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ORIGINAL ARTICLE

P. Tikuisis · P. Meunier · C.E. Jubenville

Human body surface area: measurement and prediction using three dimensional body scans

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Abstract The development of three dimensional laser scanning technology and sophisticated graphics editing software have allowed an alternative and potentially more accurate determination of body surface area (BSA). Raw whole-body scans of 641 adults (395 men and 246 women) were obtained from the anthropometric data base of the Civilian American and European Surface Anthropometry Resource project. Following surface restoration of the scans (i.e. patching and smoothing), BSA was calculated. A representative subset of the entire sample population involving 12 men and 12 women (G24) was selected for detailed measurements of hand surface area (SA_{hand}) and ratios of surface area to volume (SA/VOL) of various body segments. Regression equations involving wrist circumference and arm length were used to predict SA_{hand} of the remaining population. The overall [mean (SD)] of BSA were 2.03 (0.19) and 1.73 (0.19) m^2 for men and women, respectively. Various prediction equations were tested and although most predicted the measured BSA reasonably closely, residual analysis revealed an overprediction with increasing body size in most cases. Separate non-linear regressions for each sex yielded the following best-fit equations (with root mean square errors of about 1.3%): $BSA\ (cm^2) = 128.1 \cdot m^{0.44} \cdot h^{0.60}$ for men and $BSA = 147.4 \cdot m^{0.47} \cdot h^{0.55}$ for women, where m, body mass, is in kilograms and h, height, is in centimetres. The SA/VOL ratios of the various body segments were higher for the women compared to the men of G24, significantly for the head plus neck (by 7%), torso (19%), upper arms (15%), forearms (20%), hands (18%), and feet (11%). The SA/VOL for both sexes ranged from approximately $12 \cdot m^{-1}$ for the pelvic region to $104–123 \cdot m^{-1}$ for the hands, and shape differences were a factor for the torso and lower leg.

Keywords Human · Anthropometry · Model · Equation · Body surface area

Introduction

Body surface area (BSA) is an important parameter in the administration of drugs, in the normalization of physiological responses, and in systems design inherent in the work of clinicians, physiologists, and ergonomists. Yet BSA is very difficult to measure accurately because of the complex architecture of the human body. The most cited study on this topic is Dubois and Dubois (1916) who measured BSA by mapping the body with a paper mold. These investigators subsequently regressed BSA (in centimetres squared) using only nine subjects against the basic anthropometric measures of weight (m in kilograms) and height (h in centimetres):

$$BSA = C \cdot m^A \cdot h^B \qquad (1)$$

where the parameter values of C, A, and B were 71.84, 0.425, and 0.725, respectively.

Several other researchers have suggested various other parameter values based on larger numbers of subjects (Boyd 1935; Gehan and George 1970; Haycock et al. 1978; Shuter and Aslani 2000); however, the parameter values cited above have been shown to be relatively accurate (Shuter and Aslani 2000). The closeness in the prediction of BSA using these diverse variations in the parameter values among different researchers has been ascribed to the close relationship between the logarithmic values of m and h (Bailey and Briars 1996). That is, since the regression of Eq. 1 has often been conducted in a logarithmic form, a change in the parameter value of one variable (m or h) is largely compensated by a change in the other (Shuter and Aslani 2000). Yet, regression of a log-transformed function does not necessarily yield the best fit of the data; instead,

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P. Tikuisis (✉) · P. Meunier · C.E. Jubenville
Defence and Civil Institute of Environmental Medicine,
Human Protection and Performance,
1133 Sheppard Avenue West, PO Box 2000,
Toronto, Ontario, Canada M3M 3B9
E-mail: peter.tikuisis@dciem.dnd.ca
Tel.: +1-416-6352099
Fax: +1-416-6352132

non-linear regression should be conducted to obtain a valid fit of the data. Shuter and Aslani (2000) applied non-linear regression of Eq. 1 to the original data of Dubois and Dubois (1916) that included BSA for an additional 33 subjects where BSA was based on the length of body segments, and this led to yet another set of parameter estimates (see table later).

Three-dimensional (3D) laser scanning technology has opened up a new range of possibilities in the field of anthropometry. This technology is applicable for calculations of BSA and volume, thus providing a viable alternative to the traditional and labour-intensive method of measuring BSA by direct coverage (e.g. paper molds, foil, etc.). Jones et al. (1989) reported on the use of an optical shadow scanner for recording body contours, conceptually similar to 3D laser scanning, but no calculation of BSA was given. Recently, a large data set of reliable and accurate whole body 3D scans was made available for the calculation of BSA and its comparison to more traditional measurement methods. This data set will ultimately contain measurements of approximately 4,000 North Americans and 4,000 Europeans in the Civilian American and European Surface Anthropometry Resource (CAESAR) project (SAE 2000). Data from the first three survey sites of the CAESAR project (involving North Americans) were used in the present study and are considered representative of the general population.

The purpose of this study was:

1. To determine BSA using laser-scanned civilian adults (18–65 years old) and advanced 3D modelling software
2. To determine the most appropriate prediction of BSA
3. To compare gender-specific ratios of the surface area to volume (SA/VOL) of various segments of the body

The latter is of specific interest to thermal physiologists where high values of SA/VOL usually infer high rates of heat transfer between the body and the environment.

Methods

Model selection and treatment

The 3D whole body scan (WB4 Whole Body Colour 3D Scanner, www.cyberware.com) data used herein were obtained from the CAESAR project and selected according to the quality of the scanned image. The selected models included 641 adults (97% from of a total of 661 available) standing with arms and legs apart, and clad in tight-fitting cotton cycling shorts and sport bras for women. Of these models, 395 were men and 246 were women representing a broad range of the adult population (Table 1) with the exception of senior citizens, and individuals over 2 m in h (due to the h limitation of the scanning apparatus).

Before BSA and volume could be determined, the models had to be edited to complete those regions of the body that were hidden from the scan. Polyworks (version 5.1 PR, www.innovmetric.com) is a polygon-editing software tool that was used to fill-in small holes, smooth the model surface topology, and create patches where large gaps could not be automatically covered. The first two functions were conducted via a macroinstruction customized for this purpose. Creating a patch was sometimes necessary when the gaps in the scans were too large, such as under the upper arm and between the thighs (especially of heavily-built individuals). Since the subjects were standing during the scans, the soles of their feet could not be scanned and were approximated by flat patches. Two other areas required special attention in the models; these were the ears and hands.

It was generally found that one ear was scanned reasonably well and could be restored with minor difficulty. All models were then completed with one ear intact and the other purposely replaced by a flat patch. Subsequent calculations of the surface area and volume of the head took these alterations into account.

Hands were generally very poorly scanned and most could not be restored without an inordinate amount of effort, and in some cases not at all. Therefore, certain models that could be restored were identified and selected to represent the overall range of the entire subject population. These models included 12 men and 12 women, and as a group are referred to as G24; their anthropometric characteristics are given in Table 1. Following the same strategy used to measure the ears, it was only necessary to restore one hand and to account for the other by the simple assumption of symmetry. The hand was defined as the region inferior to the plane containing the radial and ulnar styloid (i.e. the wrist plane). Its surface area (SA_{hand}) and volume were readily determined using Polyworks.

Additional landmarks were identified on the G24 models for the purpose of regressing other body measurements to SA_{hand} and for the determination of SA/VOL of various body segments. The forearm was delimited by two planes, the superior plane that included both the medial and lateral epicondyle of the humerus (i.e. elbow plane), and the inferior plane that included the radial and ulnar styloids (at the wrist). The head and neck were combined and defined by the region superior to the trunk marked by the plane formed by the two sterno-clavicular (medial ends of clavicle) ends and the seventh cervical vertebra. The torso was bordered at the neck superiorly, as well as at the arms laterally and waist inferiorly; the arms were defined by the plane at the highest point in the axilla (underarm) and the acromion. The plane created from the left and right anterior superior iliac spine and the left and right posterior superior iliac spine defined the waist. The pelvis was bordered superiorly by the waist and inferio-laterally by the hip planes formed by the greater trochanter of the femur and the lowest point of the pelvis. The thigh was defined as the region inferior to the hip and superior to the knee where the horizontal bisector of the popliteal fossa forms the knee plane. Finally, the lower leg was defined as the

Table 1 Mean (SD) and range of age, body mass, height, and body surface area by three dimensional scanning of the 641 model subjects (395 men and 246 women), and of the G24 subjects (12 men and 12 women) selected as a representative subset of the entire subject population

Variable	Men ($n=395$)	Women ($n=246$)	Men ($n=12$)	Women ($n=12$)
Age (years)	36.1 (10.4)	37.6 (10.7)	42.8 (11.9)	42.0 (6.9)
Range	18–64	19–63	25–58	33–53
Body mass (kg)	86.0 (16.0)	65.5 (14.2)	92.4 (21.8)	70.3 (24.3)
Range	48.9–156.8	45.0–140.7	63.6–148.2	49.3–140.7
Height (cm)	177.9 (7.7)	164.3 (7.1)	178.4 (5.7)	166.3 (8.7)
Range	149.7–198.2	145.3–187.9	170.5–191.8	152.8–182.4
Body surface area (m^2)	2.030 (0.193)	1.734 (0.187)	2.110 (0.242)	1.802 (0.312)
Range	1.490–2.713	1.380–2.662	1.765–2.710	1.466–2.662

region located inferior to the knee plane and superior to the plane defined by the medial and lateral malleolus of the ankle. The complete segmentation of 1 of the subjects is shown in Fig. 1.

Data analysis

Linear and non-linear regressions were applied to the hand models of G24 for each sex. The regressors chosen were the wrist cross-sectional area and perimeter (as defined by the wrist plane), forearm length, and complete arm length using the anatomical landmarks described above. The best-fit equation based on the minimal sum of squared residuals was then applied to all remaining models in the data set to estimate BSA.

The computed BSA of all the 3D models were then compared to various published predicting equations and tested for significance using the Student's *t*-test for related measures at the 0.05 level (Statistica, www.statsoft.com). Further analyses were conducted on the results from each sex and a residual analysis of errors was conducted to determine any bias in the prediction equations.

Non-linear regressions were performed to extract the best fit of BSA for each gender. Although all equations of BSA expressed herein yield a value in centimetres squared following the usual convention, values are reported in metres squared for convenience. Sex comparisons of the SA/VOL of various body segments of the G24 subjects were tested using the Student's *t*-test for unrelated measurements at the 0.05 level.

Validation procedure

A solid machined aluminium hemisphere (10.594 cm radius) was scanned 360° (via a rotating scanner) and analysed using Polyworks. After the surface was smoothed, its area (excluding the plane) and volume were determined to be 707.5 cm^2 and 2,500.2 cm^3, respectively. These values overestimate the true area (705.1 cm^2) and volume (2,490.2 cm^3) by only 0.34% and 0.40%, respectively. It was assumed, therefore, that the error due to the analysis of the scans should not have exceeded 0.5%; errors due to the imprecision of the scans per se were uncertain since no *gold* standard of human BSA was available for validation.

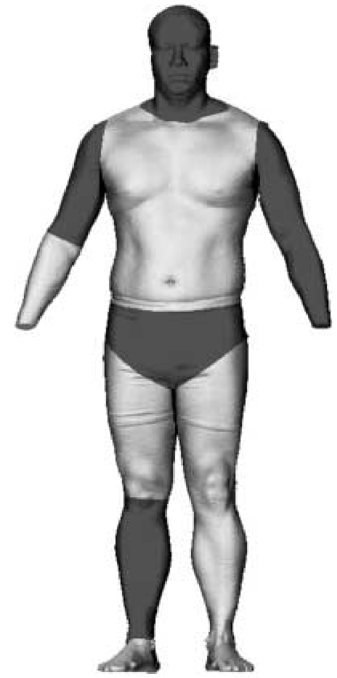

Fig. 1 Example of body segmentation

However, we conducted another validation using a human hand as a model. In this case, a cast of an adult male hand (Fig. 2) was scanned for analysis. After editing the scan as described earlier, the surface area and volume were calculated as being 539.1 cm^2 and 509.8 cm^3, respectively. Rather than attempting to validate the surface area, it was much simpler to check the volume calculation. The mean (SEM) volume of the hand was independently determined from three measurements to be 511.0 (2.7) cm^3 by the water displacement method. Thus, the volume calculated by the scanning method fell within the standard error of the actual volume (coefficient of variation less than 0.005). Considering that measurement error is generally higher with volume compared to surface area due to the additional dimension, as seen above with the example of the hemisphere, it would be fair to extrapolate that the error in the calculation of the surface area of the hand is less than 0.5% using the scanning method applied herein.

Results

Table 1 shows the measured anthropometric and calculated BSA values of all the model subjects and of the 24 subjects (G24) selected to determine $\mathrm{SA}_{\mathrm{hand}}$ and the SA/VOL ratios of various body segments. Only age showed no difference between genders. There were no significant differences in the means of the measured variables between the male and female subsets of G24 compared to the remaining subjects (383 men and 234 women) with the exception of age for men [mean (SD)] [$n = 383$, 35.9 (10.3); $P = 0.023$]. While the variances in age and h were similar between groups for each gender, the variances in m and BSA were considerably higher for the subjects of G24.

The $\mathrm{SA}_{\mathrm{hand}}$ of the 12 men and 12 women of G24 were 0.0519 (0.0053) and 0.0412 (0.0040) m^2, respectively, representing 4.95% and 4.62% (both hands) of the subjects' BSA. The best fit of $\mathrm{SA}_{\mathrm{hand}}$ (in metres squared) was obtained using a non-linear combination of wrist circumference [0.194 (0.017) and 0.168 (0.015) m for men and women, respectively] and arm length [0.637 (0.032) and 0.577 (0.038) m, respectively], as follows:

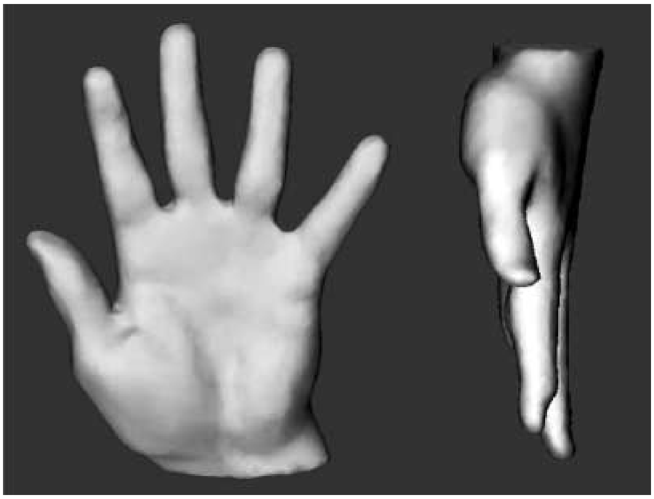

Fig. 2 Scan of hand for validation test

$$SA_{hand} = c \cdot (\text{wrist circumference})^a \cdot (\text{arm length})^b \quad (2)$$

where c, a, and b are 0.201 (0.072), 0.640 (0.266), and 0.670 (0.466) for men [root mean square error (rms) = 0.0029 m^2 or 5.6%] and 0.132 (0.049), 0.390 (0.240), and 0.859 (0.327) for women (rms = 0.0022 m^2 or 5.3%), respectively.

Table 2 compares the predictions obtained from various equations to the measured values of BSA of the 641 subjects in our study. Although all equations predicted reasonably well, only the equation cited for Gehan and George (1970) provided a prediction that was not significantly different ($P = 0.73$) from the measured result. However, a residual analysis of the fit of BSA using this equation revealed a significant ($P < 0.001$) upward slope (about 3%) with increasing BSA. That is, the equation of Gehan and George (1970) tended to underpredict BSA of small individuals and overpredict BSA of large individuals. Further examination also indicated that the equation of Gehan and George (1970) significantly overpredicted male BSA and underpredicted female BSA, as did all the equations (see Fig. 3) except Shuter and Aslani (2000) which underpredicted for both sexes. This inequality was resolved by conducting non-linear fits of Eq. 1 for each sex separately. The following equations for men and women fit the data with bias-free residuals and an overall rms error of 0.0241 m^2 or 1.26%:

$$BSA = 128.1 \cdot m^{0.44} \cdot h^{0.60}(\text{men}) \quad (3)$$

$$BSA = 147.4 \cdot m^{0.47} \cdot h^{0.55}(\text{women}) \quad (4)$$

where BSA is in centimetres squared, m in kilograms, and h in centimetres. The mean percentage error between the predicted and measured BSA for each gender is shown in.Fig. 3. A comparison of the measured and fitted BSA using Eqs. 3 and 4 is shown in Fig. 4, and Fig. 5 shows the residual errors for all 641 subjects using these equations plotted against BSA and age. Note that the majority of the residuals lie within 3% of the measured BSA, and that there is no bias with age.

Table 3 lists the SA and SA/VOL of various body segments for each gender of G24. Women tend to have higher ratios for all measured body segments compared to men, significantly for the head plus neck, torso, upper arm, forearm, hand, and foot. Also listed are the percentages of the segments' surface areas to the overall BSA, from a minimum of approximately5% for the hands to a maximum of approximately 24% for the torso.

Discussion

The small percentage error (equal to or less than 0.4%) in the determination of the size of the solid machined aluminium hemisphere used for validation purposes can be attributed to operator error. Since the 3D scanner is accurate to 0.5 mm in depth value (Daanen et al. 1997), negligible error can be attributed to the scan itself. One source of error involved the semi-automatic merging of the two scans that were required to obtain a complete scan of the hemisphere. After some minor manual alignment, an iterative routine in Polyworks matched the surfaces of the two scans to within 0.1 mm which would have resulted in very little error. A larger source of error probably occurred when the mounting base was removed by slicing and capping the hemisphere with a plane. The plane was created by selecting three vertices on the edge of the sphere. If the three vertices selected were not in perfect alignment, then the plane could have capped the hemisphere at a small offset angle to alter the surface area and volume measurement. Yet the overall error was small (equal to or less than 0.4%) and since the measurement of the human models did not require the merging of any sections, it would be fair to conclude that any measurement error of BSA would be largely attributed to the patching and smoothing procedures.

The errors due to patching and smoothing of the models should be analogous to those encountered during the physical covering with material or through the process of triangulation. In these procedures, small indentations, ripples, wrinkles, etc. are *smoothed* over and the true BSA is probably underestimated. This, however, introduces a practical concern, as to the appropriate measure of BSA. As with cartography, the measurement of all minute indentations is not necessarily meaningful. In many applications of BSA, especially in thermal

Table 2 Prediction of body surface area (*BSA*) (calculated in centimetres squared but shown in metres squared) of various equations using body mass and height of the Civilian American and European Surface Anthropometry Resource (CAESAR) subject data ($n = 641$) and comparison to the measured [mean (SD)] BSA = 1.9165 (0.2388) m^2. n is the number of subjects used by the cited investigators to calibrate the equation, *C*, *A*, and *B* are the parameters pertaining to Eq. 1, *dev%* is the percentage deviation between the mean predicted and measured BSA, and *rms%* is the percentage root mean square error. The equation of Mosteller (1987) was presented theoretically without any subject calibration

Equation	*n*	C	A	B	Mean BSA (SD)	dev%	rms%
Du Bois and Du Bois (1916)	9	71.84	0.425	0.725	1.910 (0.248)	–0.32	1.56
Boyd (1935)	197	178.7	0.484	0.500	1.927 (0.256)	0.54	1.79
Gehan and George (1970)	130	154.5	0.463	0.545	1.917 (0.249)	0.02	1.48
Haycock et al. (1978)	81	242.7	0.538	0.396	1.937 (0.272)	1.06	2.71
Mosteller (1987)	–	166.7	0.500	0.500	1.927 (0.263)	0.54	2.03
Shuter and Aslani (2000)	42	94.9	0.441	0.655	1.886 (0.246)	–1.59	2.12

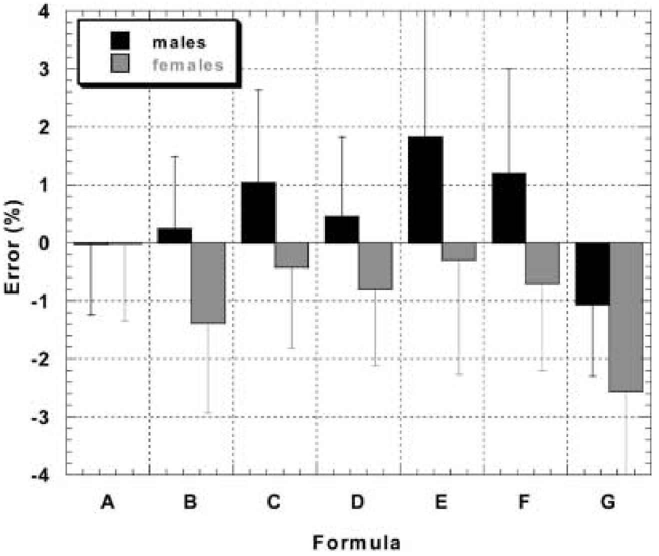

Fig. 3 Mean (SD) percentage error between the predicted and measured body surface area for *A* Eqs. 3 and 4, *B* Du Bois and Du Bois (1916), *C* Boyd (1935), *D* Gehan and George (1970), *E* Haycock et al. (1978), *F* Mosteller (1987), and *G* Shuter and Aslani (2000)

physiology, it is important to determine the area of the body that is in direct contact with the external conductive/convective medium. In most instances, this would exclude minute indentations of the body surface. Hence, one should expect that the resultant *smoothed* human models are appropriate for most applications that require BSA, and further that the errors due to the smoothing procedure are randomly dispersed. There may be, however, a slight underestimation in BSA due to the use of flat compared to curved patches in the regions of the axilla, the area between the upper legs, and the soles of the feet.

Despite the above possible sources of error in the estimation of BSA using 3D scans, comparisons with various prediction equations (Table 2) involving different methods of measuring BSA indicated a close overall agreement. Shuter and Aslani (2000) disclosed a close connection between the parameter C and the power of h (B) of Eq. 2 of all calibrated equations listed in Table 2, finding that $\mathrm{C} = 1086.2 \cdot \mathrm{e}^{-3.779 \cdot \mathrm{B}}$. Shuter and Aslani (2000) explained that such a connection was possible if the subject populations and measurement techniques of the different investigators were comparable. However, we find that the above-cited regression underestimates our value of C (112.5 compared to 128.1 and 135.9 compared to 147.4 for men and women, respectively). Considering that the broad range of our sample population encompassed the anthropometric values of the adults of the other studies, it appears that the generally slightly lower BSA that we report compared to the predictions of the other equations(Table 2) might be attributable to differences in measurement technique.

All methods of measurement, including 3D scanning, incur error that is likely to increase as the geometric complexity of the object increases. What is unknown is the magnitude of the editing errors of the 3D models that we employed compared to the errors of the traditional covering methods. However, without a gold standard of human BSA for validation, we are left to comparing these methods against well-defined geometrical shapes and incomplete substitutions of the human form. In this regard, it would be reasonable to assume that the 3D scanning method is the least susceptible of all methods to measurement error. Certainly, it has been demonstrated that 3D scanning can be accurately applied to measure known geometries such as the hemisphere, and its accurate resolution of the volume of the casted hand (Fig. 2) strongly supports its measurement of the surface area of the entire human form.

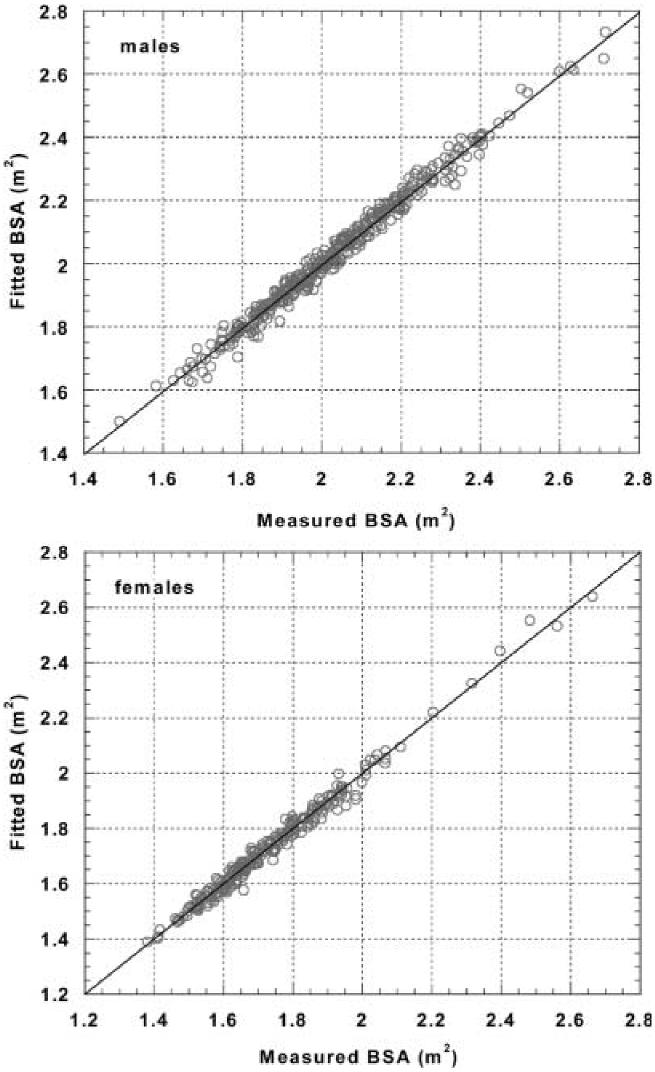

Fig. 4 Comparison of measured and fitted body surface area (*BSA*) for males and females using Eqs. 3 and 4, respectively

It was not surprising to find that regional SA/VOL values increased with decreasing radial dimension (i.e. from trunk to extremities; see Table 3). Collectively, all segments excluding the torso and pelvis account for

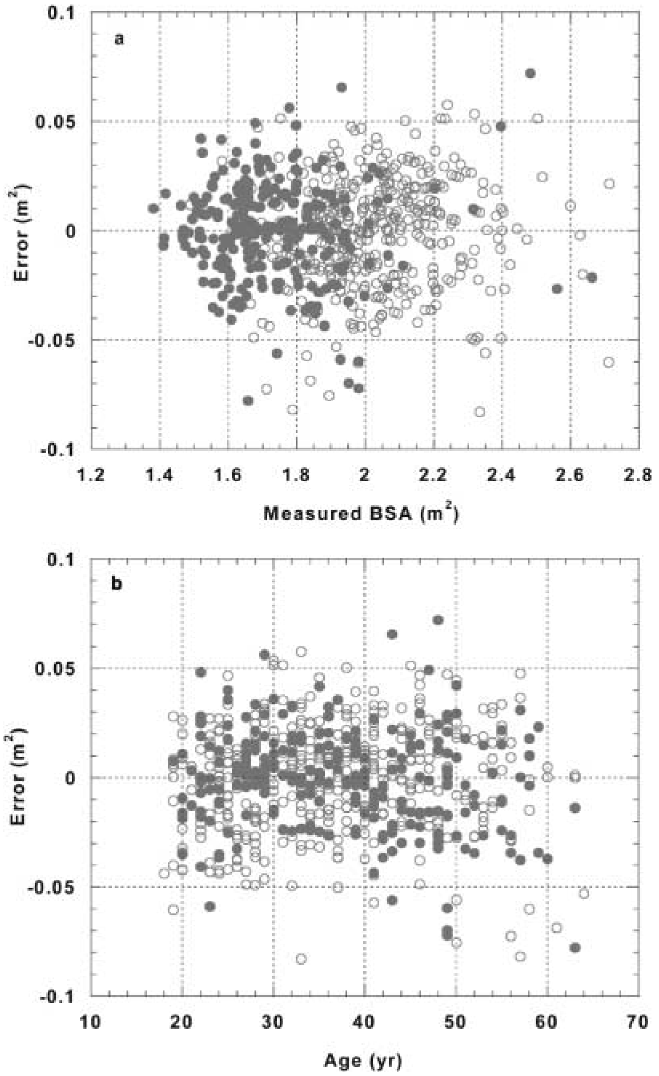

Fig. 5 Errors (predicted – measured) of the fitted body surface area (*BSA*) plotted against the **a** measured BSA and **b** age for males (○) and females (●)

approximately 69% of the total BSA but only approximately 47% of its volume, thus emphasizing the high SA/VOL of the external body segments. That women had higher SA/VOL, significantly for the head plus neck, torso, forearm, and hand, compared to men was attributed to their smaller average body size. This was confirmed by further analysis that indicated that the BSA/*m* was higher ($P = 0.014$) for the women [0.0265 (0.0031) m^2·kg^{-1}] compared to the men [0.0236 (0.0023) m^2·kg^{-1}) of G24. The implication of these findings is that they highlight specific body segments that may benefit or be adversely affected by an enhanced heat exchange with increasing SA/VOL. This is particularly apparent for the torso, upper arm, forearm, and hand where women had ratios of 15%–20% higher than their male counterparts. As a practical matter, it would seem that these regions, particularly the upper limbs and extremities, should be better protected to achieve the same degree of thermal comfort during cold exposure.

It is of academic and practical interest to determine whether the body segment SA/VOL ratio differences between genders are influenced by shape. From a theoretical perspective, the SA/VOL ratios of regular circular geometrical shapes have a constant relationship to their circumferences (CIRC). That is, SA/VOL = constant/CIRC where the constant is dimensionless and equal to 4π (12.57) for cylinders (lateral surface only) and 6π (18.85) for spheres. Table 4 lists the values of this constant regressed for certain body segments where CIRC was known. Although close, women have smaller values of this constant than men for the torso ($P = 0.025$) and lower leg ($P = 0.004$). The generally high value of the constant for the limbs (i.e. greater than 4π) suggests a conical geometry, as expected, but no sex difference was found except for the lower leg. Note that wherever a sex difference for SA/VOL occurred, the corresponding CIRC was also different (i.e. torso, upper arm, and forearm). Yet, the value of the constant (or product of SA/VOL and CIRC) was different only for the torso, indicating that shape is a factor in the sex difference of the torso SA/VOL, but not of the arm. That a small but significant sex difference in the value of the constant was also found in the lower leg where neither SA/VOL nor CIRC were different between genders also indicates a shape difference.

Table 3 Sex comparison of the mean (SD) of the surface area (metres squared), the percentage of the total body surface area (*BSA*), and the ratio of surface area (*SA*) to volume (per metre) of various body segments of the men and women of G24. The number in parenthesis after each segment ranks the segment's SA/VOL ratio in ascending order. *R* is the ratio of SA/VOL in women and men

Segment	Men ($n = 12$)			Women ($n = 12$)			
	SA	%BSA	SA/VOL	SA	%BSA	SA/VOL	*R*
Head + neck (4)	0.168 (0.009)	8.01 (0.64)	30.28 (1.39)	0.154 (0.011)	8.64 (0.78)	32.29 (1.34)	1.07*
Torso (2)	0.515(0.084)	24.28 (1.46)	13.88 (1.41)	0.418 (0.070)	23.23 (1.46)	16.55 (1.88)	1.19*
Pelvis (1)	0.155 (0.025)	7.36 (0.51)	11.58 (1.31)	0.142 (0.053)	7.77 (1.37)	12.52 (1.68)	1.08
Thighs (3)	0.426 (0.046)	20.26 (0.92)	23.43 (2.08)	0.390 (0.071)	21.64 (1.50)	24.59 (2.95)	1.05
Lower legs (5)	0.278 (0.038)	13.16 (0.53)	38.59 (4.37)	0.239 (0.047)	13.25 (0.55)	40.70 (4.54)	1.05
Feet (8)	0.130 (0.009)	6.16 (0.39)	67.59 (4.86)	0.106 (0.010)	5.92 (0.55)	74.89 (5.02)	1.11*
Upper arms (6)	0.192 (0.027)	9.09 (0.74)	41.40 (2.75)	0.163 (0.045)	8.93 (0.90)	47.49 (5.58)	1.15*
Forearms (7)	0.142 (0.018)	6.71 (0.20)	50.38 (5.24)	0.108 (0.019)	6.00 (0.37)	60.32 (7.08)	1.20*
Hands (9)	0.104 (0.011)	4.95 (0.46)	103.90 (8.39)	0.082 (0.008)	4.62 (0.45)	122.52 (9.27)	1.18*

*Significant sex difference

Table 4 Gender comparison of the mean (SD) of the ratio of surface area (*SA*) to volume (per metre), circumference (metres), and the constant regressed according to SA/VOL×CIRC (circumference) for various body segments of the men and women of G24. The locations of the CIRC measurements were the waist at the level of the umbilicous (torso), upper leg at the juncture with buttock (thigh), and at the maxima of the gastrocnemius muscle (lower leg), the flexor carpi ulnaris muscle (forearm), and the triceps muscle (upper arm)

Segment	Men ($n=12$)			Women ($n=12$)		
	SA/VOL	CIRC	Constant	SA/VOL	CIRC	Constant
Torso	13.88* (1.41)	0.956* (0.140)	13.10* (0.68)	16.55 (1.88)	0.768 (0.124)	12.50 (0.53)
Thigh	23.43 (2.08)	0.632 (0.073)	14.67 (0.33)	24.59 (2.95)	0.599 (0.090)	14.49 (0.32)
Lower leg	38.59 (4.37)	0.400 (0.045)	15.27* (0.42)	40.70 (4.54)	0.367 (0.060)	14.71 (0.43)
Upper arm	41.40* (2.75)	0.327* (0.027)	13.49 (0.73)	47.49 (5.58)	0.281 (0.051)	13.16 (1.44)
Forearm	50.38* (5.24)	0.304* (0.030)	15.15 (0.37)	60.32 (7.08)	0.257 (0.031)	15.31 (0.38)

*Significant sex difference

Unfortunately, an estimate of the whole-body BSA/VOL ratio could not be reliably made since lung volume was not determined during the scans. Had this been known, it would have been relatively simple to calculate the subject's percentage body fat using body density (*m*/volume; Durnin and Womersley 1974). Attempts at estimating lung volume were not successful. The present SA and volume measurements of the torso should be considered approximate for a standing posture, and deviations from this posture might cause shifts in the SA/VOL ratio indicated in Table 3 although this aspect was not explored.

That the prediction equations of BSA (Eqs. 3 and 4) do not exhibit an age bias (Fig. 5) suggests a robust *h*-*m* relationship with BSA that is invariant to age. This was somewhat surprising considering that *m* generally increases with age for the range considered herein, and that this *m* increase is usually unevenly distributed over the body. In other words, the form of Eq. 1 is well suited for body shapes different not only due to their sexes but also due to their ages. This concurs with the study of Holzenberger and Ruiz-Torres (1991) who examined how BSA varied with the age of older adults specifically due to a change in *h*, although no direct measure of BSA was taken.

Recall also that the data of our study were limited to individuals of 2 m or less in *h*. To determine whether Eqs. 3 and 4 could be extrapolated to individuals of greater *h*, a residual analysis of the errors against *h* was performed and the slope was found not to be significant ($r<0.01$). This would suggest that these prediction equations could be extrapolated for individuals taller than 2 m without incurring serious error.

Takai and Shimaguchi (1986) proposed a prediction model of BSA (in centimetres squared) based on a regression that included head circumference (HC in centimetres), as follows:

$$\mathrm{BSA} = -2142.0 + 617.0 \cdot m^{2/3} + 0.2453 \cdot h^2 + 0.6825 \cdot \mathrm{HC}^2 \qquad (5)$$

Application of the above equation to our entire subject population resulted in a mean underprediction of 2.85% which is worse that any of the other models tested here (Table 2). When Eq. 5 was applied only to men from 18 to 26 years of age in conformity with the subject population analysed by Takai and Shimaguchi (1986), the mean predicted BSA was 1.965 m^2 compared to the measured mean of 2.008 m^2, representing a 2.15% underprediction. Although the subjects used by Takai and Shimaguchi (1986) were generally smaller [$n=40$, *m* 59.8 (7.6) kg, *h* 168.8 (5.1) cm, HC 57.4 (1.6) cm, BSA (using a direct paper coating method) equalled 1.65 (0.12) m^2] compared to our male subjects in this age group [$n=84$, *m* 83.4 (14.7) kg, *h* 177.7 (7.2) cm, HC 57.9 (1.7) cm, measured BSA equalled 2.01 (0.18) m^2, predicted (Eq. 3) BSA equalled 2.00 (0.18) m^2], HC were not different. Consequently, it would appear that inclusion of the latter variable as a regressor does not improve the prediction of BSA.

Mosteller (1987) proposed a prediction equation of BSA that was intended to be simple to use (Table 2) and the low deviation from the measured mean of BSA confirms its applicability as a rule-of-thumb estimate. However, residual analysis indicated that this equation tends to overpredict BSA with increasing body size, as did most of the other equations (Fig. 3). Also, Bailey and Briars (1996) endorsed the equation of Gehan and George (1970) as a medical standard, but no residual analysis of the prediction had been conducted to reveal any possible biases. It is probable that the bias we uncovered was primarily due to the high number of large-mass subjects that we analysed. Previous studies have seldom included women and men whose BSA exceeded 1.9 and 2.1 m^2, respectively, in contrast to the 16% and 33% in the present study population which more accurately reflects current anthropometric trends in North America.

DuBois and DuBois (1916) formulated the parameter values of A and B (Eq. 1) under the constraint of bidimensionality such that $3\mathrm{A} + \mathrm{B} = 2$. Interestingly, while Shuter and Aslani (2000) correctly pointed out that the originally-published constraint was erroneously presented as $3\mathrm{A} \times \mathrm{B} = 2$, Shuter and Aslani (2000) erroneously presented the constraint as $3/\mathrm{A} + 1/\mathrm{B} = 2$. Bidimensionality is nearly preserved with the best-fit Eqs. 3 and 4 where $3\mathrm{A}+\mathrm{B}$ equals 1.92 and 1.96, respectively, while the summations for the other equations tested in this study (Table 2) range from 1.934 to 2.010.

In conclusion, while all cited prediction equations agreed closely with the measured BSA, they exhibited a bias with increasing body size. On the other hand, the equations separately regressed for men (Eq. 3) and women (Eq. 4) are presented herein as the most broadly-based estimates of BSA in terms of the numbers and anthropometric range of the adult population sampled, and in close adherence to the bidimensional constraint imposed by DuBois and DuBois (1916).

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References

Bailey BJR, Briars GL (1996) Estimating the surface area of the human body. Stat Med 15:1325–1332

Boyd E (1935) The growth of the surface area of the human body. University of Minnesota Press, Minn.

Daanen H, Brunsman M, Taylor S (1997) Absolute accuracy of the cyberware WB4 Whole Body Scanner. TNO Human Factors Research Institute Report (March–April 1996). TNO Human Factors Research Institute, The Netherlands

DuBois D, DuBois EF (1916) A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 17:863–871

Durnin JVGA, Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. Br J Nutr 32:77–97

Gehan EA, George SL (1970) Estimation of human body surface area from height and weight. Cancer Chemother Rep 54:225–235

Haycock G, Schwartz G, Wisotsky D (1978) Geometric method for measuring body surface area: a height-weight formula validated in infants, children and adults. J Pediatr 93:62–66

Holzenberger M, Ruiz-Torres (1991) Body surface area as a parameter of age decline. Arch Gerontol Geriatr 13:139–150

Jones PRM, West GM, Harris DH, Read JB (1989) The Loughborough anthropometric shadow scanner (LASS). Endeavour 13:162–168

Mosteller RD (1987) Simplified calculation of body-surface area. N Engl J Med 22 October:1098

Shuter B, Aslani A (2000) Body surface area: DuBois and DuBois revisited. Eur J Appl Physiol 82:250–254

Takai S, Shimaguchi S (1986) Are height and weight sufficient for the estimation of human body surface area? Hum Biol 58:625–638