models (standing posture)

Table 2 Directionless f_p values of normal- and over-weight male and female models

Category		Altitude angle (β, °)										
		0	5	15	25	35	45	55	65	75	85	90
NW_M		0.303	0.302	0.296	0.282	0.261	0.233	0.199	0.161	0.123	0.087	0.079
NW_F		0.302	0.301	0.295	0.283	0.262	0.234	0.201	0.161	0.120	0.084	0.080
OW_M			0.303	0.297	0.284	0.263	0.232	0.199	0.161	0.122	0.089	
OW_F			0.301	0.296	0.282	0.262	0.235	0.202	0.163	0.125	0.094	
	Male mean		0.303	0.297	0.283	0.262	0.232	0.199	0.161	0.122	0.088	
	Female mean		0.301	0.295	0.282	0.262	0.235	0.201	0.162	0.123	0.089	
	Overall mean	0.302	0.302	0.296	0.283	0.262	0.233	0.200	0.162	0.123	0.088	0.079

1972) and PET (Höppe 1999). The second is the proportion of total body surface area, $f_p^* = A_p/A_D = A_p/A_{eff} \times A_{eff}/A_D = f_p \times f_{eff}$. This is used for calculating quantities of absorbed direct beam solar radiation or other point source radiation (e.g., infrared heater) per unit area of the entire body surface. The purpose of the use of f_p and f_p^* is the same, i.e., to input the effect of direct beam solar radiation or other point source radiation into human thermal exchange models.

The f_p difference between normal-weight male and female models reversed around 60–90° of azimuth angle (α) (Fig. 3). Female f_p values were up to 0.017 greater before α=60–90°, and male f_p values were up to 0.014 greater after. Females' breasts and males' more open stance between the two legs seem to create this phenomenon (see Fig. 1c). In the f_p comparison of all four body type models, the maximum difference was 0.017 between normal-weight male and female models. The maximum difference between other combinations was 0.015. Fanger (1972) reported only a very small male–female difference in f_p. The results of this study produce the same conclusion.

Depending on the application, we can consider two extremes of human body orientation. The first is the directionless orientation used when people are facing a variety of different directions. Body orientation is essentially random. This mode is also used in general modeling studies when we do not know the actual body orientation. The second is the directional orientation used when people face a known, consistent direction.

Directionless f_p values of the four body types were very close (Table 2). When altitude angle (β) was up to 65°, the maximum difference was only 0.002. When β was 75° and 85°, more differences occurred between normal- and over-weight female models, 0.005 and 0.01 respectively. Therefore, the mean f_p values can be used to represent the contemporary Caucasian adult population in Canada (from the formula for mean of standing posture in Fig. 4).

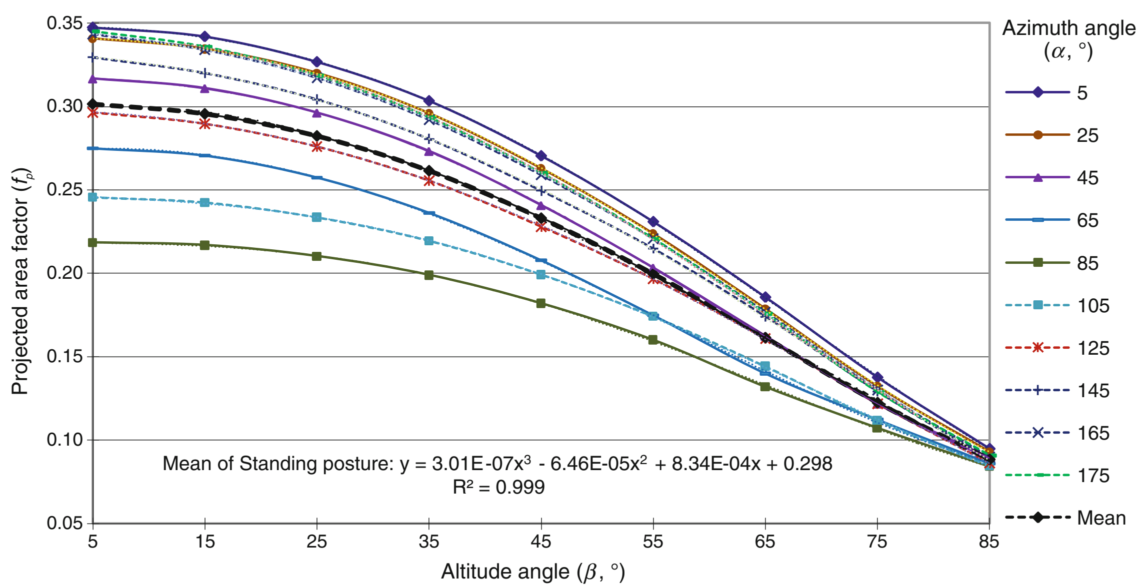

Fig. 4 Directional projected area factors (f_p) dependent on solar altitude angles (β) of the mean male and female body type models and best fit equation for azimuth angles (α) between 5° and 175°

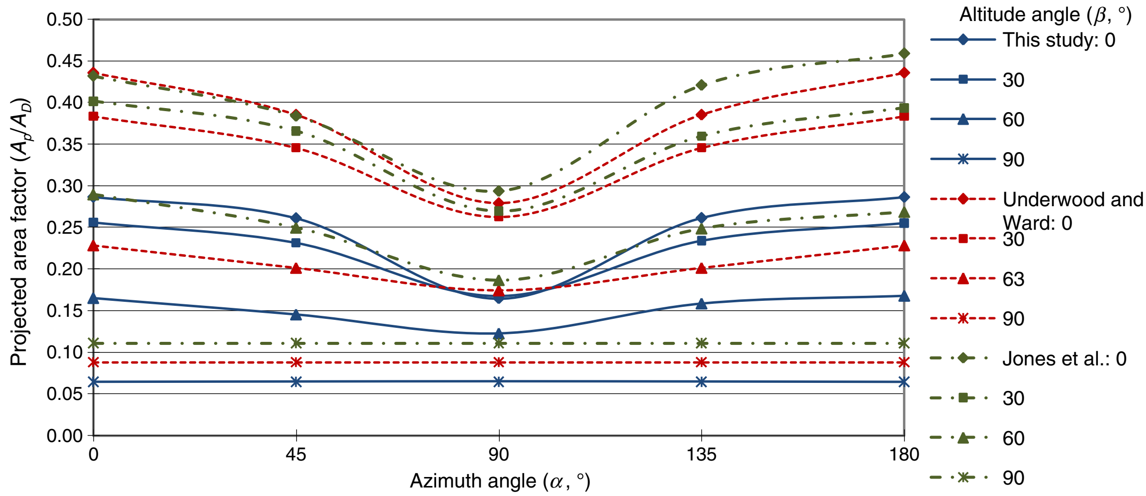

Fig. 5 Comparison of directional projected area factors (f_p^*) of the normal-weight male model for standing posture between Underwood and Ward (1966), Jones et al. (1998) and this study

If the exact direction of standing people is known, more precise estimation of f_p can be obtained from Fig. 4. The maximum directional difference in mean f_p from all body type models occurs between the front and side views of the body taken from a low β angle perpendicular to the body surface. In this study with α and β angles measured in 10° increments beginning at 5°, the maximum difference was 0.128 between α=5° and α=95° when β=5°. The differences decreased with increasing β angles.

The directional projected area factors of this study were compared with those of Underwood and Ward (1966), Jones et al. (1998), Fanger (1972), Tanabe et al. (2000) and Kubaha et al. (2004). The f_p^* values in Jones et al. (1998) and Underwood and Ward (1966) are from the ratio A_p/A_D instead of A_p/A_{eff} so their f_p^* values are expected to be lower than their unknown f_p values because A_D is larger than A_{eff}. For this comparison, adjusted f_p^* values of the normal-weight male model were used because the results reported by Jones et al. and Underwood and Ward came from males only. The greatest difference between this study and that of Jones et al. occurred at α=180° and β=0°, 0.173, and with that of Underwood and Ward at α=0° & 180° and β=0°, 0.149 (Fig. 5).

The mean directional f_p value of all four body type models combined was compared with the results of Fanger (1972), Tanabe et al. (2000) and Kubaha et al. (2004). The differences with Fanger's values were up to 0.02 at the medium altitude angle (β=45°) and from the oblique back azimuth angle, α=135° (Fig. 6). Values reported by Kubaha et al. were up to 0.022 different at the lowest altitude angle (β=15°) and the lowest azimuth angle (α=15°). The maximum difference with Tanabe et al.'s values was only 0.008. An interesting result was that the greater differences with Fanger and Tanabe et al. occurred more at the higher

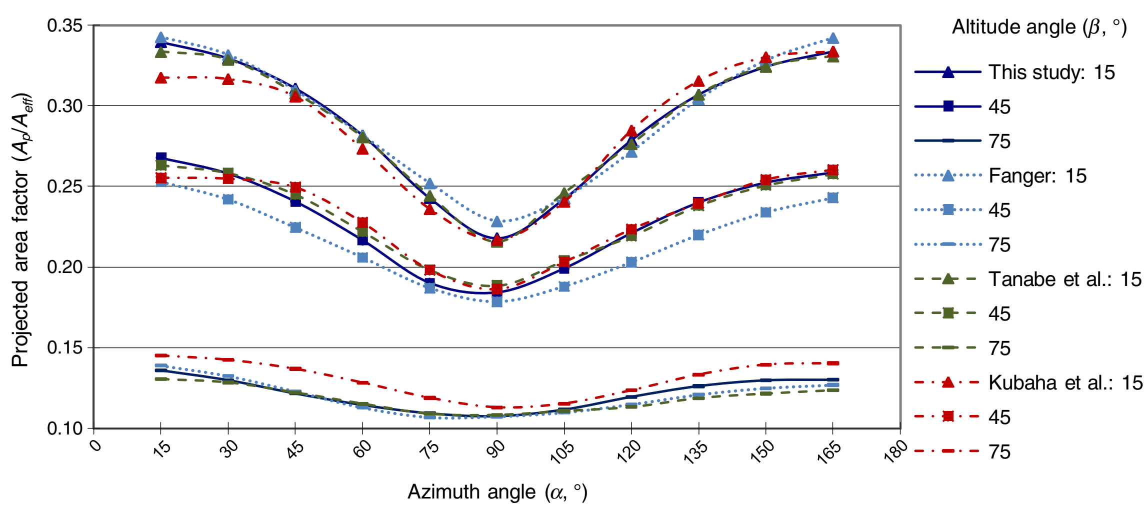

Fig. 6 Comparison of directional projected area factors (f_p) of standing posture between Fanger (1972), Tanabe et al. (2000), Kubaha et al. (2004) and this study

Table 3 Comparison of standing posture effective radiation area factor (f_{eff}) of BMI categories

Category	A_D (m^2)	A_{eff} (m^2)	f_{eff}
NW_M	1.95	1.618	0.830
OW_M	2.07	1.700	0.821
NW_F	1.65	1.359	0.824
OW_F	1.71	1.419	0.830
Mean	1.845	1.524	0.826

azimuth angles (from side to back: 90°≤α≤180°) when β is increasing and with Kubaha et al. more at the lower azimuth angles (α<90°) when β is increasing. Probably, the location of arms and hands and the stance width affect these phenomena. The 3D computer body models of Kubaha et al. and this study had more relaxed and more front-located arms and hands as well as a wider stance compared with thigh-side located hands and closer legs of the Fanger and Tanabe et al. models.

When the directionless f_p values of the four studies are compared, the greatest differences between this study and the others were: 0.012 at β=45° with Fanger, 0.011 at β=90° with Tanabe et al., and 0.01 at β=75° with Kubaha et al. All differences are small. However, differences in directionless f_p^* values are greater than those of f_p.

The differences between this study and those of Fanger and Tanabe et al. increase if f_p is multiplied by each study's different f_{eff} value (see Table 4). The maximum differences increased to 0.033 at β=40° with Fanger and 0.025 at β=0° and 45° with Tanabe et al. Differences with Kubaha et al. remained the same. Differences with the frequently used Fanger's values are nearly constant at β angles less than 60°, around 0.03.

Effective radiation area factor

A_D values used to compute effective radiation area factor (f_{eff}) were obtained from 3D computer body models in 3DS Max 9 (male=2.01 m^2, female=1.68 m^2). The mean f_{eff} value was 0.826. The maximum difference between all four body type models was only 0.009 (Table 3). Therefore, f_{eff} was not related to gender or body type for our sample of people.

The mean height, 1.74 m, (male=1.81 m, female=1.67 m) of this study was similar to subjects' heights in previous studies (Table 4). The A_D value, 1.845 m^2, was close to Kubaha et al.'s (2004) and Guibert and Taylor's (1952) studies but much greater than those of Fanger (1972) and Tanabe et al. (2000). The f_{eff} value of this study, 0.826, lies closest to that of Miyazaki et al. (1995). The absolute range between Kubaha et al.'s (2004) value, 0.84, and Fanger's (1972) widely used value, 0.725, is over 0.11.

Walking posture

Projected area factor

People's arms spread farther from the trunk and legs are located farther from each other during most of a walking stride compared with a standing posture. This will produce somewhat greater body area factors than in a standing posture.

The normal-weight male and female models had very similar directional f_p values (Fig. 7). The maximum difference between them was only 0.025 at the 2/4 position when α=195° and β=25°. The difference was close to the maximum difference between the genders for standing posture, 0.017. When α was around 180° (back of the

Table 4 Comparison of standing posture f_{eff} with previous studies

Description	Height (m)	Total body surface area (A_D, m^2)	Effective radiation area factor (f_{eff})	Subjects
This study	1.74 (male: 1.81, female: 1.67)	1.845 (male: 2.01, female: 1.68)	0.826	79 males
				60 females
Kubaha et al. (2004)	1.75	1.83	0.84	Male 3D model
Tanabe et al. (2000)	1.75	1.72	0.74	Male 3D model
Miyazaki et al. (1995)	1.71	1.58	0.83	
Horikoshi et al. (1990)	1.70	1.69	0.80	3 males
Fanger (1972)	1.72 (male: 1.78, female: 1.66)	1.74 (male: 1.86, female: 1.61)	0.725	10 males
				10 females
Underwood and Ward (1966)		Male: 1.80		25 males
		Female: 1.59		25 females
Guibert and Taylor (1952)	1.72	1.84	0.78	3 males

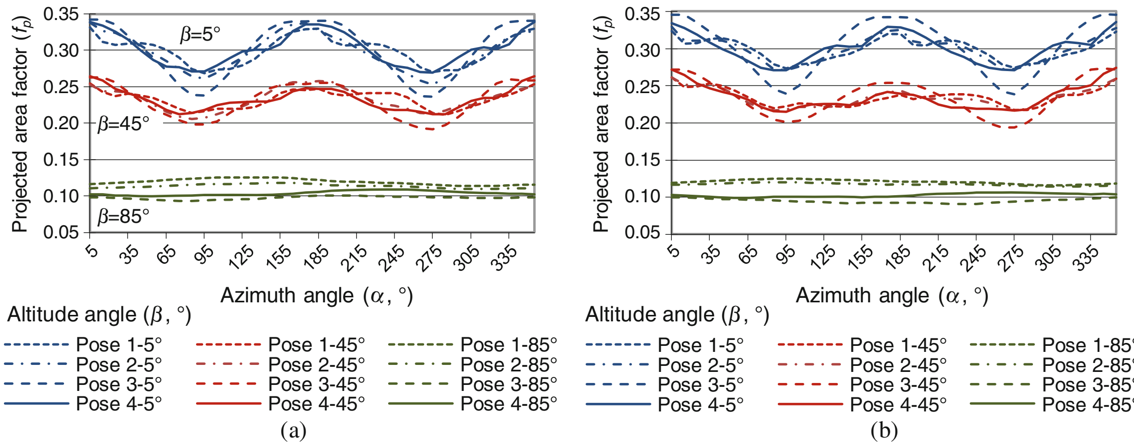

Fig. 7 Projected area factors of walking posture. **a** Normal-weight male. **b** Normal-weight female (Pose 1, 2, 3 and 4: 1/4, 2/4, 3/4 & 4/4 positions in a walking stride)

body), the normal-weight male model had slightly higher f_p values than the normal-weight female model, up to 0.0246. The opposite results happened when α was close to 0° (front of the body), up to 0.0189. This seems to be created by females' breasts and males' wider arm angles from a body. This phenomenon is very similar in standing posture.

Directional mean f_p values from all stride positions dependent on β angles can be found in Fig. 8. The maximum f_p difference among α angles was 0.072 between front (α=5° & 185°) and side (α=95° & 275°) of the body when the altitude angle was the lowest (β=5°), and the differences decreased with increasing β angles.

Directionless f_p values can be used for simple modeling when walking direction cannot be defined or is not important. Both male and female models had very small differences between stride positions, up to 0.007, until β=65° (Table 5). The greatest difference, 0.026, between the positions occurred at β=85° for the normal-weight female model. At β=85°, the overhead view where f_p is small, variation in the horizontal projection of the legs and arms has the greatest relative effect. However, the differences of mean directionless f_p values between the two gender models were only up to 0.002. Therefore, only minor differences in walking posture directionless f_p values occurred between genders and stride positions at most β angles.

The previous studies for walking posture, Ward and Underwood (1967) and Steadman (1979), were compared with this study after converting f_p to f_p^* because they used A_D to find f_p^* for direct beam solar radiation analysis and

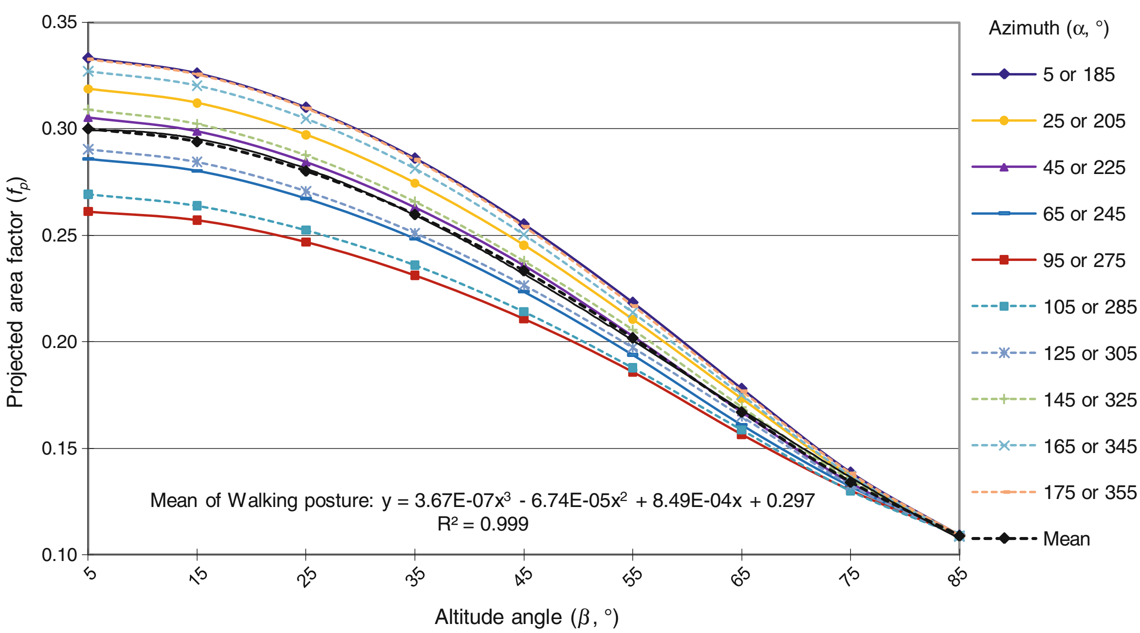

Fig. 8 Directional projected area factors (f_p) of walking posture dependent on both azimuth and altitude angles and best-fit equation

Table 5 The directionless f_p values of normal-weight male and female models

Category	Position of a stride	Altitude angle (β, °)								
		5	15	25	35	45	55	65	75	85
NW_M	1/4	0.300	0.293	0.280	0.259	0.233	0.202	0.169	0.141	0.119
	2/4	0.298	0.296	0.282	0.260	0.233	0.201	0.167	0.135	0.114
	3/4	0.300	0.293	0.279	0.258	0.231	0.199	0.162	0.126	0.098
	4/4	0.302	0.295	0.281	0.260	0.233	0.201	0.166	0.133	0.104
	Mean	0.300	0.294	0.281	0.259	0.233	0.201	0.166	0.134	0.109
NW_F	1/4	0.298	0.292	0.279	0.260	0.234	0.204	0.171	0.142	0.121
	2/4	0.299	0.293	0.280	0.260	0.234	0.203	0.169	0.139	0.117
	3/4	0.302	0.296	0.282	0.261	0.234	0.201	0.164	0.125	0.095
	4/4	0.301	0.294	0.281	0.261	0.234	0.203	0.167	0.132	0.103
	Mean	0.300	0.294	0.281	0.261	0.234	0.203	0.168	0.135	0.109
	Mean	0.300	0.294	0.280	0.260	0.233	0.202	0.167	0.134	0.109

Ward and Underwood did not define f_{eff}. Steadman's f_p^* formula (f_p^*=0.386–0.0032β, 25°≤β≤85°) for walking posture and Ward and Underwood's values were up to 0.068 and 0.207, respectively, higher than in this study (Fig. 9). The effect of the differences can be substantial for direct beam solar radiation analysis.

Effective radiation area factor

In the normal-weight male model, there was a 0.027 difference in effective radiation area factor (f_{eff}) between the four positions of a walking stride (Table 6). The greatest f_{eff} value was 0.848 at the 1/4 position where the arms were spread farthest from the torso and legs were farthest apart (Fig. 1d). The lowest was 0.821 at the 3/4 position when the legs were close together and arms were near the torso. The normal-weight female model had more variation, 0.033. The greatest f_{eff} was 0.868 at the 1/4 position, and the lowest was 0.835 at the 3/4 position. The representative f_{eff} of walking posture was 0.846 which was about 0.02 higher than f_{eff} of standing posture, 0.826. Our walking posture values are somewhat greater than the 0.80 and 0.82 assumed by Steadman (1979) for walking subjects and de Freitas et al. (1985) for runners, respectively.

The greatest f_{eff}, which occurred at the 1/4 position of the stride, was only 0.018 higher than the f_{eff} of standing posture in the normal-weight male model, but for the normal-weight female model it was 0.044 higher. Moreover, the normal-weight female model had higher f_{eff} values in all stride positions than for standing posture, but f_{eff} of the 3/4 position in the normal-weight male model was 0.009 lower than for standing posture. In standing posture, the normal-weight male model had a much wider stance between the legs than the normal-weight female model (Fig. 1c). Even though the 3/4 position in the normal-weight male model has more body movement, the legs are located closer than the wide open stance in standing posture (Fig. 1d).

Discussion

Radiation area factors have a direct effect on computed human-environment radiation exchange. Our analysis indicated that differences in radiation area factors between studies found in the available literature are greater than those between genders or body types. Brief examples of the effects of study differences on computed solar and long-wave radiation are given in this section.

A comparison between two groups of studies divided on the basis of f_{eff} values [this study and Kubaha et al. (2004) vs Fanger (1972) and Tanabe et al. (2000)] using this study's and Fanger's widely used f_{eff} and f_p^* values illustrates some of the human radiation exchange effects

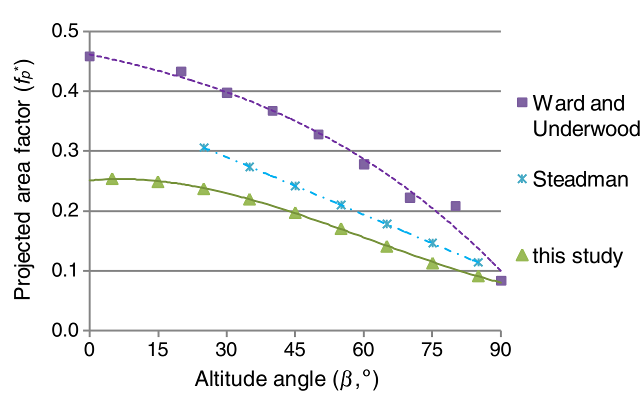

Fig. 9 Comparison of the mean directionless projected area factors (f_p^*) of normal-weight male and female models with those of previous studies, walking posture

Table 6 Effective radiation area factors (f_{eff}) of walking postures of the normal-weight male and female models

BMI category	Position of a stride	A_{eff} (m^2)	f_{eff}
NW_M	1/4	1.654	0.848
	2/4	1.632	0.837
	3/4	1.602	0.821
	4/4	1.632	0.837
	Mean	1.630	0.836
NW_F	1/4	1.432	0.868
	2/4	1.425	0.864
	3/4	1.379	0.835
	4/4	1.416	0.858
	Mean	1.414	0.856
Mean		1.521	0.846

of differences in body area factors. Absorptivities of the human body surface were assumed to be 0.7 for incoming solar radiation (R) and 0.97 for incoming longwave radiation (L).

Effects of the different body area factors are indicated by an analysis of the sensitivity of human absorbed radiation to differences in incoming radiation (Fig. 10a). Slopes of the linear regression lines are created by a combination of f_{eff} and f_p^* differences and the assumed absorptivity of the body for the radiation type. Longwave radiation (L) and diffuse beam and reflected solar radiation (K_d+K_r) are affected only by f_{eff}, which has a greater difference (0.1) than f_p^*(0.02 – 0.03), which affects direct beam solar radiation (K_b). Hence, the slopes were greater for L and K_d+K_r than for K_b (Fig. 10a). The assumed body absorptivity for L (0.97) is greater than that for R (0.7). This is the sole cause of the difference in sensitivity between L and K_d+K_r.

Absorbed longwave radiation was the radiation stream most sensitive to the f_{eff} and f_p^* differences between this study and Fanger (Fig. 10a); the least was absorbed K_b. Absorbed K_b depends on solar altitude (β). It is most sensitive to variations in incoming K_b at around β=40°, and after β=50° the slopes of the linear regression lines decline rapidly (Fig. 10b).

Gagge et al. (1969) found mean skin temperature was between 27°C and 36.5°C under steady state conditions. Within this range, differences in emitted longwave radiation from the body surface created by the 0.1 f_{eff} difference between this study and Fanger were in a very narrow range, 6 Wm^{-2} (45–51 Wm^{-2}).

Another example employs field data collected on a typical clear summer day (10 August 2002) around noon at the University of Guelph, Ontario (latitude and longitude: 43°32′N, 80°14′W, ψ_{sky}: 0.88, β: 60.9°, T_a: 29.9°C, K_b: 759 Wm^{-2}, K_d+K_r: 340 Wm^{-2}, L: 479 Wm^{-2}), the differences of f_{eff} (0.1) and f_p^*(0.022) between this study and Fanger made a gap of 24.6 Wm^{-2} in human net radiation.

The mean f_p values of the 1/4 through 4/4 stride positions for walking posture were compared with those for standing posture (Fig. 11). The directional f_p values of walking posture had less variation between front/back (α=0° and 180°) and side (α=90°) α angles with increasing β angles than those of standing posture. Also, the actual directional f_p differences between α angles of walking posture were much lower, maximum difference 0.072, than those of standing posture, 0.128. More open walking body posture reduced the f_p differences dependent on α angles.

These directional f_p differences would create up to 16 Wm^{-2} difference in absorbed K_b in walking posture and up to 29 Wm^{-2} difference in standing posture in both low and moderate solar altitude angle simulations (β=25°, K_b=350 Wm^{-2} and β=55°, K_b=700 Wm^{-2}).

If walking direction is not important or unknown and percentages of standing and walking people are unknown (e.g., square, plaza or open field), directionless f_p values for K_b analysis can be estimated from a formula for combined

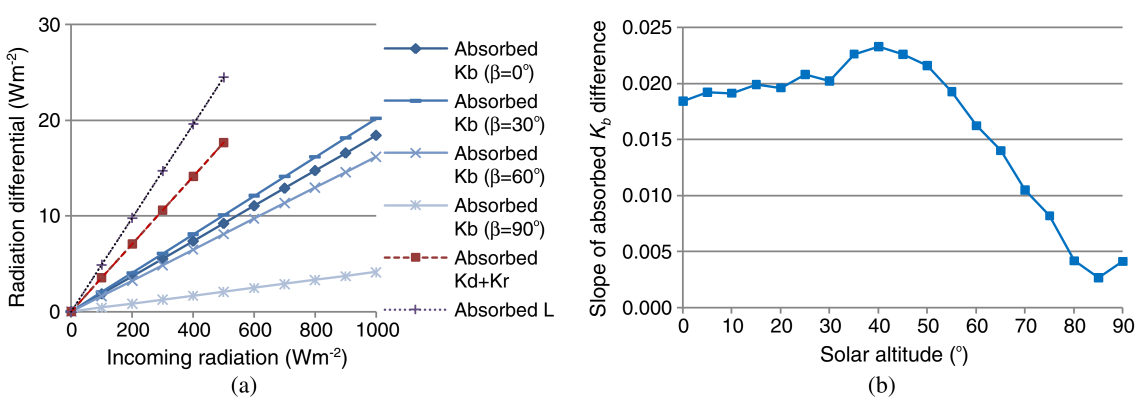

Fig. 10 Effects on modeled absorbed radiation on a body surface created by differences in body area factors between this study and Fanger (1972). **a** Differences in absorbed K_b by solar altitude, $K_d + K_r$ and L dependent on amounts of incoming radiation. **b** Slope of absorbed K_b difference (radiation differential/incoming radiation) by solar altitude

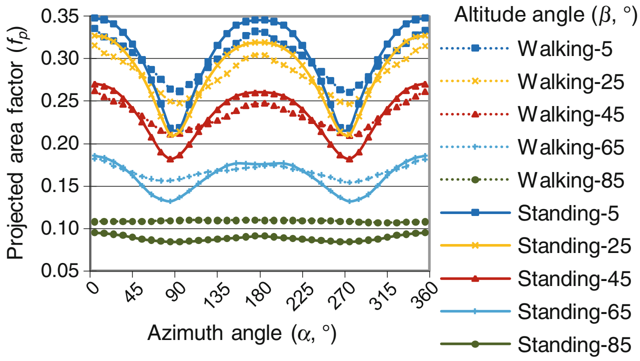

Fig. 11 Comparison of directional projected area factors (f_p) of standing and walking postures for a selection of altitude angles (β) between 5° and 85°

standing and walking postures (Fig. 12). If walking direction is known (e.g., corridors in subway stations and buildings, along sidewalks or park trails), directional f_p values for walking posture can be found in Fig. 8.

For f_{eff} values in modeling, the f_{eff} difference from mean standing and walking postures (0.836) to standing posture (0.826) and walking posture (0.846) was only 0.01, which is not important in radiation analysis. Therefore, the mean f_{eff} value, 0.836, can be used in most applications.

When directionless f_p values for walking posture from half a sphere ($0 \leq \alpha \leq 360$, $0 \leq \beta \leq 90$) and a quarter sphere ($0 \leq \alpha \leq 180$, $0 \leq \beta \leq 90$) are compared; theoretically, standing posture is symmetrical, so f_p values from a quarter sphere would be analyzed to find total f_p values from an entire sphere. Walking posture is asymmetrical, so f_p values from half a sphere should be analyzed. However, the differences in walking posture directionless f_p values between the two ways were negligible, only up to 0.001. Therefore, analysis for directionless f_p values within a quarter sphere ($0 \leq \alpha \leq 180$, $0 \leq \beta \leq 90$) can be adequate to find the total f_p values from an entire sphere even though the walking body postures are not symmetrical.

A limitation of this study was that other body types and postures were not included, i.e., under-weight and obese BMI body type categories and sitting and running postures. These body types and postures will be investigated in further studies.

Conclusions

Computation of human radiation exchange requires effective radiation area and projected area factors of the modeled subjects. Our results improve the ability to select appropriate values by: including a larger sample of people than in previous studies, focusing on both normal-weight and overweight, present-day adults, and presenting the first detailed analysis of walking posture.

Key findings include:

1. When determining human body effective radiation area and projected area factors via computer modeling, measurements every 10° are recommended as a good compromise between accuracy and data processing time.
2. Differences in f_p and f_{eff} of standing posture between the four body types (normal- and over-weight men and women) were relatively small. These results indicate that for most general modeling studies, a single value can be used regardless of gender or body type.
3. Differences between values presented in the wide variety of available studies are much greater than those found for body type. Hence, differences come more from the methods employed than from the human figures from which the body area factors were

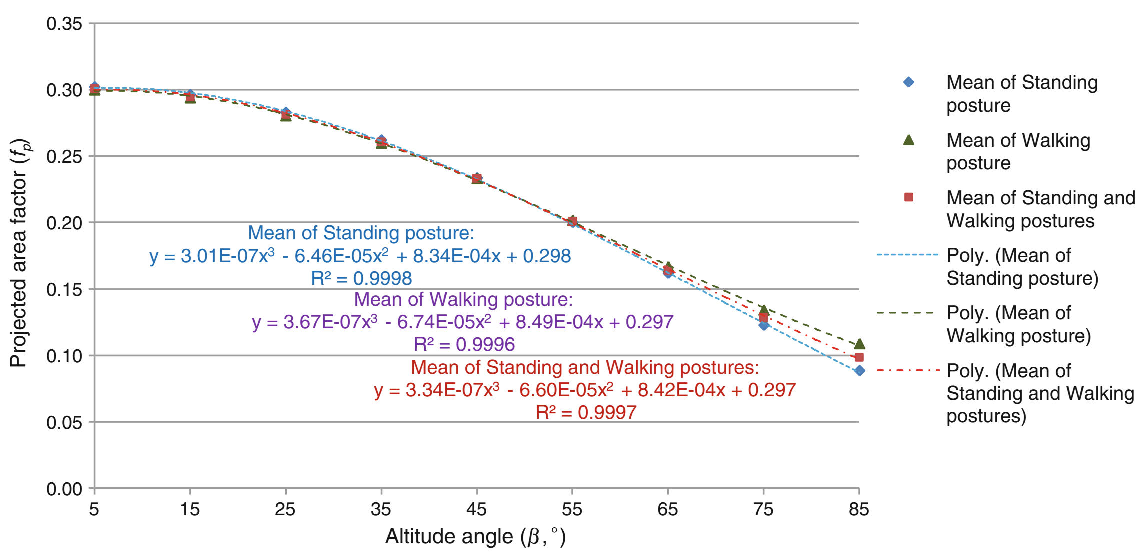

Fig. 12 Directionless projected area factors (f_p) of standing and walking postures and best-fit polynomial equations

determined. Our results, in general, tend to be closer to those of studies using methods similar to ours.

4. There were only minor differences in directionless f_p values between standing posture genders and body types, and between walking posture genders and stride positions. However, directional f_p values varied with azimuth angle (α). Large differences occurred at low altitude angles (β) that are closest to perpendicular to the vertical body surface, and differences decrease with increasing altitude angles.
5. f_{eff} values between standing (0.826) and walking (0.846) postures were not too different, thus the mean f_{eff} (0.836) could be applied in most general modeling studies where applications to a variety of people both standing and walking are of interest. Standing posture has been used in many applications where walking posture might be appropriate. The small difference in f_{eff} suggests this has not caused any major errors or invalid conclusions. However, f_p values should be selected carefully because directional and directionless f_p differences were quite large at some azimuth angles.

Digital photography and computer processing have eased the assessment of human area factors. This will allow future research on a wide variety of body figures and postures to test whether our findings of only small differences between normal- and over-weight people and standing and walking postures extend to other body types and postures. The results can be used in a variety of human thermal exchange studies and expand their applicability to a wider range of activities. These new results will be compared with diverse body area factors used in radiation components of existing human thermal exchange models in further studies.

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