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Human body surface area database and estimation formula

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ABSTRACT

This study established human body surface area (BSA) database and estimation formula based on three-dimensional (3D) scanned data. For each gender, 135 subjects were drawn. The sampling was stratified in five stature heights and three body weights according to a previous survey. The 3D body surface shape was measured using an innovated 3D body scanner and a high resolution hand/foot scanner, the total body surface area (BSA) and segmental body surface area (SBSA) were computed based on the summation of every tiny triangular area of triangular meshes of the scanned surface; and the accuracy of BSA measurement is below 1%. The results of BSA and sixteen SBSAs were tabulated in fifteen strata for the Male, the Female and the Total (two genders combined). The %SBSA data was also used to revise new Lund and Browder Charts. The comparison of BSA shows that the BSA of this study is comparable with the Du Bois and Du Bois' but smaller than that of Tikuisis et al. The difference might be attributed to body size difference between the samples. The comparison of SBSA shows that the differences of SBSA between this study and the Lund and Browder Chart range between 0.00% and 2.30%. A new BSA estimation formula, $BSA = 71.3989 \times H^{.7437} \times W^{.4040}$, was obtained. An accuracy test showed that this formula has smaller estimation error than that of the Du Bois and Du Bois'; and significantly better than other BSA estimation formulae.

1. Introduction

The purpose of this study is to establish human body surface area (BSA) database and estimation formula based on a three-dimensional (3D) anthropometrical database. BSA is a very important parameter in the normalization of physiological responses [1,20], administration of drug doses [4,15], estimation of burnt skin percentage [11], as well as body heat transfer computation [14]. Therefore, the study of BSA measurement has attracted unceasing research for two centuries.

Ever since the turn of nineteenth century, researchers have begun to measure or estimate BSA using a variety of methods. These methods include direct measurements, such as wrapping with paper, bandage, or lead plate, charging silk cloth and rolling with surface integrators; and indirect measurements, such as geometrical approximation and formula estimation [5,12]. In the turn of twentieth century, Du Bois and Du Bois [5,6] had made a major contribution in BSA measurement and estimation (Eq. (1)). They showed that the accuracy of measurement was between 5.1% and 0.13% [17], and the estimation error of their height–weight formula was within 5% in range between 100 cm and 190 cm in stature height [6]. The measurement and the formula have been taken as standards in most of the textbooks, such as UK text [7] and Lund, Browder Chart [11], etc., and have been used as base data for many later researches [3,8,9,13,18,19]:

$$BSA = 71.84 \times H^{.725} \times W^{.425} \quad (1)$$

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where *BSA* is the body surface area in cm^2; *H* is the stature height in cm; *W* is the body weight in kg.

Nevertheless, Du Bois and Du Bois' BSA measurement and formula were also questioned by many later researchers [2,8,18,19]. The questions included the accuracy of the paper coating method and the representation of nine abnormal subjects. The former are the error due to the tightness of wrapping and the error in the projection of 3D coating scraps onto 2D surface for surface area measurement; and the latter is that the body dimensions of these nine subjects, e.g. dwarfs and children, were quite different from the normal.

Now, these questions can be largely solved by the use of 3D scanning technology. The 3D body scanner is capable of measuring a large amount of subjects with great accuracy and precision [10,16,22,24]. The accuracy of the BSA measurement by scan is shown to be within 1% [19,23] and is considered to be better than the direct measurement methods of the past. Then the 3D measurement can be used to compute BSA by surface integration software with great accuracy. The 3D scanner has been used in many BSA studies [19,23].

However, in despite of the great capabilities of 3D scanners, the scan results usually exhibit many holes and unresolved details (Fig. 3). The holes are basically hid in shadow areas, such as armpits, groin areas, between the toes, etc. The unresolved details are mainly appeared on hands, feet and face, because the critical details are too fine to resolve. These holes and unresolved details are significant drawbacks in BSA measurement using 3D body scanners.

To overcome these shortcomings, this study attempted to establish a sound 3D anthropometrical database for accurate BSA measurement using 3D scanners on a large amount of subjects. It was intended that all the immeasurable holes and irresolvable details of the scan were completely eliminated using both hardware innovation and software refinement. The scan then can be used to compute BSA and segmental BSA (SBSA) to establish a complete BSA database, SBSA database as well as BSA estimation formula.

2. Materials and methods

A 3D anthropometrical database, called Taiwanese Body Bank, was used to compute BSA to establish a BSA database, to revise the SBSA of the Lund and Browder Chart, and to derive a height–weight BSA estimation formula. The Body Bank was scanned using an innovated whole body scanner incorporating with a high resolution hand/foot scanner to minimize and diminish immeasurable holes and irresolvable details. In addition, these holes and details were further eliminated using template matching method to obtain a sound body surface scan [21]. These scans were then used to compute BSA and SBSAs to establish a database and a BSA estimation formula. Finally the database and estimation formula were compared with previous studies.

2.1. *The 3D Taiwanese Body Bank*

The raw data sample of 3D Taiwanese Body Bank is a triangular-meshed digital human model measured by 3D scanners from subject's body surface shape. The human subjects research protocol was approved by JIRB (Joint Institutional Review Board) Taiwan.

2.1.1. *Sampling*

The 3D Taiwanese Body Bank consists of 270 subjects, including 135 males and 135 females. These subjects were drawn from Taiwanese worker's population, aged between 18 and 64. The sampling was stratified in five stature heights (XL, L, M, S, and XS) and three body weights (slim, medium, and fat) according to the distribution of a previous sizable anthropometrical survey [25]; the sampling strata and anthropometric distribution are shown in Table 1. The men (named as "The Male" in this study) have a mean stature height of 167.2 cm (SD 6.2 cm) and a mean body weight in BMI (body mass index) of 22.8 kg/m^2 (SD 5.0 kg/m^2); and the women (named as "The Female") are 155.4 cm (SD 5.6 cm) and 22.9 kg/m^2 (SD 5.3 kg/m^2), respectively. The results of goodness of fit test shown in Table 2 indicate that the distribution of the stature height and body weight (in BMI) of this database is not significantly different from the previous survey (all *p*-values are greater than 0.05). It can be said that this database is a good representation of the population.

2.1.2. *The 3D scanners*

Two scanners, an innovated Gemini 3D whole body scanner and a high resolution Gemini hand/foot scanner, were used for measurement. This innovated 3D whole body scanner was designed by ITRI Taiwan (Industrial Technology and Research Institute). On the original four horizontal measuring heads, the body scanner was especially added two slanting measuring heads, which pointing upward 35° as shown in Fig. 1. These two slanting measuring heads were used to scan the shadow regions, such as the armpits and the groin areas, so the immeasurable holes can be diminished or reduced. The high resolution hand/foot scanner, shown in Fig. 2, was also specifically used to enhance the resolution of hands and feet. Fig. 3(a) illustrates the improvement of these two slanting

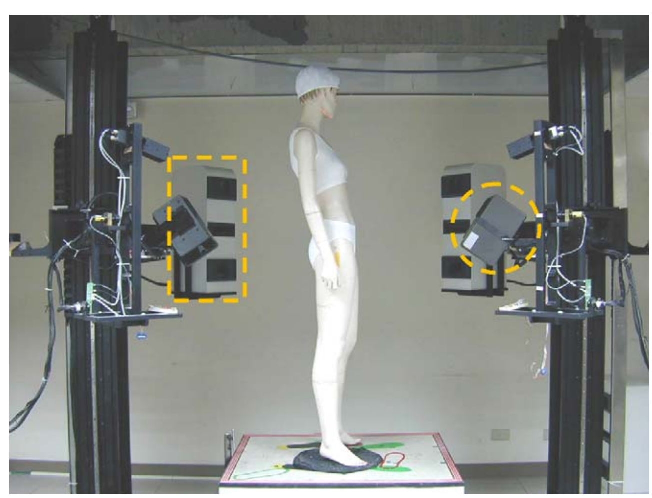

Fig. 1 – The modified Gemini 3D whole body scanner consisting of six measuring heads, four positioned horizontally (one of them marked in rectangular dotted line) and two slanted 35° upward (one of them marked in circled dotted line).

Table 1 – The anthropometric distribution of the database stratified in 5 stature heights (cm) and 3 body weights (kg/mg^2) for (a)The Male (b)The Female and (c)The Total (two genders combined).

Stature height group		Body weight group									Sub-total		
Size	Definition	Slim BMI <18.5			Medium 18.5 < BMI < 27			Fat BMI > 27			*N*	Range	Mean (SD)
		N	Range	Mean (SD)	N	Range	Mean (SD)	N	Range	Mean (SD)			
(a) The Male (*N* = 135)													
XL	>175.8	3	177–185.5	181.8 (4.4)	4	177–191.5	182.8 (6.4)	3	177–181.5	179.2 (2.3)	10	177–191.5	181.4 (4.7)
L	169.9–175.8	10	170–175	172.3 (2.0)	12	170–175.5	172.3 (1.8)	10	170–175.5	171.9 (1.8)	32	170–175.5	172.2 (1.8)
M	164.0–169.9	15	165–169.5	167.3 (1.4)	21	164–169.5	166.7 (1.7)	15	164.5–169.5	167.4 (1.8)	51	164–169.5	167.1 (1.7)
S	158.1–164.0	10	160–163	161.6 (0.9)	12	159–163.5	161.3 (1.8)	10	159.5–163	161.4 (1.2)	32	159–163.5	161.4 (1.5)
XS	<158.1	3	149–157.5	153.5 (4.3)	4	155–158	156.4 (1.3)	3	156–157.5	156.8 (0.8)	10	149–158	155.7 (2.6)
Sub-total		41	149–185.5	167.2 (7.3)	53	155–191.5	167.2 (6.0)	41	156–181.5	167.1 (5.8)	135	149–191.5	**167.2 (6.2)**
Mean (SD) body weight = **22.8 (5.0)**													
(b) The Female (*N* = 135)													
XL	>162.8	3	163.5–167	165.2 (1.8)	4	163–176	169.5 (5.5)	3	163–167	165.3 (2.1)	10	163–176	167.0 (4.0)
L	157.9–162.8	10	158–161.5	159.9 (1.3)	12	158–162	160.6 (1.1)	10	158–162	159.0 (1.3)	32	158–162	159.9 (1.3)
M	152.9–157.9	15	154–157	155.4 (0.9)	21	153–157	155.2 (1.4)	15	153–157	154.8 (1.4)	51	153–157	155.1 (1.3)
S	147.9–152.9	10	148–152	150.3 (1.4)	12	148.5–152.5	150.6 (1.5)	10	148–152.5	150.9 (1.3)	32	148–152.5	150.7 (1.4)
XS	<147.9	3	144–146	145.0 (1.0)	4	143–147.5	145.8 (1.9)	3	141.8–146.5	144.4 (2.4)	10	141.8–147.5	145.1 (1.8)
Sub-total		41	144–167	155.2 (5.8)	53	143–176	155.8 (5.8)	41	141.8–167	154.9 (5.2)	135	141.8–176	**155.4 (5.6)**
Mean (SD) body weight = **22.9 (5.3)**													

(c) The Total (*N* = 270)

	N	Height		Weight	
		Range	Mean (SD)	Range	Mean (SD)
Total	270	141.8–191.5	161.3 (8.4)	14.0–36.3	22.8 (8.3)

Table 2 – Comparison of sampling distribution between Taiwanese Body Bank and the previous survey.

Gender	Previous survey			Taiwanese Body Bank			Goodness of fit test			
	N	Stature height	Body weight	N	Stature height	Body weight	Stature height df = 4		Body weight df = 2	
		Mean (SD)	Mean (SD)		Mean (SD)	Mean (SD)	Chi-square	*p*-Value	Chi-square	*p*-Value
Male	1122	166.8 (6.0)	22.5 (5.1)	135	167.2 (6.2)	22.8 (5.0)	0.0613	0.9995	0.1352	**0.9346**
Female	1310	155.2 (4.9)	23.1 (5.4)	135	155.4 (5.6)	22.9 (5.3)	0.0334	**0.9999**	0.3042	**0.8589**

Height: cm; weight: kg/m^2.
Note: all *p*-values >0.05.

measuring heads; and Fig. 3(b) shows the improvements of the hand and foot scans. Finally, template matching software was used further to completely seal all the small holes remained. The final result of the scan was sound and complete, as illustrated in Fig. 3(c).

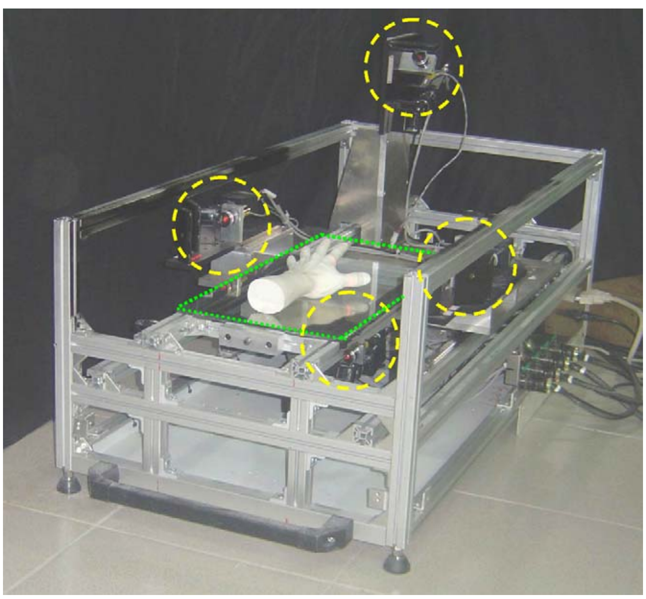

Fig. 2 – The Gemini hand/foot scanner and its interior mechanism. It consists of four measuring heads (marked in circled dotted line) and a transparent tempered glass platform (marked in parallelogram dotted line).

2.2. *The BSA and SBSA measurement*

After the final scan result was acquired, the Anthro3D software was used to compute BSA. The computation algorithm is based on the summation of every tiny triangular area of triangular meshes of the scanned surface. In theory, the computing error of this numerical integration method was only subjected to the partition fineness limited by the resolution level of the scanners.

Then, the scan was further dissected into sixteen body segments to compute SBSA. The demarcations are similar to that of the Lund and Browder Chart [11] and Du Bois and Du Bois [5,17]. However, there are two differences between this study's and the Lund and Browder's. Firstly, in Lund and Browder Chart, all of the anterior and posterior SBSA values were simply halves (50%) of that segments' SBSA. In this study, all of the anterior and posterior SBSA were computed from truly dissected body segment, except the upper arm, lower arm and hand. Secondly, in Lund and Browder Chart, the foot is extended straight from ankle and then demarcates into anterior and posterior parts. It is unnatural and difficult to apply. Therefore, this study demarcated the foot into sole and the remainder. The detailed descriptions of demarcations are listed in Appendix A.

For testing the repeatability of segmentation of Anthro3D software, a subject's scan data was dissected ten times and the

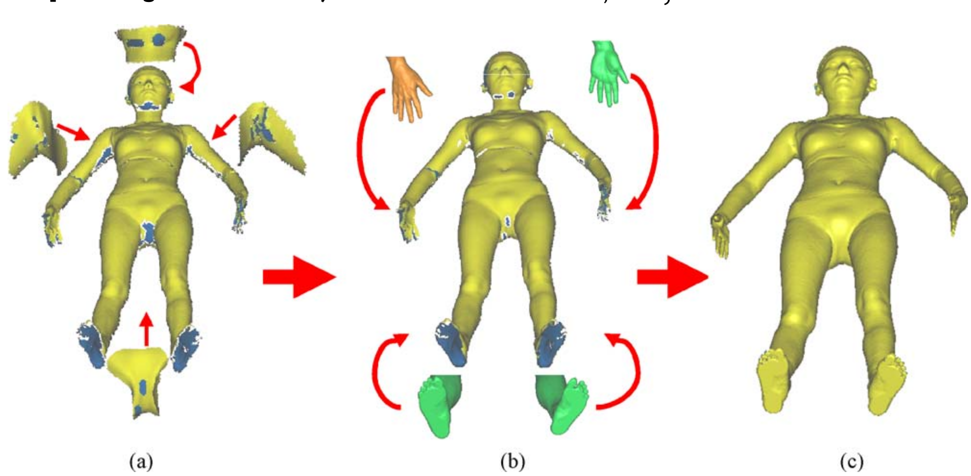

Fig. 3 – The improvement of the modified Gemini 3D whole body scanner and the hand/foot scanner. (a) To patch the immeasurable holes, (b) to patch the unresolved hands/feet, and (c) the final result of the scan after template-matched patch for the small holds.

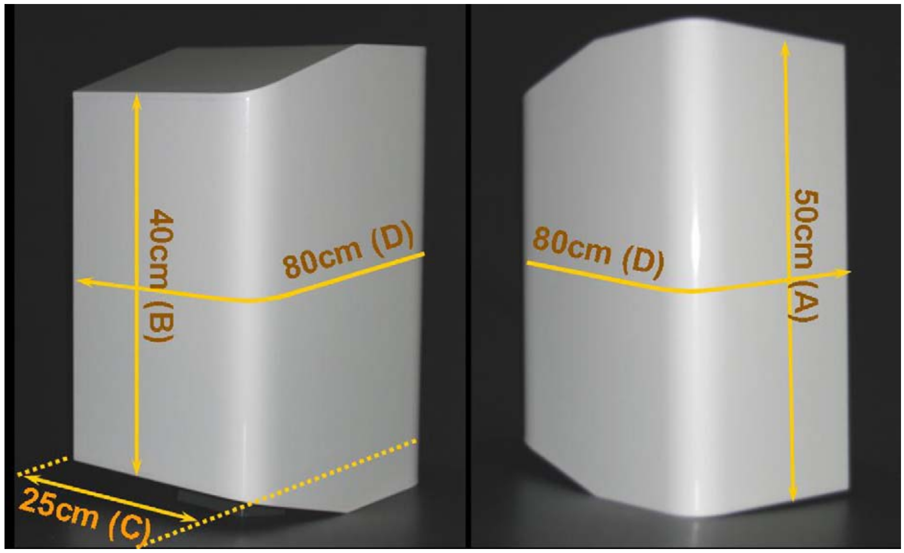

Fig. 4 – The simple-shaped box for accuracy checking of Gemini 3D whole body scanner.

SBSA and %SBSA of it were computed accordingly. The results indicated that the biggest difference was 13.07 cm^2 for SBSA and 0.07% for %SBSA arose from the posterior head segment. The average difference was 5.02 cm^2 for SBSA and 0.03% for %SBSA.

2.3. *Accuracy*

The accuracy of the Gemini 3D whole body scanner was verified by a wooden box as shown in Fig. 4, to compare the 1D measurements and surface area of the scan against the true caliper measurements. The size of the box is 25 cm × 40 cm × 50 cm which is close to the size of a human torso. On the box, four measurements, A (50 cm), B (40 cm), C (25 cm) and D (80 cm) were chosen. The box was scanned with five different angles, since the surface angle in relation to the measuring head could affect scan result due to reflected laser intensity. The five angles were perpendicular (0°), slanted 30°, 40°, 50° and 60°.

The four measurements (A–D) and surface area were compared and tabulated in Table 3. The mean measurement error of four 1D measurements is 0.20 cm, 0.32 cm, 0.23 cm,

Table 3 – The accuracy level of the Gemini 3D whole body scanner measurement system.

		1D measurements (cm)					Surface area (cm^2)
		A	B	C	D	Mean	
True		50	40	25	80		3720
0°	Scan	49.84	40.01	25.50	80.15		3711.63
	Error	−0.16	0.01	0.50	0.15	0.20	−8.46
	%Error	−0.32	0.02	2.00	0.18	0.63	−0.22
30°	Scan	49.80	40.39	25.66	79.96		3708.28
	Error	−0.20	0.39	0.65	−0.05	0.32	−11.84
	%Error	−0.40	0.97	2.62	−0.06	**1.00**	−0.31
40°	Scan	49.78	40.23	25.49	80.00		3701.99
	Error	−0.22	0.23	0.49	0.00	0.23	−18.20
	%Error	−0.43	0.57	1.95	−0.01	0.74	−0.48
50°	Scan	49.97	40.16	25.41	79.94		3698.65
	Error	−0.03	0.16	0.41	−0.06	0.17	−**21.58**
	%Error	−0.06	0.40	1.65	−0.07	0.55	−**0.57**
60°	Scan	50.05	40.17	24.56	79.79		3712.70
	Error	0.05	0.17	−0.45	−0.22	0.22	−7.38
	%Error	0.10	0.43	−1.79	−0.27	0.65	−0.20
Mean (SD)		49.89 (0.12)	40.19 (0.14)	25.33 (0.44)	79.97 (0.13)		3706.65 (**6.12**) CV = **0.17%**
Mean error		0.13	0.19	0.50	0.09	**0.23**	−**13.49**
Mean % error		0.26	0.48	2.00	0.12	**0.72**	−**0.36**

Note: "True" = true size, "scan" = the data of 3D scan.

Table 4 – The accuracy level of the Gemini hand/foot scanner measurement system.

		1D measurement				Surface area			
		True (cm)	Scan (cm)	Error (cm)	%Error	True (cm^2)	Scan (cm^2)	Error (cm^2)	%Error
Sphere	Diameter	7.0	7.01	0.01	0.14%	153.938	154.940	1.002	**0.65%**
Rectangular prism	Height	15.0	15.05	0.05	0.35%	540.000	537.220	**−2.780**	−0.52%
	Length	9.0	8.96	−0.04	−0.44%				
	Breadth	9.0	8.94	**−0.06**	**−0.67%**				
Combined						693.938	692.160	−1.782	−0.26%

Note: "True" = true size, "Scan" = the data of 3D scan.

0.17 cm, 0.22 cm (0.63%, 1.00%, 0.74%, 0.55% and 0.65%) in scanned angle 0°, 30°, 40°, 50° and 60°, respectively. These errors were all below 0.32 cm and the mean error is 0.23 cm (0.72%), all below 1.00% in accuracy. On the other hand, the measurement errors of surface area of the box were −8.46 cm^2, −11.84 cm^2, −18.20 cm^2, −21.58 cm^2, −7.38 cm^2 (−0.22%, −0.31%, −0.48%, −0.57% and −0.20%) in scanned angle 0°, 30°, 40°, 50° and 60°, respectively. These errors were all below 21.58 cm^2 and the mean error was −13.49 cm (−0.36%), all below 0.57% (≪1.0%) in accuracy. Additionally, the precision (reproducibility) of BSA measurement was about ±6.12 cm^2 (0.17%).

The accuracy of the hand/foot scanner was checked using a calibration block, also to compare the 1D measurements and surface areas of the scan against the true caliper measurements. The calibration block consists of a 7 cm diameter sphere and a 15 cm × 9 cm × 9 cm rectangular prism as shown in Fig. 5, which approximates to the size of a human hand or foot.

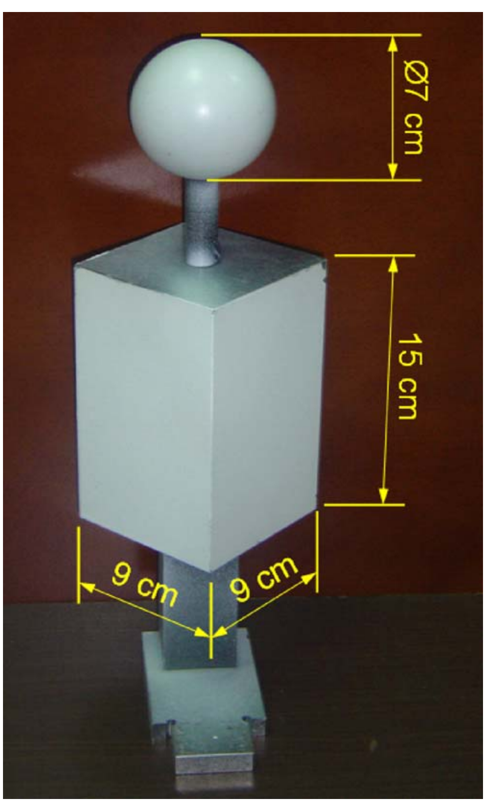

Fig. 5 – The calibration block for accuracy checking of Gemini hand/foot scanner.

The measurement error for the spherical diameter was +0.01 cm (+0.14%); while for the rectangular prism was +0.05 cm (+0.35%) in height; −0.04 cm (−0.44%) in length, and −0.06 cm (−0.67%) in breadth as tabulated in Table 4. They were all below 0.06 cm, or 0.67% (≪1.0%) in accuracy. Likewise, the error in surface area of the sphere is +1.002 cm^2 (+0.65%); while for the rectangular prism is −2.780 cm^2 (−0.52%). If these two surface areas were combined as a whole, the error then reduces to −1.782 cm^2 (−0.26%). It can be said the accuracy level of the BSA measurement was below 2.780 cm^2 or 0.65% (≪1.0%).

2.4. *Data presentation and analyses*

First, the BSA data of this study was tabulated for the Male, the Female, and the Total (two genders combined) separately. For each gender, the tables were tabulated in fifteen strata; each stratum consisted of range, mean and standard deviation (SD). For the Total, only mean and SD were presented, for the stratification of the Male and the Female is different. Then this database was compared with the study of Du Bois and Du Bois [5,17] and Tikuisis et al. [19]. The significance of these two studies are that the Du Bois and Du Bois is the most referenced study, and the samples of Tikuisis et al. are measured by a 3D scanner similar to this study.

Secondly, the SBSA of sixteen body segments, including SBSA and %SBSA, was tabulated for mean and SD of the Male, the Female and the Total. The %SBSA is defined as the percentage of SBSA divided by BSA (% of SBSA/BSA). The revised Lund and Browder Charts for the Male, the Female and the Total were also offered. As for the stratified results in fifteen body types will be shown on website for browsing. Then the %SBSA database was compared with the percentages on the original Lund and Browder Chart.

For developing the BSA estimation formula, three BSA estimation formulae were derived for the Male, the Female, and the Total similar to Du Bois and Du Bois' formula ($BSA = AH^xW^y$, 1916) but not restricted to its proportional scaling ($x + 3y = 2$) characteristics. Subsequently, the BSAs of additional ten male and ten female samples (not in Body Bank) were used to estimate the goodness of these formulae. This result of comparison would conclude the most preferable BSA estimation formula of this study.

Afterward, based on the BSAs of the additional ten male and ten female samples, the concluded formula was com-

Table 5 – The BSA (cm^2) database of (a) The Male, (b) The Female and (c) The Total.

Stature height group	Body weight group									Sub-total		
	Slim			Medium			Fat					
	BMI <18.5			18.5 < BMI < 27			BMI > 27					
	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD
(a) The Male (N = 135)												
XL	17,389.91–17,800.77	17,651.25	227.11	17,623.73–20,297.69	18,861.14	1212.81	20,301.09–21,670.31	21,063.03	697.59	17,389.91–21,670.31	19,158.74	1617.27
L	15,521.22–16,902.14	16,256.41	571.29	16,428.95–19,695.10	17,879.63	967.52	19,638.79–21,203.80	20,698.23	492.99	15,521.22–21,203.80	18,253.18	1840.02
M	15,132.82–15,538.43	15,362.56	184.17	15,837.4–18,888.44	17,186.94	896.18	18,756.75–19,421.61	19,011.06	274.89	15,132.82–19,421.61	17,186.86	1408.23
S	14,158.18–15,345.69	14,536.94	302.94	15,012.63–17,903.01	15,363.25	600.67	17,378.28–18,095.01	17,730.94	394.54	14,158.18–18,095.01	15,844.93	1433.61
XS	13,198.70–14,308.46	13,900.74	610.63	14,630.60–15,288.63	14,868.68	310.38	16,644.06–17,068.80	16,789.08	242.44	13,198.70–17,068.80	15,154.42	1256.55
Sub-total	13,198.70–17,800.77	15,439.70	1126.85	14,630.60–20,297.69	16,882.26	1378.18	16,644.06–21,670.31	19,097.90	1586.77	**13,198.70–21,670.31**	**17,117.05**	**1921.08**
(b) The Female (N = 135)												
XL	14,679.02–15,543.77	15,114.87	432.42	15,730.76–18,456.10	17,000.25	1159.20	18,264.14–19,224.74	18,838.69	507.29	14,679.02–19,224.74	16,986.17	1690.55
L	13,912.19–14,898.54	14,359.71	334.58	14,315.80–17,452.00	15,764.99	871.22	16,853.97–19,506.58	17,836.27	582.29	13,912.19–19,506.58	15,973.11	1512.03
M	12,347.05–14,077.70	13,241.96	632.35	13,792.74–15,799.71	14,875.89	455.48	16,292.97–18,507.62	17,596.17	593.40	12,347.05–18,507.62	15,195.40	1571.17
S	12,129.58–13,586.45	12,649.75	432.91	13,265.16–14,720.97	14,217.07	488.10	16,052.20–16,720.72	16,588.58	158.89	12,129.58–16,720.72	14,468.38	1481.02
XS	11,661.29–12,261.78	11,909.01	313.72	13,126.86–13,971.16	13,368.14	404.53	14,784.88–16,068.66	15,540.44	671.41	11,661.29–16,068.66	13,582.09	1551.89
Sub-total	11,661.29–15,543.77	13,409.65	980.03	13,126.86–18,456.10	14,974.56	1107.14	14,784.88–19,224.74	17,349.47	1103.31	**11,661.29–19,224.74**	**15,220.56**	**1758.13**

(c) The Total (N = 270)

	Range	Mean	SD
Total	11,661.29–21,670.31	16,168.80	6277.81

Table 6 – The comparison between BSA (cm^2) databases of (a) The total samples of this study, Du Bois and Du Bois, and Tikuisis et al., (b) A single sample of This study and Du Bois and Du Bois.

	This study			Du Bois & Du Bois			Tikuisis et al.		
	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD
(a) The total samples of this study, Du Bois and Du Bois, and Tikuisis et al									
The Male	13,198.70–21,670.31	17,117.05	1921.08	14,901–19,000	17,395	1624	14,900–27,130	20,300	1930
The Female	11,661.29–19,224.74	15,220.56	1758.13	16,451–18,592	17,522	1514	13,800–26,620	17,340	1870
The Total	11,661.29–21,670.31	16,168.80	6277.81	**14,901–19,000**	**17,431**	**1465**	**13,800–27,130**	**19,165**	**2388**

Subject	Height (cm)	Weight (kg)	BMI (kg/m^2)	BSA-measured (cm^2)	BSA-estimated (cm^2)	Error (cm^2)	%Error
(b) The single sample of This study and Du Bois and Du Bois							
M087 (this study)	180.3	74.0	23	19,547.31	19,336.89	**−210.42**	−1.08%
E.F.D.B. (Du Bois & Du Bois)	179.2	74.1	23	19,000	19,262.34	**262.34**	1.38%
Difference	−1.1	0.1	0	−547.31	**−74.55**	51.39	0.30%
%Difference	−0.6%	0.1%	1%	−2.80%	−0.39%	24.68%	28.27%

pared with seven other formulae, including the formula of Du Bois and Du Bois [6], Boyd [3], Gehan and George [8], Haycock et al. [9], Mosteller [13], Shuter and Aslani [18] and Tikuisis et al. [19].

Finally, for testing the famous Du Bois and Du Bois' formula (Eq. (1)), the estimation errors of this BSA database would be tabulated for mean and maximum errors in fifteen strata.

3. Results and discussion

3.1. *The BSA and SBSA database*

The detailed results of BSA database for the Male and the Female were tabulated in fifteen strata in Table 5. The males had a mean BSA of 17,117.05 cm^2 (SD 1921.08 cm^2) ranged from 13,198.70 cm^2 to 21,670.31 cm^2; while in the females' it was 15,220.56 cm^2 (SD 1758.13 cm^2) ranged from 11,661.29 cm^2 to 19,224.74 cm^2. The total mean BSA was 16,168.80 cm^2 (SD 6277.81 cm^2).

These results were then compared with the study of Du Bois and Du Bois [5,17] and Tikuisis et al. [19] as listed in Table 6(a). The samples of these two studies were Caucasians while this study's are Orientals. The mean BSA of Du Bois and Du Bois' seven adults (the two children were excluded), was 17,431 cm^2 (SD 1465 cm^2) ranged from 14,901 cm^2 to 19,000 cm^2. And the mean BSA of Tikuisis et al.'s 641 samples was 19,165 cm^2 (SD 2388 cm^2) ranged from 13,800 cm^2 to 27,130 cm^2. It seemed that the BSA of Caucasian was larger than ours; however, the representative of their samples had

Table 7 – The reduced SBSA and %SBSA database of the Male, the Female and the Total.

Samples' attributes	Male				Female				Total			
	SBSA (cm^2)		%SBSA		SBSA (cm^2)		%SBSA		SBSA (cm^2)		%SBSA	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Head												
Head-anterior	783.37	92.50	4.58%	0.35%	723.85	58.81	4.80%	0.45%	753.61	83.23	4.69%	0.42%
Head-posterior	439.64	54.87	2.59%	0.34%	436.74	49.36	2.89%	0.35%	438.19	51.96	2.74%	0.39%
Trunk												
Neck-anterior	223.50	45.66	1.31%	0.24%	172.39	34.21	1.14%	0.20%	197.95	48.52	1.22%	0.24%
Neck-posterior	252.07	49.08	1.48%	0.26%	215.61	48.27	1.42%	0.28%	233.84	53.01	1.45%	0.27%
Trunk-anterior	2555.59	370.64	14.89%	0.86%	2294.83	376.04	15.00%	1.21%	2425.21	407.96	14.94%	1.05%
Trunk-posterior	1927.86	303.85	11.23%	0.81%	1628.94	229.39	10.70%	0.81%	1778.40	316.82	10.97%	0.86%
Buttocks	837.64	118.50	4.89%	0.50%	806.84	144.55	5.28%	0.73%	822.24	135.64	5.09%	0.65%
Arm												
Upper arm	716.55	98.76	4.18%	0.26%	614.52	79.35	4.03%	0.22%	665.54	105.62	4.11%	0.25%
Fore-arm	535.69	69.88	3.13%	0.15%	435.15	63.22	2.85%	0.21%	485.42	87.51	2.99%	0.24%
Hand	405.61	48.83	2.38%	0.20%	344.67	48.22	2.26%	0.17%	375.14	59.21	2.32%	0.19%
Leg												
Thigh-anterior	880.42	110.71	5.15%	0.33%	847.13	104.22	5.57%	0.31%	863.78	110.39	5.36%	0.38%
Thigh-posterior	759.50	100.15	4.44%	0.34%	712.73	87.06	4.70%	0.36%	736.12	97.21	4.57%	0.38%
Shank-anterior	575.79	81.96	3.36%	0.24%	505.20	71.11	3.32%	0.23%	540.50	85.31	3.34%	0.23%
Shank-posterior	599.31	83.85	3.50%	0.21%	529.57	63.65	3.48%	0.23%	564.44	84.50	3.49%	0.22%
Foot	335.76	65.31	1.97%	0.34%	255.76	55.85	1.68%	0.34%	295.76	70.81	1.82%	0.35%
Sole	240.05	64.92	1.41%	0.38%	225.95	48.50	1.49%	0.32%	233.00	59.28	1.45%	0.35%

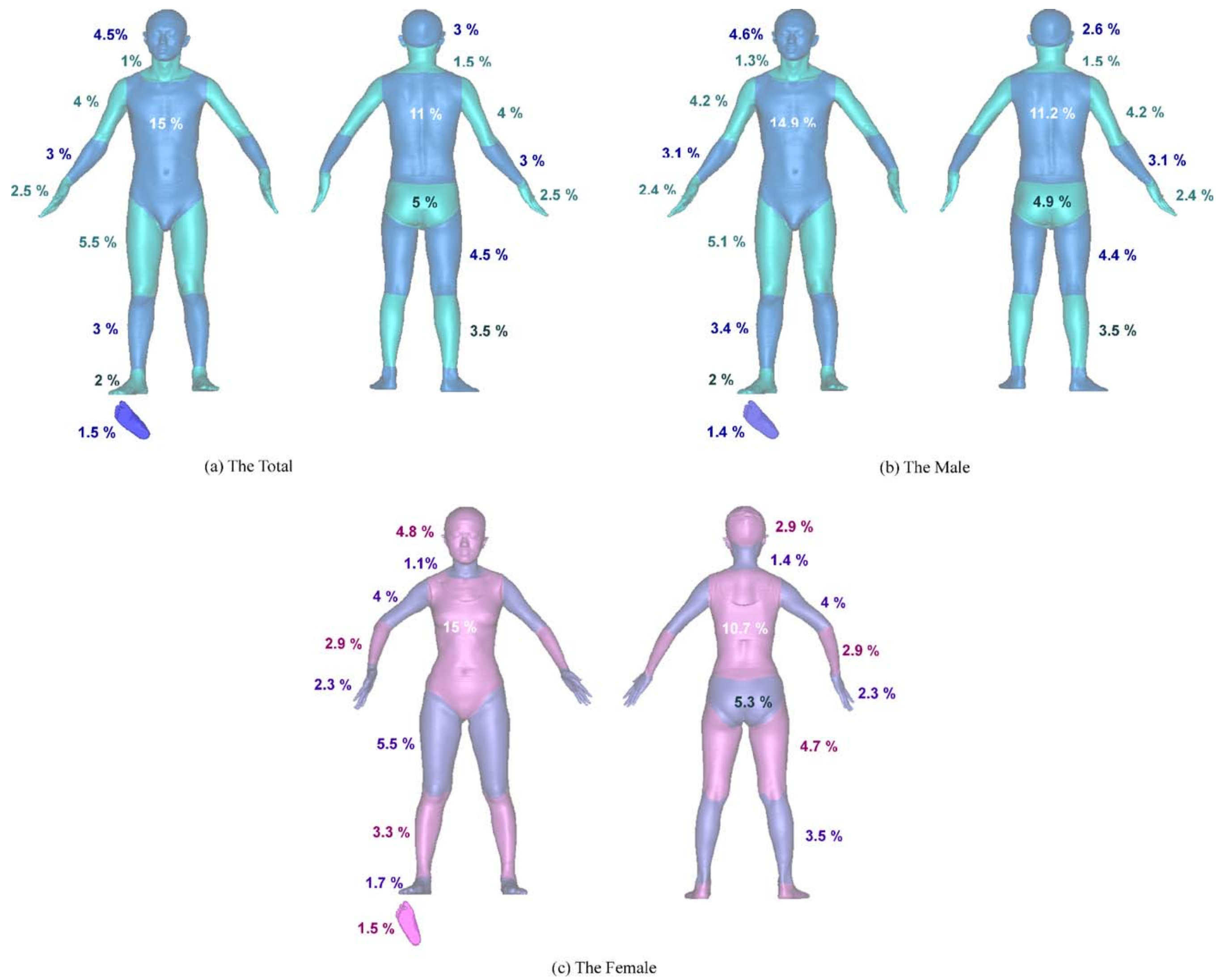

Fig. 6 – The revised Lund and Browder Chart for (a) the total (two gender combined), (b) the male, and (c) the female.

not been discussed. Additionally, two samples with almost the same body type (BMI), one from this study and another from the Du Bois and Du Bois, were chosen for comparison, as shown in Table 6(b). Using Du Bois and Du Bois' formula (Eq. (1)), the estimated BSAs are very close, and the difference between these two is only $-74.55\ \mathrm{cm}^2$. However, the estimation error of this study, $-210.42\ \mathrm{cm}^2$, was a little better than that of Du Bois and Du Bois' own sample, $262.34\ \mathrm{cm}^2$. It is believed that there is no significant difference between the body types of Orientals and Caucasians in relation to the measurement and estimation of BSA.

The mean (and SD) SBSA and %SBSA of the Male, the Female and the Total are shown in Table 7. For convenient reference, the revised Lund and Browder Chart is shown in Fig. 6 and the %SBSAs of it were simplified from Table 7. Fig. 6(a) stands for the total of two genders, and is for quick reference. While Fig. 6(b) and (c) stands for specific male and female %SBSA, respectively, and offer more accurate reference. Unlike the original Lund and Browder Chart, the anterior and posterior %SBSA of head, neck, trunk, thigh and shank were different, according with the asymmetry of these body segments. More detailed results of SBSA and %SBSA of sixteen body segments for the male and the female were also tabulated in fifteen strata, and can be referenced on website http://3dal.ie.nthu.edu.tw.

Next, the %SBSA of this database was compared with the percentage in Lund and Browder Chart. It is noted here that the foot %SBSA and the sole %SBSA of this study were combined in order to compare with that of Lund and Browder Chart, so the number of segments is only fifteen in Table 8, because the demarcation was somewhat different in these two studies.

Take a glance on the fifteen segments in Table 8, the largest differences in %SBSA arose from the trunk-anterior (the Male −1.89%, the Female −2.00%, and the Total −1.94%) and trunk-posterior (the Male +1.77%, the Female +2.30%, and the Total +2.03%). The trunk-anterior of this study was consistently larger and the trunk-posterior was consistently smaller. These differences can be explained as the difference in demarcations. In fact, the difference of the trunk (trunk-anterior, trunk-posterior and buttocks combined) between these two studies is very small. It should be noted here that in both this study and Lund and Browder's, the posterior aspect of the

Table 8 – The comparison of %SBSA between this study and the Lund and Browder (1944) Chart.

Samples' attributes		Male				Female				Total			
		This study	Lund and Browder	Difference	%Difference	This study	Lund & Browder	Difference	%Difference	This study	Lund & Browder	Difference	%Difference
Head	Head-anterior	4.58%	3.50%	**−1.08%**	−23.65%	4.80%	3.50%	**−1.30%**	**−27.04%**	4.69%	3.50%	**−1.19%**	**−25.39%**
	Head-posterior	2.59%	3.50%	0.91%	**35.24%**	2.89%	3.50%	0.61%	21.11%	2.74%	3.50%	0.76%	**27.78%**
Neck	Neck-anterior	1.31%	1.00%	−0.31%	−23.71%	1.14%	1.00%	−0.14%	−11.95%	1.22%	1.00%	−0.22%	−18.25%
	Neck-posterior	1.48%	1.00%	−0.48%	**−32.35%**	1.42%	1.00%	−0.42%	**−29.51%**	1.45%	1.00%	−0.45%	**−30.96%**
Trunk	Trunk-anterior	14.89%	13.00%	**−1.89%**	−12.67%	15.00%	13.00%	**−2.00%**	−13.30%	14.94%	13.00%	**−1.94%**	−12.99%
	Trunk-posterior	11.23%	13.00%	**1.77%**	15.72%	10.70%	13.00%	**2.30%**	21.45%	10.97%	13.00%	**2.03%**	18.51%
	Buttocks	4.89%	5.00%	0.11%	2.20%	5.28%	5.00%	−0.28%	−5.33%	5.09%	5.00%	−0.09%	−1.71%
Arm	Upper arm	4.18%	4.00%	−0.18%	−4.26%	4.03%	4.00%	−0.03%	−0.82%	4.11%	4.00%	−0.11%	−2.57%
	Fore-arm	3.13%	3.00%	−0.13%	−4.02%	2.85%	3.00%	0.15%	5.18%	2.99%	3.00%	0.01%	0.37%
	Hand	2.38%	2.50%	0.12%	5.25%	2.26%	2.50%	0.24%	10.59%	2.32%	2.50%	0.18%	7.85%
Leg	Thigh-anterior	5.15%	4.75%	−0.40%	−7.73%	5.57%	4.75%	−0.82%	−14.67%	5.36%	4.75%	−0.61%	−11.33%
	Thigh-posterior	4.44%	4.75%	0.31%	6.88%	4.70%	4.75%	0.05%	1.11%	4.57%	4.75%	0.18%	3.91%
	Shank-anterior	3.36%	3.50%	0.14%	4.09%	3.32%	3.50%	0.18%	5.50%	3.34%	3.50%	0.16%	4.79%
	Shank-posterior	3.50%	3.50%	0.00%	−0.02%	3.48%	3.50%	0.02%	0.44%	3.49%	3.50%	0.01%	0.21%
	Foot + sole	3.38%	3.50%	0.12%	3.60%	3.18%	3.50%	0.32%	10.20%	3.28%	3.50%	0.22%	6.80%
Head		7.17%	7.00%	−0.17%	−2.40%	7.69%	7.00%	−0.69%	−8.94%	7.43%	7.00%	−0.43%	−5.78%
Neck		2.79%	2.00%	−0.79%	**−28.29%**	2.55%	2.00%	−0.55%	**−21.70%**	2.67%	2.00%	−0.67%	−25.14%
Trunk		31.01%	31.00%	−0.01%	−0.04%	30.98%	31.00%	0.02%	0.06%	31.00%	31.00%	0.00%	0.01%
Arm		9.68%	9.50%	−0.18%	−1.85%	9.15%	9.50%	0.35%	3.87%	9.41%	9.50%	0.09%	0.93%
Leg		19.83%	20.00%	0.17%	0.84%	20.24%	20.00%	−0.24%	−1.20%	20.04%	20.00%	−0.04%	−0.19%

Table 9 – The comparison between the formula of this study, Du Bois and Du Bois' and other famous formulae. (a) absolute and percentage errors, (b) p-values for significances of difference.

Formulae		Error (cm^2) mean (SD)	%Error mean (SD)	Error (cm^2) Max.	%Error max.
(a) Absolute and percentage errors					
This study	$BSA = 71.3989 \times H^{0.7437} \times W^{0.4040}$	**147.39 (90.92)**	0.91% (0.59%)	312.82	**2.33%**
Du Bois and Du Bois	$BSA = 71.84 \times H^{0.725} \times W^{0.425}$	**214.32 (160.48)**	1.32% (0.96%)	593.98	**3.36%**
Boyd	$BSA = 3.207 \times H^{0.3} \times (W \times 1000)^{(0.7285 - 0.0188 \times \mathrm{LOG}(W \times 1000))}$	**402.60 (313.38)**	2.40% (1.60%)	1257.62	6.61%
Gehan and George	$BSA = 235 \times H^{0.42246} \times W^{0.51456}$	338.48 (265.92)	2.02% (1.35%)	1058.11	5.56%
Haycock et al.	$BSA = 242.65 \times H^{0.3964} \times W^{0.5378}$	401.25 (291.46)	2.41% (1.52%)	1096.44	5.76%
Mosteller	$BSA = (H \times W/3600)^{(1/2)} \times 10{,}000$	329.44 (241.36)	1.99% (1.30%)	829.93	4.36%
Shuter and Aslani	$BSA = 94.9 \times H^{0.655} \times W^{0.441}$	338.03 (223.50)	2.08% (1.34%)	853.80	4.71%
Tikuisis et al.	$BSA = 128.1 \times H^{0.60} \times W^{0.44}$	242.33 (163.25)	1.48% (0.97%)	627.38	3.46%

	This study	Du Bois & Du Bois	Boyd	Gehan & George	Haycock et al.	Mosteller	Shuter & Aslani	Tikuisis et al.
(b) p-Values for significances of difference								
This study	–	0.211	**0.000**	**0.005**	**0.001**	**0.013**	**0.003**	**0.029**
Du Bois and Du Bois	0.211	–	**0.022**	0.082	**0.021**	0.084	0.051	0.587

trunk is divided into two segments – the trunk-posterior and the buttocks, but the whole area of the anterior aspect only belonged to one segment – the trunk-anterior. Therefore, the SBSA of the trunk-posterior would be smaller than the trunk-anterior. The Lund and Browder divided 26% into two equal halves, 13% for trunk-anterior and 13% for trunk-posterior. On the other hand, the SBSA for the trunk-anterior was about 14.94% (about 15%) and for the trunk-posterior 10.97% (about 11.0%). Nevertheless, the sum of these two SBSAs in both studies seems to be about the same.

Similarly, the difference of head-anterior was also large. The differences were −1.08%, −1.30% and −1.19% for the Male, the Female and the Total, respectively. On Lund and Browder Chart, the 7% of the head is also equally divided into 3.5% for each of the head-anterior and the head-posterior. It is evident, the human head is not symmetric for their anterior and posterior parts, and the SBSA of anterior head should larger than the posterior head. As shown in Table 8, the SBSA is about 4.7% for the head-anterior and 2.7% for the head-posterior.

If the whole body is considered as 5 gross regions (head, neck, trunk, arm, and leg) the differences in %SBSA between this study and the Lund and Browder Chart are all smaller than 0.79% (<1.0%). In a similar manner, if we look at the %difference which characterizes as the percentage of the difference (the %SBSA of the Lund and Browder Chart subtracts the %SBSA of this study) divided by the %SBSA of this study. The %differences were all smaller than 8.94% (<9.0%), except the neck. The %difference of the neck was the highest, −25.14% for the Total (−28.29% for the Male, and −21.70% for the Female). This is because the neck% was very small (2.7% in this study, 2.0% in Lund and Browder Chart), therefore a small error of 0.7% makes significant difference.

3.2. *BSA estimation formula*

Similar to Du Bois and Du Bois' formula but not restricted to its proportional scaling ($x + 3y = 2$) characteristics, three estimation formulae each for the Male, the Female and the Total were derived as Eqs. (2)–(4), respectively. The correspondent R^2 are very high, 0.97, 0.97 and 0.99. Then, the BSAs of additional ten male and ten female samples (not in Body Bank) were used to estimate the goodness of these formulae. For the Male, the mean estimation error was 0.92% and the Female 0.98%, and the Total was only as small as 0.91%. These estimation errors were tested, and the p-value of ANOVA is 0.697, not significant. This results indicate that the estimation errors was not systematic related to these three formulae, therefore Eq. (4) (the formula for the Total) is selected as the sole formula of this study.

The Male

$$BSA = 79.8106 \times H^{.7271} \times W^{.3980} \tag{2}$$

The Female

$$BSA = 84.4673 \times H^{.6997} \times W^{.4176} \tag{3}$$

The Total

$$BSA = 71.3989 \times H^{.7437} \times W^{.4040} \tag{4}$$

where H is the stature height in cm; W is the body weight in kg; BSA is the body surface area in cm^2.

Table 10 – The comparison between the BSA (cm^2) of this database and the estimated BSA based on Du Bois and Du Bois' (1916) formula.

Stature height group	Body weight group														
	Slim					Medium					Fat				
	BSA-measured mean	BSA-estimated mean	%Error mean	%Error mean	%Error max.	BSA-measured mean	BSA-estimated mean	Error mean	%Error mean	%Error max.	BSA-measured mean	BSA-estimated mean	Error mean	%Error mean	%Error max.
(A) The Male															
XL	17,651.25	17,525.04	180.68	0.72%	−1.21%	18,861.14	18,858.23	69.12	0.37%	−0.52%	21,063.03	21,445.32	382.29	1.79%	3.40%
L	16,256.41	16,063.91	265.67	1.65%	−3.91%	17,879.63	17,630.25	332.90	1.84%	**−5.06%**	20,698.23	20,627.67	355.99	1.73%	−4.20%
M	15,362.56	15,253.81	139.19	0.91%	−1.82%	17,186.94	17,003.65	158.02	0.93%	−3.39%	19,011.06	18,891.66	282.90	1.48%	−2.82%
S	14,536.94	14,645.06	281.27	1.90%	−3.90%	15,363.25	15,818.63	357.15	2.18%	**−5.53%**	17,730.94	18,100.90	455.24	2.57%	3.64%
XS	13,900.74	13,545.98	354.76	2.58%	−3.93%	14,868.68	14,731.11	289.75	1.96%	−3.97%	16,789.08	16,958.30	203.22	1.22%	2.82%
Sub-total	15,439.70	15,345.96	167.14	**1.08%**	**−3.93%**	16,882.26	16,800.24	191.10	**1.13%**	**−5.53%**	19,097.90	19,176.37	296.84	**1.56%**	**−4.20%**
(b) The Female															
XL	15,114.87	15,125.27	141.18	0.94%	1.55%	17,000.25	16,890.29	109.96	0.66%	−1.22%	18,838.69	19,128.59	289.89	1.53%	1.97%
L	14,359.71	14,291.15	223.95	1.55%	−2.58%	15,764.99	15,698.85	201.68	1.28%	3.91%	17,836.27	17,776.20	558.28	3.09%	**−5.53%**
M	13,241.96	13,627.21	260.92	1.95%	4.95%	14,875.89	14,755.73	275.91	1.85%	−4.02%	17,596.17	17,362.39	271.18	1.55%	−4.63%
S	12,649.75	12,962.49	309.77	2.43%	4.71%	14,217.07	14,000.58	230.51	1.60%	−2.96%	16,588.58	16,353.65	155.87	0.95%	−2.13%
XS	11,909.01	11,977.94	235.00	2.00%	3.50%	13,368.14	13,383.46	327.76	2.43%	4.14%	15,540.44	15,285.52	331.22	2.15%	−3.05%
Sub-total	13,409.65	13,510.95	210.95	**1.61%**	**4.95%**	14,974.56	14,858.28	231.78	**1.56%**	**4.14%**	17,349.47	17,348.00	120.95	**0.71%**	**−5.53%**

Then, based on the BSAs of the additional ten male and ten female samples, Eq. (4) was compared with seven other formulae, such as the Du Bois and Du Bois [6], Boyd [3], Gehan and George [8], Haycock et al. [9], Mosteller [13], Shuter and Aslani [18] and Tikuisis et al. [19]. As shown in Table 9(a), the mean (SD) absolute error of this study is 147.39 cm^2 (SD 90.92 cm^2), while of these seven formulae range between 214.32 cm^2 (SD 160.48 cm^2) and 402.60 cm^2 (SD 313.38 cm^2). The mean %Error and maximum %Error of the Eq. (4), 0.91% and 2.33%, was the smallest among these eight formulae. The next smaller are the Du Bois and Du Bois', 1.32% and 3.36%; and then Tikuisis et al.'s. It was noted that these two latter studies were also direct measurement, the Du Bois and Du Bois' was measured using paper wrapping and the Tikuisis et al.'s 3D scanning.

For testing the significance of the difference between these estimation formulae, the Kruskal–Wallis Test was used on the absolute errors of these eight formulae owing to the non-homogeneity of variances between these error groups. The result showed that these eight error groups are significantly different (p-value 0.005). Particularly, the Mann–Whitney tests indicated that Eq. (4) is significantly better than all of the rest except for the formula of Du Bois and Du Bois, as shown in Table 9(b). However, the formula of Du Bois and Du Bois is only significantly better than that of Haycock et al. and Boyd.

Finally, the Du Bois and Du Bois' [6] formula (Eq. (1)) was used to estimate the BSA database of this study. The estimated BSAs are compared with the scanned BSA of this study in Table 10 in the form of estimation errors (Error) and percentage errors (%Error). The mean %Error of the slim, medium and fat groups for the male were 1.08%, 1.13%, 1.56%, and for the female 1.61%, 1.56%, 0.71%, respectively. The maximum %Error of the slim, medium and fat groups for the male are −3.93%, −5.53%, −4.20%, and for the female were 4.95%, 4.14%, −5.53%, respectively. The maximum %Error ranged in between 3.93% and −5.53%, and two of them exceeded 5%.

4. Conclusion

By the use of innovative 3D scanning and software technology, a sound and complete BSA database was established. Based on the accuracy checking of the 3D scanners and BSA integration software used in this study, both 1D measurements and surface area integration are all within 1.0%. In contrast, Du Bois and Du Bois indicated that the accuracy of paper coating method ranged between 0.13% and 5.1% depending on the tightness of wrapping. Furthermore, on the capacity of 3D scanners, two slanted measuring heads and template matching method are added in this study to completely eliminate the immeasurable holes and irresolvable details. It is believed by so doing, the scanning result of this study will be better improved than the scanning result of Tikuisis et al. [11].

The BSA database of this study is complete, because it consists of the Male, the Female and the Total (two genders combined) of good population representation. Each gender consists of 135 subjects and stratified into 5 stature heights and 3 BMI levels. The database consists of detailed information of BSA, SBSA, and %SBSA and %difference in relation to the Lund and Browder Chart. This database will be useful not only for medical application, but also for later research reference. The Total is the average of all 270 subjects of two genders combined; it can be used as a quick reference. The comparison of BSA shows that the BSA of this study is comparable with the 7 adults of the Du Bois and Du Bois' but smaller than that of the Tikuisis et al. The difference might be attributed to body size difference between the samples. The comparison of SBSA shows that the differences of SBSA between this study and the Lund and Browder Chart range only between 2.32% and −1.75%, the difference is mainly due to the difference in demarcation difference. The demarcation of this study is an improved version of the Lund and Browder Chart, because the anterior and posterior aspect of a segment regions, e.g. the trunk and the head is truly partitioned based on silhouette lines instead of simply divided into halves.

The regression analyses of this study indicate that only a BSA estimation formula derived from the Total (Eq. (4)) is good for both genders, in other words, no gender-specific estimation formulae are necessary. The comparison of this formula with previous studies shows that the estimation error of Eq. (4) is significantly better than all of the rest except for the formula of Du Bois and Du Bois. However, the formula of Du Bois and Du Bois is only significantly better than that of Haycock et al. and Boyd.

Conflict of interest

There is no conflict of interest for authors of this paper.

Appendix A

Head: Divided from the lower margin of the mandible to its posterior border, thence to tip of the mastoid process and in a straight to the external occipital protuberance. The head was then separated into anterior and posterior parts.
Neck: Divided by the shortest line from the supraclavicular notch to the spinous process of the 7th cervical vertebra. The neck was also separated into anterior and posterior parts.
Upper arm: Divided from the acromion process anteriorly and posteriorly to the upper border of the axilla. The upper arm was acquired after the lower arm and hand were split in the next two steps.
Lower arm: Divided by a line drawn from the upper edge of the olecranon around to the antecubital fold.
Hand: Divided by the line at right angles to long axis of forearm drawn at level of tip of ulna.
Thigh: Divided from the perineal point going posteriorly in the natal fold to the upper border of the great trochanter, thence medically in a straight line to the perineal point. After the shank and foot were split in the next two steps, the thigh was acquired.
Shank: Divided by the line at level of lower border of patella. And then, it was divided into anterior and posterior parts.
Foot: Divided by the line at level of tip of lateral malleolus. The surface area of sole was calculated as well.
Anterior and posterior trunk: After the dividing of head, neck, arms and legs, the rest part was divided by a line along the anterior edge of the trapezius muscle and a vertical line from the midaxilla, and then it was split into anterior and posterior parts. The posterior part still needed to divide out for buttock parts in the next step.
Buttocks: Divided by a line vertical from the upper posterior corner of the trochanter to the point where it meets the iliac crest.

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