Appendix A

Thesis philosophical context of study design and biostatistics analysis

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The publications were described in this thesis could be divided as two part of philosophical contexts. The summarized studies in chapter 3, their details were revealed in Appendix B and C, used philosophical context and biostatistics analysis detailing in model prediction philosophy which is discussed in section 1 in this appendix. The study demonstrated in Appendix D and including as part of thesis in chapter 4 had philosophical aspect mainly in effect modification which is discussed in section 2 in this appendix.

1. Model prediction philosophy

1.1 Basic assumptions

The prediction for height and body weight in this thesis imitate concept of diagnostic prediction research but there are some different points. While prediction of outcome or response occurrence in diagnostic prediction research is categorized variable (disease or non – disease, sometime is called occurrence of disease), prediction outcome of height and body weight is continuous variable. However, both of them are categorized as descriptive element of relation and based on linearity association assumption between single or multiple predictor(s) or determinant(s) [X(s)] and response or outcome variable [Y]. Relation between response variable and predictor(s) or covariate(s) could be demonstrated as following mathematic functions.[1-2]

Outcome (Y) = function of determinant(s) [X_1, X_2, X_3, …..]
Height prediction = function [body length(s)]
Body weight prediction = function [body circumference or its combination, height]

Regarding continuous outcome, linear regression model is used in analytic procedures. On these backgrounds, there are two points of concern during analytic procedure, *"linearity of regression"* and "*model selection criteria*".[3]

Linearity of relation between outcome and predictor variables is very important. Violations of linearity are extremely serious for model validation and result in error prediction value especially when model is extrapolated beyond the range of the sample. Nonlinearity could be evident in a plot of the "added variable plot (AV plot)" or a plot of "residuals versus predicted values" or "residuals versus fitting values".[3] The points should be symmetrically distributed around a diagonal line in AV plot or a horizontal line in residuals versus predicted values or residuals versus fitting values. The following example graphs (Figure A1 – A3) in model creation procedure were demonstrated linearity relation between variable of chest circumference and body weight.

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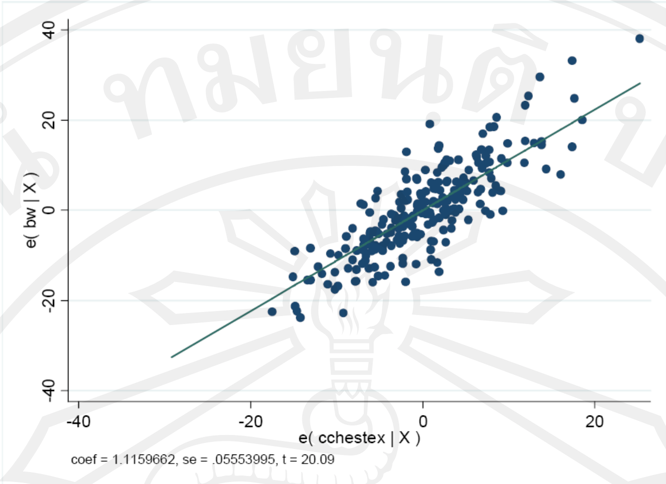

Figure A1 Added variable plot (AV plot) of chest circumference and body weight

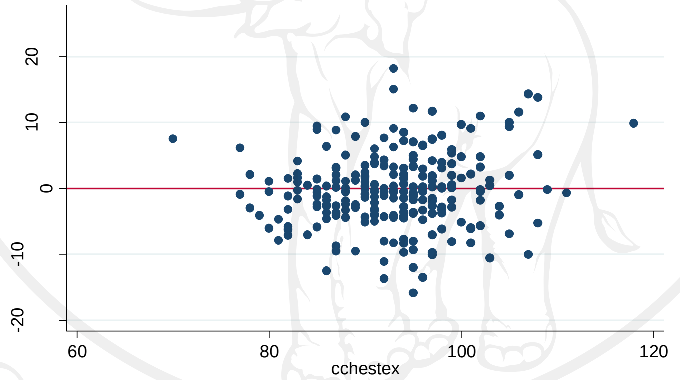

Figure A2 Residual versus predict plot of chest circumference

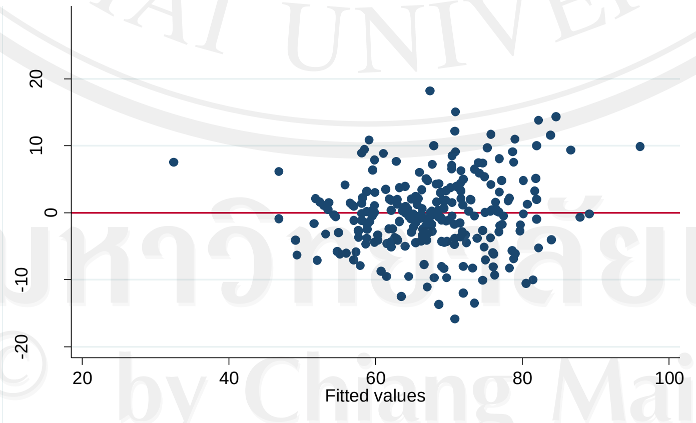

Figure A3 Residual versus fitting plot of chest circumference

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In the point of selection model statistics, correlation co-efficient(r), adjusted R square (adjusted R^2), Akaike's information criteria (AIC) and Bayesian's information criteria (BIC) were used in our thesis model selection methods.[3] These biostatistics reason backgrounds are discussed point by point.

Even though adjusted R square and mean square error (MSE) have the similar meanings in statistical models but different aspects. The following formula are demonstrated the detail of equation calculation method.[3]

$$MSE = VAR(E) + (ME)^2$$
$$R\ square = 1 - MSE/VAR(Y)$$

Where MSE=Mean square error, VAR (E) = Variance of error, ME=Mean error, VAR(Y) =Variance of Y

Of these equations, MSE concerned only model error, while adjusted R square considers error in terms of MSE over independent variance or alteration. These mean that R square considers the relation of error over an independent variable alteration. Therefore, in terms of fitting model, report with adjusted R square was preferred and gave more information than MSE.

In addition to adjusted R square, the selected models were decided using AIC and BIC value.[3] Detailing of each method was demonstrated as follows:

$$AIC = -2\log p(L) + 2p$$
$$BIC = -2\log p(L) + p\log(n)$$

Where p (L) = likelihood, p=number of parameter in model, n=number of sample size

The concepts of both AIC and BIC are to select the model that minimized the negative likelihood penalized by the number of parameters in the model. Unlike AIC, BIC also depends on sample size n. From a Bayesian perspective, BIC is designed to find the most probable model given the data.

Due to a fixed parameter at objective that was comprised of only two or three parameters and the same number of sample size. The AIC and BIC in body weight and height prediction in the studied, therefore, had the same direction. However, these parameters showed different aspects to the adjusted R square and different meaning so the study reports demonstrated all of them in each predictive model.[4-5]

1.2 Step of analysis and validation of height and body weight prediction

Step 1: Random selection of sample from pooled sample for testing or modeling groups and validation groups which categorized by age group and gender.

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Step 2: Univariable linear regression selecting variables using correlation (r), adjusted R square, AIC and BIC categorized by age group and gender.

Step 3: Multivariable linear regression with selected prediction variable(s) categorized by age group and gender.

Step 4: Adjusted the constant coefficient(s) and interception for simple number and assigned as "Simple formula".

Step 5: Validation both of original formula and simple formula to validation sample and demonstrate of error, relative error (%) as well as demonstrated as Bland – Altman plot.

Step 6: ± demonstrate error tolerance in each covariate model with 95% confidence interval.

2. Effect modifications philosophy

2.1 Basic assumptions

Modifier or modifier factor is the external factor which results in alteration the effect size and direction between determinant and event relation. The modifier factor might increase or decrease the effect size as well as direction alteration. Therefore, it cannot to conclude the occurrence relation with the same effect size and direction to all samples if this relation is disturbed by modifier factor. Sometime this phenomenon called "effect modification" (clinical epidemiological term) or "interaction of effect" (statistical term).[1-2] The modifier factor can be demonstrated as the following figure A4 – A5

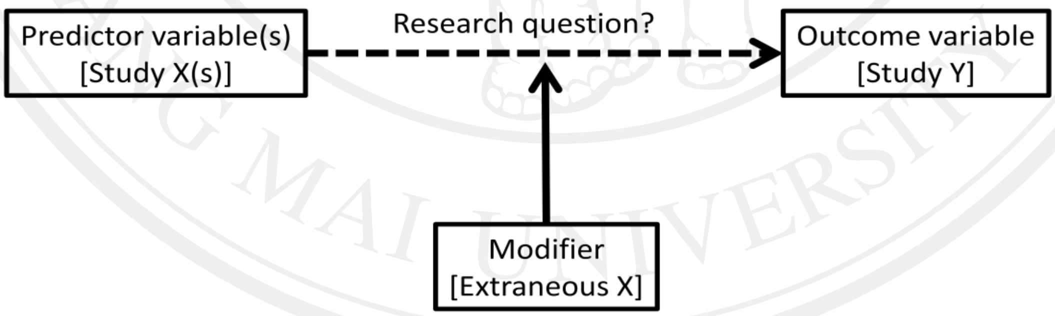

Figure A4 Relation between predictor(s), outcome and modifier

In the study based of this thesis in Appendix C, the study demonstrated the effect of age spectrum as modifier on body fat prediction using anthropometric parameter of body mass index (BMI), sex and age which were demonstrated in Figure A5.

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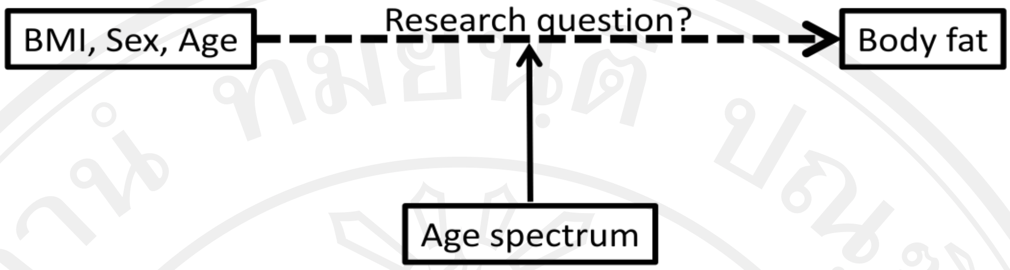

Figure A5 Relation between predictors (BMI, sex and age), outcome (body fat) and modifier (age spectrum)

The study in Appendix D is categorized as descriptive element which demonstrates the modifier effect between age spectrum and age. The mathematic function of modifier or interaction effect is demonstrated as the following equations.

Outcome (Y) = function of determinants [X_1, X_2, (X_1X_2)]..... If X_2 is modifier

Therefore, the outcome and determinants relation in term of modifier effect between age and age spectrum to body composition components could be demonstrated as the following equations.

Body composition components = function [BMI, Sex, Age, Age spectrum, (Age x Age spectrum)]

2.2 Step of analysis

The analysis planning to demonstrate the modifier of age spectrum in study in Appendix D was performed as following steps.

Step 1: Demonstration of body composition component differences in each age group.

Step 2: Multivariable analysis with selected variables of sex, age, body mass index and nutritional status in each age group.

Step 3: Demonstration of modifier effect of age spectrum (younger and older) with age

Step 4: Demonstration of predictive error in previous calculation formula without age spectrum concern.

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Appendix B

Chittawatanarat K, Pruenglampoo S, Trakulhoon V, Ungpinitpong W, Patumanond J. Height prediction from anthropometric length parameters in Thai people. Asia Pac J Clin Nutr 2012;21:347-54.

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Original Article

Height prediction from anthropometric length parameters in Thai people

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Height is an important clinical parameter. However, there were no specific measurements available for particular clinical situations. Although many anthropometric measurements were suggested, no formula was recommended in Thailand. The objective of this study was to develop a formula for height prediction with acceptable validity. Two thousand volunteers were included and were divided consecutively according to both age and gender. Model and validation groups were further separated independently. Linear regression was analyzed to create a predictive formula. Ten parameters were included and analyzed. Of these, demispan, sitting height and knee height were selected with a correlation coefficient of more than 0.5 and significant F test in all age groups and genders. All single parameters and the highest predictive value of double (sitting and knee height) and triple regression models (demispan, sitting and knee height) were proposed and these were modified into a simple formula. After validation of both formulas the correlation, quantitative error and relative error were comparable. The simple formula had more than 90% precision with an error of up to 10 cm in the validation group (89.7 to 99.0% in range). Of these, knee height had the least predictive error in all subgroups. The double and triple models had decreased error only in the younger group. In summary, anthropometric parameters with demispan, sitting height, knee height and combination could be applied to height prediction in the adult Thai with acceptable error. These formulas should be applied only in people who could not be directly measured.

Key Words: anthropometry, body measure, body height, linear models, Thai

INTRODUCTION

Height is an important clinically measured parameter along with BMI and body surface area calculation. These measurements play an inevitable part in drug dose adjustment, nutrition assessment and requirements, as well as for risk stratification.[1-3] Nevertheless, there are some limitations for obtaining this crucial information in special clinical situations such as immobilized patients, elderly people, emergency and critically ill patients. Of these situations, visual estimation is one of the most common methods to guess the patient height. However, this method has an unreliable result. A study of pre-operative supine patients used visual estimation for height by different observers demonstrating marked variation in the ability to assess these characters accurately.[4] A more scientific method was recommended by the prediction of patient stature via the anthropometric measurement model. Although there were many suggested formulas for height prediction with some selected anthropometric measurements such as ulnar length, knee height, hand dimension, demispan and arm span, and an inaccurate prediction may occur due to the relationship between the anthropometric measurement and height depending on ethnic specific differences, gender and age.[5-15] With our best knowledge, even though there are some studies of stature prediction in the Asian population, all of them focused on elderly people and there is no suggestive formula to predict height in Thailand.[15-17] Therefore, the objective of this study was to get a more appropriate model to predict height by anthropometric measurement in the adult Thai population.

MATERIALS AND METHODS

The authors enrolled healthy Thai volunteers by an invitation announcement in the Faculty of Medicine, Chiang Mai University via public information posters and the hospital web site. Four research assistants were trained in the measurement method for each anthropometric parameter and reliability testing was performed before data

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Table 1. Methods of anthropometric length parameter measurements

Parameters (cm)	Position	Point of measurement method
Height	Standing with bare feet	Vertically in midline from heel to vertex (the topmost position of the head)
Demispan	Supine or sitting with shoulder full extension laterally	At ventral surface, started from mid manubrium passed over shoulder, elbow and wrist to tip of third finger.
Biaxillary length	Supine or sitting with arm adduction close to body	At ventral surface, measurement side to side at the junction of deltopectoral groove and anterior axillary fold
Neck length	Sitting with fully neck extension	At posterior, started at external occipital protuberance to tip of spinous process of 7th cervical spine (vertebral prominens at root of neck).
Humeral length	Supine or sitting with 90 degree elbow flexion	At lateral aspect, started point at tip of acromioclavicular eminent to tip of olecranon of elbow of non-dominant arm.
Forearm length	Supine or sitting with elbow extension	At palmar surface, started at olecranon process of elbow to the prominent bone of wrist (styloid process) of non-dominant arm.
Hand length	Supine or sitting	At palmar surface, started at last crease of wrist to tip of mid finger (3rd finger) of non-dominant hand.
Sitting height	Sitting in fully erect posture	Vertically in the midline from upper border of sitting chair to vertex (the topmost point of the head). (Figure 1)
Thigh length	Sitting position or supine with 90 degree flexion of knee and 30-45 degree of hip	From mid inguinal point directed to upper border of patella on ventral surface.
Knee height	Supine or sitting with 90 degree flexion of knee and neutral of ankle	At lateral aspect, started point under the heel of foot and passed over the lateral malleolus to the upper most point of femur condyles. (about 4 cm. proximal to the patella).
Foot length	Supine or sitting	From the tip of heel at posterior to tip of first toe.

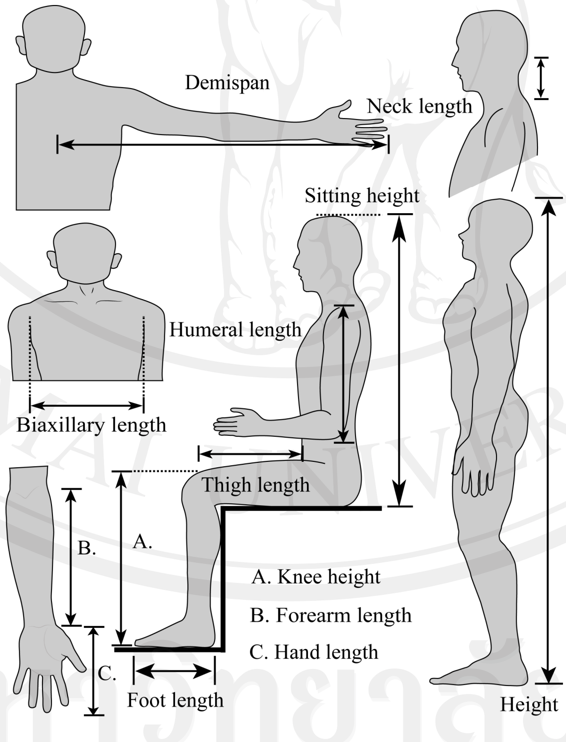

Figure 1. Measurement of anthropometric length parameters

collection. We excluded volunteers whose age was less than 18 years old, amputated limb(s), inability of ambulation, inability to lie down, chronic disease which might interfere with measured parameters such as liver cirrhosis, renal failure, chronic steroid use and edematous limb(s). This study was approved by the Faculty of Medicine, Chiang Mai University Ethics Committee.

We measured and collected height, demispan, biaxillary length, humeral length, forearm length, hand length, thigh length, knee height and foot length with a standard measuring tape utilizing the same reference points. Details of the method of measurement were described in Table 1. All parameters were recorded in cm.

The estimated sample included was at least 200 healthy volunteers. However, age and gender were concerned as interactive parameters. Therefore, we further divided the age group into elder and younger group with a cut-off point for age at 60 year-old, based on the official retirement age in our country as well as our previous work which suggested significantly difference body composi-

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tion in Thai people above this cut-off point.[18] With these determinations, we intended to collect at least 200 volunteers in each age group and gender. We expected incomplete data of about 20%. Therefore, we expected a data collection of 250 volunteers in each subgroup. Due to external validation after modeling, we also collected the same sample size for this purpose. Therefore, the overall sample was two thousand volunteers.

All of the continuous variable data between age group and gender were tested for normal distribution with a visual inspection of the histogram and the Shapiro-Wilk W test and reported as mean±SD. Group differences were calculated using Student's *t* test for normally distributed continuous variables and Mann-Whitney U test for nonparametric continuous variables. The same groups with the different formula measurements of error and relative error were calculated using paired *t* test for normal distribution and Wilcoxon sign rank test for nonparametric continuous variables. The univariable and multivariable linear regression models were used to identify the relationship between independent variable(s) and height. A statistical difference was defined as *p*-value less than 0.05.

Parameters selection, modeling and validation

Two thousand volunteers were separated consecutively and independently into four groups by age group and gender. Each group was further consecutively divided into two groups, the model group and the validation group, which were independent with an equal size of volunteers.

For parameter selection, five-hundred volunteers in each group were used in these processes. These were performed first by testing the interaction of age group and gender based on a previous hypothesis. Parameters were decided via modeling selection by correlation value and significant model fitting R square test (F-test). We determined parameters which were put into the model prediction that should have a correlation coefficient of more than 50% and significant fitting model R square test in all subgroups.

After the parameters selection, modeling creation was performed by linear regression in each modeling subgroup sample of 250 volunteers. Individual and combination model were selected based on R square value, log likelihood, Akaike's information criteria (AIC) and Bayesian's information criteria (BIC). Parameters which had multicollinearity property were excluded. Single, double and triple parameters were proposed for the final linear regression models. The coefficient and intercept of the model had been confined to a simple number which was defined as a simple linear regression formula.

For external validation, predicted height was calculated and the difference was compared to the actual height in the other equal sized volunteer in each validation subgroup of 250 volunteers. The deviated value was reported in error quantity and relative error to actual height in percentages. Original regression formulas and modified simple formulas were compared together with correlation coefficient, error quantity and relative error. The level of error and relative error were divided into four groups, <5, 5-10, 10.1-20 and more than 20 % respectively. Agreements of two methods were tested by kappa statistics based on error level.

RESULTS

From May 2010 to May 2011, a total of two thousand volunteers were divided into groups of five hundred each in accordance with age group and gender. Eleven parameters of height, length and span were demonstrated in Table 2. Of these, all parameters were significantly different between gender and age group except humeral length, forearm length, hand length and thigh length between age groups in females. Of these differences, we suspected an interaction of these parameters to the height prediction model and beta coefficient which was tested in selected predicted parameters (knee height, demispan and sitting height). The authors found significant interaction within gender and the defined age group. Interaction between age and predictive parameters in each gender and age group of younger (<60 years) and older (≥60 years) individuals were tested again before formula creation. The authors found that there were no significant difference of interaction between age and predictive variables of knee height, demispan and sitting height in all subgroup. Therefore, the authors divided the prediction model in each age group and gender and did not add an age variable into the predictive parameters model. To select parameter to model, the authors' consideration was based on the correlation coefficient (r), R square value (R^2) and F test which are demonstrated in Table 3 for each subgroup.

Table 2. Anthropometric length parameters by gender and age group

Measurement parameters (cm)	Male*			Female*		
	<60 yrs (n=500)	≥ 60 yrs (n=500)	*p*	<60 yrs (n=500)	≥ 60 yrs (n=500)	*p*
Height	166.1±6.0	162.1±7.2	<0.01	155.1±5.4	151.9±6.4	<0.01
Demispan	86.9±4.9	84.2±5.3	<0.01	79.9±4.1	79.4±4.5	0.05
Biaxillary length	38.8±3.5	36.3±3.6	<0.01	36.2±4.2	35.7±3.8	0.04
Neck length	10.3±1.2	9.8±1.2	<0.01	9.8±1.4	9.6±1.1	<0.01
Humeral length	36.3±3.4	34.2±4.6	<0.01	33.5±3.0	33.2±3.3	0.15
Forearm length	25.0±2.3	24.5±2.4	<0.01	23.2±2.0	23.1±2.1	0.45
Hand length	18.4±1.2	18.1±1.4	<0.01	17.1±1.1	17.2±1.2	0.28
Sitting height	85.9±3.9	82.2±5.3	<0.01	81.0±3.3	78.3±4.5	<0.01
Thigh length	39.3±4.0	38.7±3.7	<0.01	35.2±3.1	35.2±3.4	0.89
Knee height	48.6±3.3	47.3±3.7	<0.01	42.1±3.0	43.1±3.6	<0.01
Foot length	24.9±1.5	24.4±2.1	<0.01	22.5±1.3	23.0±1.7	<0.01

* *p* <0.01 for all comparisons between males and females

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Table 3. Correlation coefficient(r), adjusted R^2 and *p*-value for anthropemetric length parameters and actual height

Measurement parameters	Male						Female					
	<60 yrs (n=500)			≥ 60 yrs (n=500)			<60 yrs (n=500)			≥ 60 yrs (n=500)		
	r	R^2	*p*	r	R^2	*p*	r	R^2	*p*	r	R^2	*p*
Demispan	0.55	0.27	<0.01	0.58	0.28	<0.01	0.52	0.30	<0.01	0.53	0.34	<0.01
Biaxillary length	0.20	0.04	0.96	0.35	0.08	0.48	0.20	0.04	0.58	0.28	0.12	0.15
Neck length	0.17	0.01	0.37	0.24	0.08	0.12	0.08	0.03	0.52	0.28	0.06	0.02
Humeral length	0.41	0.08	<0.01	0.30	0.10	0.05	0.28	0.16	0.03	0.31	0.09	0.72
Forearm length	0.35	0.08	<0.01	0.35	0.04	0.20	0.28	0.12	<0.01	0.21	0.12	0.76
Hand length	0.39	0.15	0.37	0.47	0.13	0.93	0.39	0.15	0.12	0.37	0.22	0.72
Sitting height	0.59	0.35	<0.01	0.54	0.27	<0.01	0.59	0.35	<0.01	0.52	0.29	<0.01
Thigh length	0.61	0.20	0.21	0.71	0.40	<0.01	0.44	0.37	<0.01	0.64	0.51	<0.01
Knee height	0.87	0.42	<0.01	0.91	0.72	<0.01	0.65	0.76	<0.01	0.85	0.84	<0.01
Foot length	0.43	0.22	0.10	0.51	0.17	0.01	0.48	0.19	<0.01	0.41	0.26	0.89

r= correlation coefficient, R^2= Adjusted R-square

Only three parameters (demispan, sitting height and knee height) were chosen for model prediction which was previously mentioned in the selection criteria. Even though we did not include some parameters in the model prediction because there was less correlation coefficient and the F test was not significant in every subgroup, the humeral length, forearm length and thigh length had potential trends in some volunteer groups.

After parameter selection, model creations were performed by linear regression in the modeling group of 250 volunteers each. All single parameters were selected to create a regression model formula in each subgroup and demonstrated in Table 4. For double and triple parameters, the authors selected only the most beneficial in the additional parameter for outcome predictions by comparing R square, log likelihood, AIC and BIC in each model. The authors found that together the predictive model of double parameter between sitting height and knee height had the highest predictive capacity with the above criteria in which R^2 in males and females were 0.79 to 0.82 and 0.68 to 0.71, respectively. In addition, these parameters also had the lowest AIC and BIC values when compared to the other double selected parameters model. For triple parameters, multicollinearity of parameter in model occurred when knee height and thigh length were combined in the model in the younger male group. The most predictable model of triple parameters included demispan, sitting height and knee height, which demonstrated the regression model in Table 4 in each subgroup. For these criteria, the authors proposed five models for height prediction in each subgroup. As the formula difficulty was a concern, the original regression formulas were adapted into modified simple formulas. The coefficient and intercepts were adjusted to the nearest integer number and produced better psychological understanding.

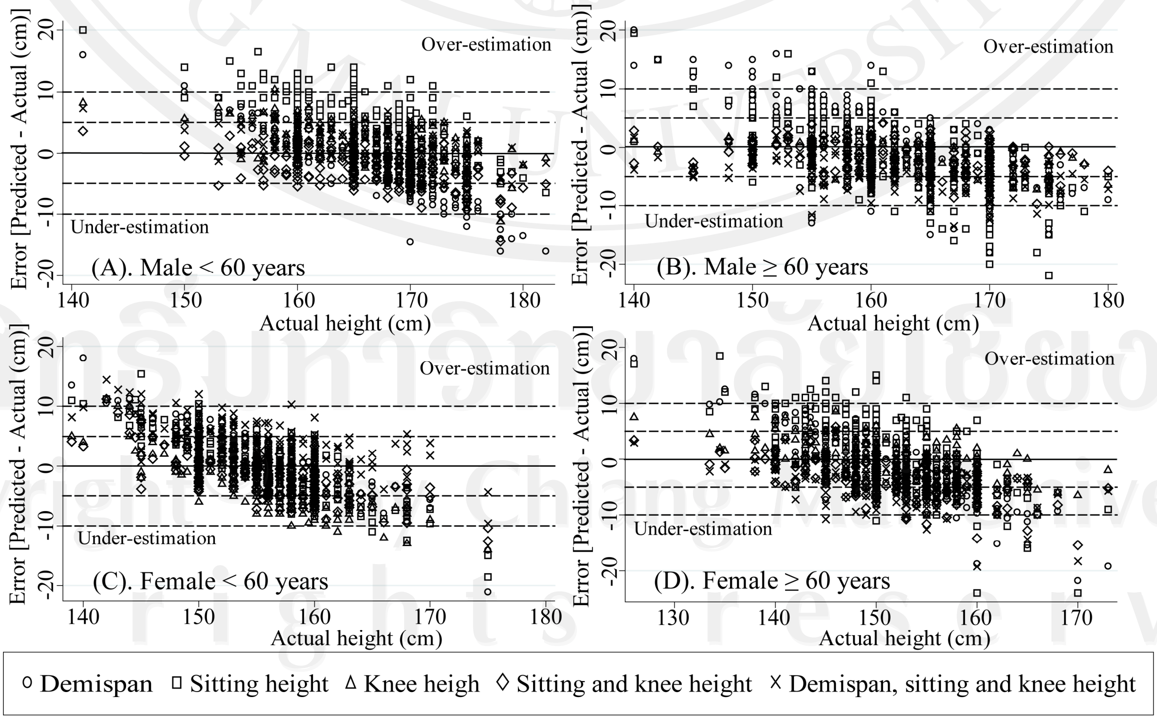

Figure 2. Error (Predicted – Actual) and actual height classified by gender and age groups. (A). Male <60 years. (B). Male ≥60 years. (C). Female <60 years. (D). Female ≥60 years.

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Table 4. Height prediction and error by regression and modified simple formula

Parameters	Regression formula†	r‡	E ‡§	RE ‡§	Simple formula†	r‡	E‡§	RE ‡§
Male<60								
D	118.75+0.55(D)	0.67	4.1±3.0* (-13.1/18.5)	2.5±1.9* (-7.3/13.1)	120+0.5(D)	0.67	4.4±3.3* (-16.0/16.0)	2.5±1.9* (-9.0/11.3)
S	88.60+0.90(S)	0.59	4.1±2.9* (-12.6/16.0)	2.5±1.7* (-7.2/11.3)	85+1.0(S)	0.59	5.9±3.9* (-8. /20.0)	2.5±1.7* (-4.6/14.2)
K	89.44+1.58(K)	0.87	2.5±1.8 (-12.7/8.7)	1.5±1.1 (-7.1/5.6)	90+1.6(K)	0.87	2.8±2.0 (-11.2/10.4)	1.68±1.3 (-6.5/5.6)
S+K	72.75+0.30(S) +1.40(K)	0.89	2.3±1.7* (-11.6/8.9)	1.40±1.1* (-6.5/5.6)	70+0.3(S) +1.4(K)	0.89	3.0±2.2 (-14.4/6.1)	1.8±1.3 (-8.1/3.9)
D+S+K	69.27+0.09(D)+ 0.27(S)+1.35(K)	0.90	2.2±1.7* (-12.6/8.3)	1.34±1.0* (-7.1/5.2)	70+0.1(D)+ 0.3(S)+ 1.3(K)	0.90	2.6±2.0* (-10.8/10.0)	1.5±1.2* (-6.1/6.3)
Male≥60								
D	83.80+0.92(D)	0.51	5.3±4.1* (-20.0/17.4)	3.2±2.5* (-11.7/12.4)	80+1.0(D)	0.51	5.1±4.1* (-18.0/20.0)	3.2±2.7* (-10.6/14.3)
S	79.93+0.99(S)	0.51	5.3±4.4* (-22.8/18.6)	3.3±2.6* (-13.0/13.3)	80+1.0(S)	0.51	5.2±4.2* (-22.0/19.5)	3.2±2.6* (-12.6/13.9)
.K	80.31+1.73(K)	0.92	2.2±1.3 (-5.7/5.3)	1.4±0.8 (-3.3/3.4)	80+1.7(K)	0.94	2.4±1.9 (-7.6/3.6)	1.5±1.2 (-4.3/2.3)
S+K	64.90+0.29(S)+ 1.55(K)	0.92	2.3±1.5 (-8.3/5.6)	1.4±0.9 (-4.9/3.5)	65+0.3(S) +1.5(K)	0.93	2.6±2.0 (-9.9/4.2)	1.6±1.2 (-5.8/2.6)
D+S+K	53.56+0.29(D)+ 0.25(S)+1.33(K)	0.92	2.7±1.8* (-10.7/5.3)	1.5±1.2 (-6.4/3.5)	55+0.3(D)+ 0.2(S)+1.3(K)	0.93	4.6±2.6* (-13.5/2.1)	2.8±1.6* (-8.1/8.9)
Female<60								
D	101.92+0.67(D)	0.65	3.6±3.0 (-21.5/17.5)	2.3±2.0 (-12.3/12.5)	100+0.7(D)	0.65	3.6±3.1* (-21.1/18.1)	2.4±2.1* (-12.1/12.9)
S	88.4+0.82(S)	0.56	3.7±3.1* (-18.5/15.6)	2.4±2.0* (-5.8/9.8)	90+0.8(S)	0.56	3.7±3.1* (-18.6/15.4)	2.4±2.0* (-10.6/10.6)
K	108.27+1.11(K)	0.70	3.2±2.6 (-10.1/14.0)	2.1±1.7 (-6.0/7.2)	110+1.0(K)	0.70	4.2±2.9 (-14.0/11.0)	2.7±1.8 (-8.0/7.7)
S+K	74.41+0.52(S) +0.92(K)	0.77	2.9±2.3* (-10.5/13.0)	1.9±1.5* (-6.0/9.2)	75+0.5(S) +0.9(K)	0.76	3.3±2.4* (-12.6/11.2)	2.1±1.5* (-7.2/7.8)
D+S+K	60.36+0.30(D)+ 0.45(S)+0.80(K)	0.79	3.1±2.4 (-10.5/10.3)	2.0±1.5 (-6.0/7.2)	60+0.3(D)+ 0.5(S)+ 0.8(K)	0.81	3.9±2.9 (-9.6/14.3)	2.5±1.9 (-5.4/10.1)
Female≥60								
D	96.82+0.70(D)	0.57	4.4±3.5* (-20.0/19.8)	3.0±2.4* (-11.4/9.9)	95+0.7(D)	0.57	4.5±3.5* (-21.8/18.0)	2.9±2.3* (-12.8/14.3)
S	73.5+1.00(S)	0.46	5.0±3.9* (-25.5/17.0)	3.3±2.5* (-15.9/12.6)	75+1.0(S)	0.46	5.1±4.0* (-24.0/18.5)	3.4±2.7* (-15.0/13.8)
K	87.49+1.50(K)	0.87	2.71±1.94 (-6.0/9.0)	1.8±1.3 (-3.9/6.3)	87+1.5(K)	0.87	2.7±1.9 (-6.5/8.5)	1.78±1.31 (-4.2/6.0)
S+K	64.36+0.43(S) +1.25(K)	0.87	2.6±2.0 (-11.4/10.0)	1.7±1.3 (-6.7/6.8)	65+0.4(S) +1.2(K)	0.87	4.1±2.8* (-15.4/ 5.8)	2.7±1.8* (-9.1/4.0)
D+S+K	52.19+0.24(D)+ 0.41(S)+1.14(K)	0.87	2.6±2.2 (-13.4/5.8)	1.7±1.5 (-8.4/6.6)	50+0.2(D)+ 0.5(S)+1.0(K)	0.85	4.1±3.0* (-19.3/5.4)	2.7±1.9* (-12.1/3.7)

† Formula derived from modeling groups (250 in each subgroup), ‡ Correlation coefficient and error calculated from validation groups (250 in each subgroup). § Mean±S.D. (minimum / maximum), * $p<0.05$ when comparing to knee height model error or relative error.
r= correlation coefficient, E= Absolute error (cm), RE = Relative error [Relative error=(Predicted height – Actual height) x 100/(Actual height)], D=Demispan, S=Sitting height, K=Knee height, S+K= Sitting and Knee height, D+S+K= Demispan, sitting and knee height.

In the regression model, the correlation co-efficient ranged from 0.46 to 0.92. Of these, the leg length or knee height model had the highest prediction in the single parameters formula. However, there was a slightly lower and comparable correlation coefficient with the double and triple parameters. Error and relative error in the single parameters were significantly lower in the knee height model, except for the demispan model in the younger

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female group. Although the reason for this phenomenon is unknown, there was also a tendency for difference in both error and relative error with *p*-value as 0.10. As a reference in the knee height formula, the double parameter models had a significantly decreased error only in the younger ages in both genders, while the triple parameters model had more precision in the younger male group when compared with the knee height model. Error and relative error on increasing age had equal distribution in each subgroup of age and gender in both regression- and simple formulas.

For simple formula validation, in which intercepts and coefficients were adjusted, correlative coefficient, error quantity and relative error between original and modified formulas were calculated and compared. The correlation coefficients in each formula were comparable. In addition,, kappa agreements between original and modified formulas were also comparable in all formulas except in the triple parameter model in the older female which had a higher error in the simple formula. Figure 2 demonstrated the error quantity over actual height. The error prediction in the validation group of demispan, sitting height, knee height, double and triple modified simple models up to 10% were 5.7, 9.5, 1.0, 1.1 and 2.6% respectively. The authors further stratified actual height into three groups (shorter, normal and taller groups which was defined as less than 140, 140-160 and more than 160 cm, respectively). Of these criteria, there were trends of over estimation in the sample that had an actual height of less than 140 cm, while under-estimations were observed in an actual height of more than 160 cm. Most of prediction error of more than 10 cm occurred in the demispan and sitting model (under-estimation 3.4 and 3.8%, over-estimation 2.8 and 6.5%, respectively) while the other modified simple models had up to 1.7% over and under-estimation.

DISCUSSION

Even though height is an important parameter in clinical practice there are limitations in some clinical situations. Anthropometric measurements for height prediction were suggested to solve this problem and many formulas have been reported. These measurements included sitting height, demispan, arm span, ulnar length, hand dimensions and knee height.[5,8-9,11-17] However, ethnic differences, gender and age are a major concern in this regard for application and external validation for other populations. In Asian groups, one Malaysian elderly prediction model had reported and confirmed significant differences between it and other ethnic groups. In addition, these deviations also occurred within other Asian models.[16] For this reason, as well as a lack of Thai data reported for these relationships, the authors designed these anthropometric measurements to propose an appropriate and simple relation model with acceptable validity for height prediction in the adult Thai population.

The authors endeavored greatly to simplify the formula. Therefore, a stratified prediction model based on an interaction term might achieve these purposes. Of these, both gender and age groups were tested, and revealed significant interactions among the anthropometric parameters and height prediction. These findings are comparable to previous studies.[15-17,19] Although previous formulas proposed by Chumlea *et al*. using knee height and age as predictive variables for height prediction have been proposed in elderly western people.[13] The age variable was not included into prediction formulas in our models because there was no significant interaction between age and predictive variables of knee height, demispan and sitting height after subgroups were divided by gender and age group. In addition, error and relative error on increasing age had no correlation error in each of our validation subgroups.

For the selection of anthropometric predictors, at least six parameters were suggested that could be a single independent variable to stature prediction but the present study showed only three parameters (demispan, sitting height and knee height) in all subgroups.[5,8-9,11-17] However, humeral length and forearm length might be predictors in younger volunteers according to the present data. Although there is no exact theoretical clarification, these phenomenon might be explained by vertebral degenerative changes in the elderly while the arm length remains stable.[15] Thigh length was the other interesting predictor in the elderly. However, the authors did not select this variable in their prediction model for two reasons. Firstly, there was no significant alteration (F test; *p* value) during the model selection process in the younger male group. In addition, there was a multicollinearity effect with other parameters in the double and triple predictor model, especially with knee height. Secondly, there were variations of measurement between measurers due to difficulty in landmark location in fat volunteers and is precision depended on the hip and knee position.

The authors created regression models with 1000 volunteers (250 in each group). Of these, simple regression models were modified from the original regression formula. Both formulas were validated with the other 1000 volunteers (250 each). Correlation, quantitative error and relative error were comparable and produced acceptable results between the original and simple formulas. In the single parameters group, knee height had the highest correlation and less error compared to the others within the groups. Therefore, the knee height models were used as references for comparing errors between formulas in each subgroup. Double and triple parameters might decrease error in only some subgroups. However, contrast results occurred in the elderly male and female groups. (Table 4)

The simple model had more than 90% precision with error up to ten cm in the validation group (89.7 to 99.0% in range). Of these, the precision error occurred differently and depended on the actual stature. The shorter group had more over-estimation while vice versa was observed in higher group, and negative correlation was significant in all subgroups (Figure 2). These correlations had the same direction with a recent Italian study on middle aged volunteers by knee height prediction.[19] However, these were different from a previously reported elderly Chinese arm span model which demonstrated negative correlation error only in the male gender.[15]

Although the authors endeavored to control and monitor every step of the investigation process as well as during data analyses, there were some inevitable limitations. Firstly, 95% of the volunteers in the present study had

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census registration in the northern region of Thailand. However, census registration might not reflect the original residence. Secondly, although measurement training had been performed before data collection the different body figure might lead to different results because of ill-defined measurement landmarks and these resulted in a measurement bias. Thirdly, model creations were performed based on healthy subjects. Although we endeavor to propose several length variables for height prediction and we expected these might be applied to subjects with unknown height. However, external validation into diseased patients should be performed in future studies. Finally, there was an unequal distribution in terms of age, nearly 60% of subjects were between 60-70 years of age; although there was no significant interaction between age and the measured parameters. In addition, distribution of error in each gender and age group were equally scattered. However, future study for external validation and precision might be over or under estimating in elderly people age more than 70 years. Therefore, the authors suggested the utilization of these formulas should be applied only for unavailable stature data in specific clinical situations.

In conclusion, anthropometric parameters with demispan, sitting height, knee height and combination could be applied for height prediction in the adult Thai population. Although knee height had the highest precision as a single predictive parameter others parameters were also proposed with acceptable error. A combination of double and triple model might decrease actual deviation only in younger people. However, over-estimation might be a concern in shorter people and vice versa in taller people. Therefore, formula prediction should be used only in cases when direct measurement of height is not possible.

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AUTHOR DISCLOSURES
All authors have no conflict of interest. This study was a part of thesis in the epidemiology PhD project of Assistant Professor Kaweesak Chittawatanarat.

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Original Article

Height prediction from anthropometric length parameters in Thai people

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藉由體長參數預測泰國人的身高

身高為一個重要的臨床參數。然而對於特定的臨床狀態，卻沒有一個專一的測量方法。雖然有許多體位測量方法被建議用來估量泰國人民的身高，但尚未有一個公式用於計算身高。這篇研究之目的在於發展出一個有效且能用以預測身高的公式。將 2000 位自願者根據年齡及性別加以區分。模式組及效度組再進一步獨立區分。用線性迴歸分析產生預測模式。共測量 10 個參數並放入分析。在這 10 個參數當中，中指尖到胸骨中心的距離、坐高及膝高與身高的相關係數，無論在男性或女性，及在各年齡層均大於 0.5，且皆具有顯著相關。接著提出這 3 個參數單獨、具有高預測值的雙變項(坐高與膝高)及三變項的迴歸模式，並加以修飾成簡化的公式。在進行原始及簡化公式的效度檢測後，發現兩者在相關係數、量性誤差及相對誤差都不相上下。按照誤差上限 10 公分的條件下，簡化的公式在效度組有大於 90%的精確度(範圍是 89.7%至 99.0%)。而這些單獨變項中，膝高在各組別有最小的預測誤差。雙變項及三變項模式只有在年輕族群有降低誤差。總結而論，體位參數中以中指尖到體中央的距離、坐高、膝高以及兩者或三者合併模式可用來預測泰國成人的身高，而其誤差是可以被接受的範圍。但這些公式應只被用於無法直接測量身高的人。

關鍵字：體位、體位測量、身高、線性模式、泰國人

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Appendix C

Chittawatanarat K, Pruenglampoo S, Trakulhoon V, Ungpinitpong W, Patumanond J. Development of gender- and age group-specific equations for estimating body weight from anthropometric measurement in Thai adults. Int J Gen Med 2012;5:65-80.

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ORIGINAL RESEARCH

Development of gender- and age group-specific equations for estimating body weight from anthropometric measurement in Thai adults

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Video abstract

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Background: Many medical procedures routinely use body weight as a parameter for calculation. However, these measurements are not always available. In addition, the commonly used visual estimation has had high error rates. Therefore, the aim of this study was to develop a predictive equation for body weight using body circumferences.

Methods: A prospective study was performed in healthy volunteers. Body weight, height, and eight circumferential level parameters including neck, arm, chest, waist, umbilical level, hip, thigh, and calf were recorded. Linear regression equations were developed in a modeling sample group divided by sex and age (younger <60 years and older ≥60 years). Original regression equations were modified to simple equations by coefficients and intercepts adjustment. These equations were tested in an independent validation sample.

Results: A total of 2000 volunteers were included in this study. These were randomly separated into two groups (1000 in each modeling and validation group). Equations using height and one covariate circumference were developed. After the covariate selection processes, covariate circumference of chest, waist, umbilical level, and hip were selected for single covariate equations (Sco). To reduce the body somatotype difference, the combination covariate circumferences were created by summation between the chest and one torso circumference of waist, umbilical level, or hip and used in the equation development as a combination covariate equation (Cco). Of these equations, Cco had significantly higher 10% threshold error tolerance compared with Sco (mean percentage error tolerance of Cco versus Sco [95% confidence interval; 95% CI]: 76.9 [74.2–79.6] versus 70.3 [68.4–72.3]; $P < 0.01$, respectively). Although simple covariate equations had more evidence errors than the original covariate equations, there was comparable error tolerance between the types of equations (original versus simple: 74.5 [71.9–77.1] versus 71.7 [69.2–74.3]; $P = 0.12$, respectively). The chest containing covariate (C) equation had the most appropriate performance for Sco equations (chest versus nonchest: 73.4 [69.7–77.1] versus 69.3 [67.0–71.6]; $P = 0.03$, respectively). For Cco equations, although there were no differences between covariates using summation of chest and hip (C+Hp) and other Cco but C+Hp had a slightly higher performance validity (C+Hp versus other Cco [95% CI]: 77.8 [73.2–82.3] versus 76.5 [72.7–80.2]; $P = 0.65$, respectively).

Conclusion: Body weight can be predicted by height and circumferential covariate equations. Cco had more Sco error tolerance. Original and simple equations had comparable validity. Chest- and C+Hp-containing covariate equations had more precision within the Sco and Cco equation types, respectively.

Keywords: body weight, anthropometry, circumference, Thai, linear models

Introduction

One of the common important clinical measurement parameters is body weight. Many clinical situations utilize body weight as a variable for the determination of nutrition

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requirements, drug dose administration, resuscitation process, pulmonary tidal volume estimation and hemodynamic assessments.[1–4] However, there are many limitations to obtaining body weight in some clinical practice situations especially in nonambulatory elderly people, and emergency and critically ill patients. A special instrument is required for direct measurement in these patients. Nevertheless, it might be unavailable due to limited resources in developing countries. Although visual estimation is the most common method of estimating weight, the current literature has reported great inaccuracies with this method compared with the actual body weight. In addition, the precision of this method is operator-dependent.[5–8] These errors might lead to adverse and ineffective treatment outcomes.[8,9] To diminish predictive error, one study that was performed in an emergency department (ED) setting demonstrated that anthropometric measurement had greater accuracy of around 20% within a 10% error threshold than visual estimation by ED providers.[10] Although these more scientific anthropometric measurements to estimate body weight have been proposed, ethnic differences and measurement parameter distinctions might impact predicted validity.[11–14] In addition, some parameters used in equations are hard to assess in general practice especially those requiring skinfold thickness.[10,15,16] To our best knowledge, there is no recommended formula to predict body weight with circumferential anthropometric parameters in the Thai or Asian populations. Therefore, the aims of this study were to obtain appropriate and precise methods to estimate actual body weight using circumferential parameters from different parts of the body as well as to propose a simple estimation equation with acceptable validity which could be applied conveniently for general medical practice.

Methods

The authors performed a prospective cross-sectional study which enrolled healthy Thai adult volunteers by an invitation announcement to the Faculty of Medicine, Chiang Mai University via public information posters and the hospital Web site. Four research assistants were trained in the measurement method for each circumferential anthropometric parameter and reliability testing was performed before data collection with kappa agreement with more than 95% with up to 5% error. The authors excluded volunteers whose age was less than 18 years, amputated limb(s), inability of ambulation, inability to lie down, and chronic disease which might interfere with measured parameters such as liver cirrhosis, renal failure, chronic steroid use, and edematous limb(s). This study was approved by the Faculty of Medicine, Chiang Mai University Ethics Committee.

The authors measured and collected body weight and body circumferences as well as demographic data, sex, age, occupation, and habitats. Body circumferences were measured in supine position with a cloth tape measure up to 1 mm width at eight levels including neck, chest, waist, umbilical level, and hip, arm, thigh, and leg circumferences. The measurement method and reference points are described in Table 1. Actual body weight was measured by the same digital weighing apparatus (Zepper TCA-200A-RT; Bangkok, Thailand) and recorded in kilograms with one decimal point. Height was measured by a standard measurement board and all subjects were positioned for height measurement with head, shoulder blades, buttocks, and heels touching the board. This measurement was recorded in centimeters.

The study sample was separated randomly and independently into two groups, a regression modeling group, in whom regression equations were developed to estimate body weight, and a validation group, in whom the equations were tested. The estimated sample size in each group was 250 volunteers based on differences of physiological status and body composition between younger and elderly people as well as each gender distinction.[17] The authors further divided the people by age group and sex. Age was classified into two

Table 1 Methods of anthropometric circumferential parameter measurements

Covariates	Point of measurement method
Neck	Level at cricoid cartilage in anterior and midpoint between external occipital protuberance and tip of spinous process of 7th cervical spine (vertebral prominens at root of neck) in posterior
Arm	Level at midpoint between tip of acromioclavicular eminent to tip of olecranon of elbow of nondominant arm
Chest	At full expiration, measurement at upper chest on the level of junction between the deltopectoral groove and tip of anterior axillary fold
Waist	Narrowest part of abdominal circumference above umbilicus or measurement above umbilicus 1–1.5 inches in cases that could not identify the narrowest part
Umbilical level	Level of umbilicus at anterior and about 1.5–2.0 inches above the superior posterior iliac spine at posterior
Hip	Widest part of hip, level of pubic symphysis at anterior and ischial tuberosity at posterior
Thigh	Level at midpoint between inguinal point and upper border of patella
Calf	Level at midpoint between heel and upper most point of femur condyles (approximately 4 cm proximal to the patella)

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groups with a cut-off at 60 years by the official retirement age in the authors' country as well as a previous study background in which there were different body compositions in elderly people.[17] The total estimated population included in this study was 2000 healthy volunteers.

Statistical analysis, parameters selection, modeling, and validation

All of the continuous variable data between age groups and sex were tested for normal distribution with a visual inspection of the histogram and the Shapiro–Wilk W test and reported as mean ± SD. Group differences were calculated using Student's *t*-test for normally distributed continuous variables and Mann–Whitney *U* test for nonparametric continuous variables. The univariable and multivariable linear regression model was used to identify the relationship between independent variable(s) and body weight. A statistical difference was defined as *P* value less than 0.05.

Covariate parameters were decided for the modeling selection by considering correlation values between circumferential variables and body weight. For the equation creation, the authors conformed to the basic theoretical background of alteration of weight depending on the height and volume of an object. Therefore, height was included in the equation covariate in all of the calculated formulas.[11] The authors developed an estimation equation for body weight divided by age group and sex. The formula used was as follows:

$$\text{Body weight (kg)} = b_1\,(\text{Covariate}) + b_2\,(\text{Height}) + a$$

where (b_1) and (b_2) were the regression coefficients and (a) represented the intercept.

Equations using these single circumferential variables for prediction were determined as single covariate equation or formula (Sco). The authors had concerns that individual disproportion of the body figure in chest and torso might affect the model validation and might result in prediction error. Therefore, the combination of circumference of chest together with hip, waist or umbilical level circumference were performed (Chest + Hip [C+Hp]; Chest + Umbilical level [C+U] and Chest + Waist, [C+W]) and behaved as an independent covariate in the present study equations. These summation-containing variables were determined as combination covariates equation or formula (Cco). The model structure of linearity or violation of linearity between covariates and body weight were verified by residuals versus fitting and predictor plots. To provide the simplest formula, numbers of entered covariates were limited as much as possible in each regression model. Forward and backward stepwise regressions were performed. Multicollinearity covariates in the regression model were separated into independent models. Individual models were selected for further validation based on comparison of adjusted R-square value, Akaike's information criteria (AIC) and Bayesian's information criteria (BIC) in each model prediction. The original regression formulas were modified to simple formulas with adjusted covariate coefficients and constant value to ordinary and memorized number. First, covariate coefficient values were estimated and titrated to the nearest value which could accompany the same value between gender and age group in each covariate equation. Second, mean covariate values were substituted and an intercept value was estimated to the nearest number in each equation. In the case of difference error after modified formula, the coefficient would be adjusted and titrated to minimized error. The final adjusted coefficients and intercept was defined as the modified simple formula.

For external validation, predicted body weight was calculated and the difference was compared to the actual body weight in the other equal-sized volunteer in each validation subgroup. The deviated value was reported in error quantity and relative error to actual body weight in percent. Original regression formulas (original formula) and modified simple formulas (simple formula) were compared together with correlation coefficient, error quantity, and relative error. Absolute errors (predicted weight – actual weight) were compared between equations and stratified by gender and equation types (original or simple formulas) using the paired *t*-test. The performances of equations between type equations were tested by level of relative error which was divided into two groups with error more than 10% or 20% of actual body weight. These cut-points were based on previous studies.[10,11] The agreements of two methods were tested by kappa statistics based on the relative error level. In addition, percentage of error tolerance (100 – percentage of error) in the 10% and 20% thresholds were reported in each covariate equations.

Results

From May 2010 through May 2011, 2000 volunteers were included in this study and divided into four subgroups as mentioned previously. In Table 2, there were no differences between the modeling and validation group of all collected variables. However, almost all volunteers (96.0% to 99.6%) were registered residents in the northern region of Thailand.

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Table 2 Characteristics of subjects in model formulation and validation group classified by sex and age groups

Parameters	Age < 60 years		*P*	Age ≥ 60 years		*P*
	Modeling	Validation		Modeling	Validation	
Sex (%)						
Female	250 (50)	250 (50)	1.00	250 (50)	250 (50)	1.00
Male	250 (50)	250 (50)		250 (50)	250 (50)	
Profession (%)						
Female						
Farmer	36 (14.40)	47 (18.80)	0.50	32 (12.80)	31 (12.40)	0.59
Officer	37 (14.80)	39 (15.60)		36 (14.40)	44 (17.60)	
Private	33 (13.20)	39 (15.60)		15 (6.00)	20 (8.00)	
Worker	79 (31.60)	69 (27.60)		18 (7.20)	22 (8.80)	
Others	65 (26.00)	56 (22.40)		149 (59.60)	133 (53.20)	
Male						
Farmer	41 (16.53)	43 (17.34)	0.83	50 (20.00)	37 (14.80)	0.37
Officer	43 (17.34)	47 (18.95)		40 (16.00)	39 (15.60)	
Private	35 (14.11)	28 (11.29)		17 (6.80)	17 (6.80)	
Worker	82 (33.06)	88 (35.48)		28 (11.20)	22 (8.80)	
Others	47 (18.95)	42 (16.94)		115 (46.00)	135 (54.00)	
Habitats (%)						
Female						
Northern	240 (96.0)	242 (96.8)	0.63	247 (98.80)	246 (98.40)	0.70
Others	10 (4.0)	8 (3.2)		3 (1.20)	4 (1.60)	
Male						
Northern	244 (98.39)	248 (99.60)	0.18	248 (99.20)	248 (99.20)	1.00
Other	4 (1.61)	1 (0.40)		2 (0.80)	2 (0.80)	
Age (years)						
Female	46.34 ± 10.21	45.80 ± 9.87	0.61	67.22 ± 6.24	67.43 ± 6.71	0.72
Male	43.63 ± 11.28	43.85 ± 11.10	0.83	69.22 ± 7.41	69.75 ± 7.60	0.43
Body weight (kg)						
Female	57.89 ± 10.41	57.06 ± 10.50	0.38	54.27 ± 10.27	54.51 ± 10.73	0.80
Male	67.55 ± 10.85	67.66 ± 11.52	0.91	60.62 ± 10.84	59.84 ± 11.75	0.44
Height (cm)						
Female	155.62 ± 5.46	154.94 ± 5.61	0.17	152.13 ± 6.60	151.48 ± 6.43	0.26
Male	166.42 ± 6.29	166.09 ± 6.36	0.55	162.65 ± 7.11	161.72 ± 7.02	0.14
BMI (kg/m^2)						
Female	23.74 ± 4.00	23.89 ± 3.95	0.67	23.39 ± 3.90	23.69 ± 4.10	0.41
Male	24.37 ± 3.55	24.50 ± 3.82	0.68	22.84 ± 3.36	22.78 ± 3.65	0.85
Neck (cm)						
Female	33.80 ± 2.82	33.54 ± 2.89	0.31	33.82 ± 2.96	33.95 ± 2.89	0.60
Male	38.50 ± 2.94	38.77 ± 3.09	0.32	37.53 ± 3.03	37.52 ± 3.36	0.99
Chest (cm)						
Female	86.74 ± 8.25	86.20 ± 8.05	0.46	87.47 ± 8.33	87.82 ± 8.67	0.64
Male	92.61 ± 7.20	92.72 ± 7.62	0.87	90.34 ± 7.20	89.82 ± 7.94	0.45
Hip (cm)						
Female	94.32 ± 8.26	93.56 ± 8.41	0.31	94.92 ± 9.22	95.36 ± 9.41	0.60
Male	95.44 ± 7.51	95.26 ± 7.95	0.79	94.76 ± 8.06	94.05 ± 8.68	0.35
Umbilical (cm)						
Female	81.37 ± 10.16	80.47 ± 10.09	0.32	84.30 ± 10.98	84.89 ± 10.97	0.55
Male	84.69 ± 9.64	84.76 ± 9.69	0.93	86.33 ± 9.23	85.44 ± 9.73	0.29
Arm (cm)						
Female	28.13 ± 3.47	27.81 ± 3.34	0.29	27.40 ± 3.55	27.57 ± 3.18	0.56
Male	29.84 ± 3.11	29.86 ± 3.21	0.93	28.28 ± 2.97	27.90 ± 3.20	0.18
Waist (cm)						
Female	77.54 ± 9.65	76.64 ± 9.89	0.31	80.64 ± 9.93	81.26 ± 10.16	0.49
Male	82.25 ± 9.30	82.56 ± 9.57	0.71	83.49 ± 8.74	82.76 ± 9.31	0.37
Thigh (cm)						
Female	46.99 ± 5.64	46.64 ± 5.50	0.48	42.94 ± 5.92	43.53 ± 5.96	0.27
Male	47.85 ± 5.47	47.64 ± 5.94	0.69	42.85 ± 5.01	42.65 ± 5.56	0.67
Calf (cm)						
Female	33.46 ± 3.51	33.40 ± 3.55	0.86	32.51 ± 4.37	32.32 ± 4.15	0.61
Male	35.16 ± 4.54	35.07 ± 4.71	0.82	33.37 ± 4.54	33.14 ± 4.60	0.58

Abbreviation: BMI, body mass index.

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At the variables selection process after forward and backward stepwise linear regression, the authors found that the torso circumferences of waist, hip, and umbilical level had multicollinearity properties with each other in the model-creating covariates and these were the major reason to enter these variables separately in each model.

In Table 3, although there were significant correlations of all circumference parameters, only chest, hip, umbilical level, waist, arm, and thigh circumference had a correlation coefficient of more than 70% in at least three quarters of all subgroups in each covariate equation. However, the authors selected only chest, hip, umbilical level, and waist circumference for further validation and performance assessments after consideration of R-square, AIC, and BIC values (Table 3). Cco equations of C+Hp, C+U, and C+W showed increased correlation coefficients and R-square value as well as decreases in the AIC and BIC values when they were compared to the same level of the Sco (Table 3). Therefore, the authors finally decided to select equations comprised of chest, hip, umbilicus, and waist, C+Hp, C+U, and C+W to validate the processes (Table 4).

The coefficients of the equation were confined to a simple number and the intercept of the equation was also adjusted using the average of the covariates values. These modified simple formulas were demonstrated in Table 4. Although correlation coefficients were lower in some simple formulas, most of them were comparable and all had a statistically significant relation with a *P* value of less than 0.01 (Table 5). While the simple equations of weight prediction could be switched between sex in elderly volunteers except waist-containing covariate equations (Waist and C+W equations) in younger volunteers, only

Table 3 Correlation coefficient (*r*), adjusted R-square (R^2), Akaike's information criteria (AIC), and Bayesian's information (BIC) of single and combination covariates classified by sex and age groups

Covariate	<60 years				≥60 years			
	r	R^2	AIC	BIC	*r*	R^2	AIC	BIC
Neck								
Female	0.70	0.54	1689.00	1699.56	0.69	0.58	1660.84	1671.41
Male	0.65	0.55	1704.94	1715.50	0.72	0.64	1649.64	1660.20
Chest								
Female	0.84	0.75	1535.90	1546.46	0.81	0.73	1553.37	1563.94
Male	0.80	0.69	1615.30	1625.86	0.81	0.70	1605.35	1615.92
Hip								
Female	0.84	0.72	1560.60	1571.17	0.76	0.67	1602.66	1613.22
Male	0.82	0.71	1592.28	1602.84	0.74	0.62	1661.14	1671.70
Umbilical								
Female	0.84	0.78	1509.53	1520.09	0.66	0.62	1636.88	1647.44
Male	0.81	0.73	1578.45	1589.02	0.78	0.72	1587.35	1597.91
Arm								
Female	0.77	0.69	1594.11	1604.68	0.78	0.68	1589.01	1599.58
Male	0.70	0.58	1687.81	1698.38	0.71	0.62	1660.59	1671.15
Waist								
Female	0.87	0.82	1457.49	1468.05	0.68	0.62	1635.62	1646.19
Male	0.82	0.75	1560.49	1571.05	0.79	0.73	1573.42	1583.98
Thigh								
Female	0.74	0.59	1661.03	1671.60	0.74	0.62	1637.98	1648.54
Male	0.61	0.48	1741.29	1751.86	0.80	0.69	1613.92	1624.49
Calf								
Female	0.61	0.44	1739.78	1750.3	0.68	0.54	1680.49	1691.05
Male	0.53	0.40	1776.26	1786.82	0.64	0.55	1704.52	1715.08
C+Hp								
Female	0.90	0.83	1438.54	1449.11	0.83	0.76	1521.05	1531.62
Male	0.88	0.79	1509.10	1519.67	0.84	0.74	1569.06	1579.62
C+U								
Female	0.88	0.82	1451.23	1461.79	0.78	0.72	1555.27	1565.83
Male	0.86	0.79	1512.09	1522.66	0.85	0.77	1531.95	1542.51
C+W								
Female	0.89	0.83	1434.26	1444.83	0.79	0.72	1554.79	1565.35
Male	0.86	0.79	1511.31	1521.88	0.85	0.78	1522.96	1533.53

Abbreviations: C+Hp, chest + hip circumference; C+U, chest + umbilical level circumference; C+W, chest + waist circumference.

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Table 4 Sex- and age group-specific original regression and modified simple formula derived from modeling formulation group

Age	<60 years		≥60 years	
Type	Original equation	Simple equation	Original equation	Simple equation
Chest				
Female	1.01 (C) + 0.39 (H) – 90.33	1 (C) + (H/3) – 80	0.90 (C) + 0.43 (H) – 90.72	1 (C) + (H/3) – 85
Male	1.12 (C) + 0.39 (H) – 100.4	1 (C) + (H/3) – 80	1.05 (C) + 0.35 (H) – 91.95	1 (C) + (H/3) – 85
Hip				
Female	1.00 (Hp) +0.32 (H) – 87.37	1 (Hp) + (H/3) – 90	0.76 (Hp) + 0.50 (H) – 93.08	0.8 (Hp) + (H/2) – 95
Male	1.10 (Hp) +0.36 (H) – 97.38	1 (Hp) + (H/3) – 85	0.81 (Hp) + 0.49 (H) – 94.72	0.8 (Hp) + (H/2) – 95
Umbilical				
Female	0.83 (U) + 0.49 (H) – 86.46	0.8 (U) + (H/2) – 85	0.58 (U) + 0.67 (H) – 97.00	0.8 (U) + (H/2) – 90
Male	0.85 (U) + 0.49 (H) – 85.42	0.8 (U) + (H/2) – 80	0.77 (U) + 0.55 (H) – 96.20	0.8 (U) + (H/2) – 90
Waist				
Female	0.90 (W) + 0.48 (H) – 86.44	1 (W) + (H/2) – 95	0.65 (W) + 0.62 (H) – 92.69	1 (W) + (H/2) – 100
Male	0.89 (W) + 0.50 (H) – 89.08	1 (W) + (H/2) – 100	0.83 (W) + 0.55 (H) – 98.93	1 (W) + (H/2) – 105
C+Hp				
Female	0.58 (C+Hp) + 0.31 (H) – 94.82	0.6 (C+Hp) + (H/3) – 100	0.47 (C+Hp) + 0.43 (H) – 96.47	0.6 (C+Hp) + (H/3) – 105
Male	0.65 (C+Hp) + 0.31 (H) – 107.05	0.6 (C+Hp) + (H/3) – 100	0.57 (C+Hp) + 0.31 (H) – 96.34	0.6 (C+Hp) + (H/3) – 105
C+U				
Female	0.50 (C+U) + 0.42 (H) – 91.70	0.5 (C+U) + (H/2) – 105	0.41 (C+U) + 0.55 (H) – 99.59	0.5 (C+U) + (H/2) – 110
Male	0.56 (C+U) + 0.40 (H) – 97.75	0.5 (C+U) + (H/2) – 105	0.52 (C+U) + 0.40 (H) – 96.42	0.5 (C+U) + (H/2) – 110
C+W				
Female	0.51 (C+W) + 0.42 (H) – 91.06	0.6 (C+W) + (H/3) – 90	0.43 (C+W) + 0.51 (H) – 96.24	0.5 (C+W) + (H/2) – 105
Male	0.56 (C+W) + 0.41 (H) – 99.51	0.6 (C+W) + (H/3) – 95	0.54 (C+W) + 0.40 (H) – 98.07	0.5 (C+W) + (H/2) – 110

Abbreviations: C+Hp, chest + hip circumference; C+U, chest + umbilical level circumference; C+W, chest + waist circumference.

three formulas using chest, C+Hp, and C+U had these properties (Table 4).

Model validity was tested in three aspect questions. First, which models between Sco and Cco were appropriate equations in term of precision? Second, do simple formulas have the similar prediction value comparing with original regression model? Third, which covariate equation should be recommended in Sco and Cco? For the first question, in addition to each formula, fittings were compared and verified using correlation coefficient (r), adjusted R-square, AIC, and BIC which were demonstrated in Table 3. They also were tested by absolute error difference (Table 5 and Figure 1). We observed that the Cco equations had more correlation coefficient and adjusted R-square as well as less AIC and BIC than the Sco equations which could be interpreted that Cco have had better model fitting than the Sco. In addition, performance of equations with each covariate prediction was tested. Absolute errors were compared and demonstrated as the differences of them within formula types comparing between single versus single (SS), combination versus combination (CC), and combination versus single covariate (CS) formulas; these were demonstrated in Figure 1 as varying shade colors of green (SS), blue (CC), and red (CS) bars, respectively. In Figure 1, SS and CC had comparable total evidence of significant comparison pairs to total pairs (SS versus CC: 33.33% [16/48] versus 37.5% [9/24]; $P = 0.73$). However, there was significantly higher evidence of distinctly CS pairs than non-CS (CC and SS) pairs (CS versus non-CS: 69.79% [67/96] versus 34.72% [25/72]; $P < 0.001$, respectively). These could be interpreted that comparison within the same type of Sco or Cco equations were comparable, but comparison between the different types of equation had significant difference errors. In addition, at the error threshold at 10% and 20% (Table 7 and Figure 4), the tolerance threshold of error in Cco had more accuracy than Sco (mean percentage error tolerance of Cco versus Sco [95% confidence interval (95% CI); *P* value]: 10%; 76.9 versus 70.3 [74.2–79.6 versus 68.4–72.3; $P < 0.01$] and 20%; 96.8 versus 94.5 [95.7–97.7 versus 93.2–95.8; $P < 0.01$]). The subgroup analyses on sex, age group, and type of equations (Figure 4) also had corresponding results. Therefore, the Cco equations had more precision and error tolerance than Sco equations.

The second question aimed to compare the performance of original and modified simple formulas. The authors demonstrated these performance errors in two aspects. First, using critical error levels, which were determined into two thresholds of error and error tolerance at 10% and 20% (Tables 6, 7, and Figure 4). Second, quantitative errors of equation were demonstrated by Bland–Altman plot, in which each error value was located on their actual body weight (Figures 2 and 3). By

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Table 5 Validation of original regression and modified simple formula from validation group classified by sex and age groups

Parameter	Original formula			Simple formula		
	*r**	Error (kg)†	RE (%)†	*r**	Error (kg)†	RE (%)†
Age < 60 years						
Chest						
Female	0.87	3.65 ± 3.71	6.49 ± 6.58	0.87	3.73 ± 3.72	6.71 ± 6.87
Male	0.84	4.69 ± 4.16	7.12 ± 6.54	0.84	4.87 ± 4.15	7.38 ± 6.51
Hip						
Female	0.86	4.27 ± 3.50	7.45 ± 5.74	0.86	4.38 ± 3.63	7.58 ± 5.85
Male	0.86	4.58 ± 3.70	6.75 ± 5.22	0.86	4.83 ± 4.05	6.95 ± 5.18
Umbilical						
Female	0.87	4.11 ± 3.22	7.32 ± 5.82	0.87	4.07 ± 3.18	7.30 ± 5.87
Male	0.87	4.57 ± 3.48	6.90 ± 5.36	0.87	5.37 ± 3.90	8.46 ± 6.90
Waist						
Female	0.88	3.84 ± 3.05	6.87 ± 5.65	0.89	4.30 ± 3.42	7.83 ± 6.67
Male	0.87	4.46 ± 3.42	6.67 ± 5.09	0.87	4.68 ± 3.71	6.88 ± 5.23
C+Hp						
Female	0.92	3.13 ± 2.76	5.59 ± 4.99	0.92	3.72 ± 3.10	6.78 ± 5.97
Male	0.90	3.91 ± 3.18	5.77 ± 4.53	0.90	3.91 ± 3.18	5.92 ± 4.89
C+U						
Female	0.91	3.37 ± 2.82	6.00 ± 4.98	0.91	3.56 ± 2.91	6.27 ± 4.89
Male	0.89	4.05 ± 3.29	6.10 ± 5.16	0.89	4.09 ± 3.49	6.05 ± 5.09
C+W						
Female	0.91	3.34 ± 2.80	5.94 ± 4.94	0.91	4.01 ± 3.16	7.25 ± 6.01
Male	0.89	4.07 ± 3.39	6.02 ± 4.99	0.89	4.44 ± 3.56	6.51 ± 5.07
Age ≥ 60 yrs						
Chest						
Female	0.84	4.40 ± 3.96	7.98 ± 6.47	0.83	4.53 ± 4.01	8.24 ± 6.68
Male	0.86	4.46 ± 4.01	7.58 ± 6.67	0.86	4.52 ± 4.07	7.63 ± 6.66
Hip						
Female	0.84	4.55 ± 3.74	8.74 ± 7.40	0.84	4.92 ± 4.03	9.73 ± 8.66
Male	0.81	5.32 ± 4.56	9.31 ± 8.26	0.81	5.38 ± 4.57	9.49 ± 8.45
Umbilical						
Female	0.80	4.97 ± 4.29	9.34 ± 8.17	0.78	5.36 ± 4.37	10.17 ± 8.74
Male	0.88	4.47 ± 3.61	7.54 ± 5.94	0.88	4.40 ± 3.49	7.52 ± 6.03
Waist						
Female	0.78	4.99 ± 4.53	9.41 ± 8.57	0.76	5.90 ± 5.39	11.50 ± 11.17
Male	0.88	4.52 ± 3.55	7.67 ± 6.06	0.88	4.71 ± 3.45	8.10 ± 6.16
C+Hp						
Female	0.88	3.91 ± 3.23	7.38 ± 6.10	0.88	4.19 ± 3.50	7.98 ± 6.84
Male	0.88	4.28 ± 3.79	7.28 ± 6.26	0.88	4.17 ± 3.74	7.22 ± 6.45
C+U						
Female	0.85	4.34 ± 3.58	8.21 ± 7.06	0.85	5.01 ± 3.83	9.30 ± 7.06
Male	0.91	3.75 ± 3.13	6.41 ± 5.47	0.91	3.87 ± 3.31	6.51 ± 5.52
C+W						
Female	0.84	4.44 ± 3.85	8.25 ± 6.94	0.84	4.62 ± 3.85	8.76 ± 7.59
Male	0.91	3.75 ± 3.16	6.49 ± 5.73	0.91	4.41 ± 3.54	7.29 ± 5.54

Notes: *$P < 0.01$ all; †mean ± SD.
Abbreviations: *r*, correlation coefficient; RE, relative error; C+Hp, chest + hip circumference; C+U, chest + umbilical level circumference; C+W, chest + waist circumference; SD, standard deviation.

critical error threshold of 10% and 20%, almost all simple equations had a higher error than the original formula (Table 6). However, there were no differences between the types of equations in term of error tolerance in both critical levels (Table 7 and Figure 4C). All kappa agreement (Table 6) correlations of error occurrence between the original and simple formulas had higher than 50% in all paired formulas except the C+U older female (0.43), C+W older male (0.47) in 10% threshold, and waist of the younger male (0.33) in the 20% threshold. However, these pair error occurrences between original and

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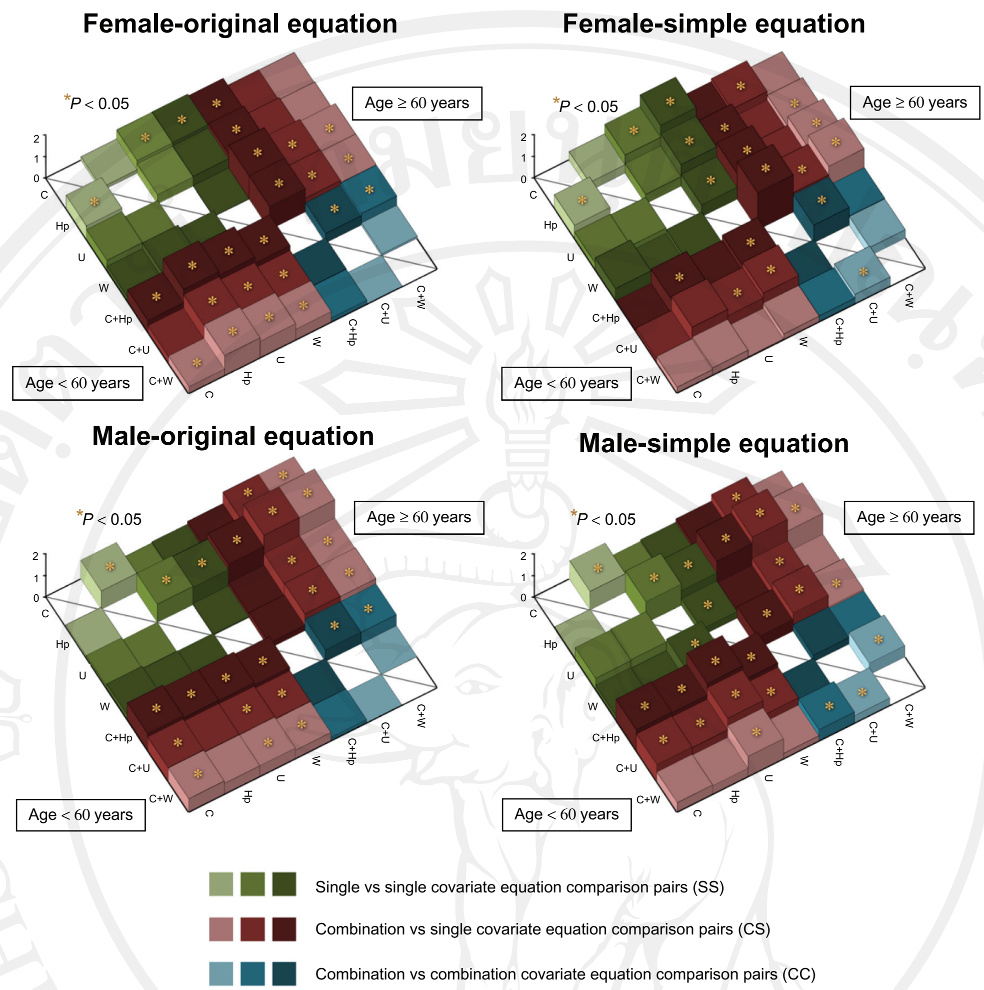

Figure 1 Absolute error difference between each covariate equation classified by type of formula, sex, and age groups.

Notes: Three-dimensional graphs show the comparison pattern of mean error difference between difference equation classified by equation type and sex. The diagonal line in each three-dimensional graph separates comparison performance within age group (above, ≥60 years; below, <60 years). Green, red, and blue colors are the comparisons between single versus single (SS), combination versus single (CS), and combination versus combination covariate equation, respectively (CC). *Significant difference between models, $P < 0.05$.

simple formulas had significant agreement with a P value of less than 0.01 (Table 6). Of these agreements between original and simple equations, median agreement in the Sco equations was slightly higher than the Cco equations but there were no statistical differences (Median [interquartile range; IQR] Sco versus Cco: 10%; 0.79 [0.24] versus 0.66 [0.20]; $P = 0.14$ and 20%; 0.74 [0.13] versus 0.66 [0.25]; $P = 0.13$). Subgroup analyses on sex and age group also had accorded results (female versus male: 10%; 0.66 [0.19] versus 0.79 [0.24]; $P = 0.24$ and 20%; 0.72 [0.14] versus 0.77 [0.30]; $P = 0.34$. Younger versus older: 10%; 0.72 [0.21] versus 0.74 [0.24]; $P = 0.82$ and 20%; 0.74 [0.24] versus 0.74 [0.18]; $P = 0.57$). Quantitative error over actual body weight using Bland–Altman plots was demonstrated in Figure 2 (Sco equations) and Figure 3 (Cco equations). Of these figures, although most of prediction error was contained in two standard deviations, a negative correlation of error over actual body weight could be observed especially in the Sco equations and these correlations had more conversions to the baseline in Cco equations. However, in Figures 2 and 3, we could observe that both prediction formulas had the tendency to overestimation in lower body weights (less than 40 kg) and underestimation in higher body weights (more than 90 kg).

The third question was to select the appropriate equation by the anthropometric validation result criteria in a previous study which had around one-third occurrence on the total population of anthropometric body weight predicted formula at the 10% error threshold.[10] With this criterion, acceptable performance equations were observed and selected depending on age group and sex as follows: first, in males, all Sco in both age groups could be included with this criterion, second, in females, selected equations were dependent on age groups. While all Sco could be selected in the younger female, only both chest Sco (original and simple; 31.2% and

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Table 6 Performance and error agreement between original regression and modified simple formula divided by sex and age group

Parameters	Error ≥ 10%			Error ≥ 20%		
	Original[a]	Simple[a]	Kappa*	Original[a]	Simple[a]	Kappa*
Age < 60 years						
Chest						
Female	51 (20.4)	54 (21.6)	0.89	7 (2.8)	12 (4.8)	0.73
Male	62 (24.8)	66 (26.4)	0.85	10 (4.0)	12 (4.8)	0.81
Hip						
Female	77 (30.8)	77 (30.8)	0.85	5 (2.0)	8 (3.2)	0.61
Male	63 (25.2)	66 (26.4)	0.78	7 (2.8)	4 (1.6)	0.72
Umbilical						
Female	72 (28.8)	68 (27.2)	0.80	6 (2.4)	8 (3.2)	0.85
Male	60 (24.0)	83 (33.2)	0.53	8 (3.2)	14 (5.6)	0.72
Waist						
Female	52 (20.8)	65 (26.0)	0.61	9 (3.6)	12 (4.8)	0.85
Male	60 (24.0)	69 (27.6)	0.53	4 (1.6)	2 (0.8)	0.33
C+Hp						
Female	39 (15.6)	56 (22.4)	0.63	4 (1.6)	8 (3.2)	0.66
Male	38 (15.2)	45 (18.0)	0.61	3 (1.2)	4 (1.6)	0.57
C+U						
Female	42 (16.8)	44 (17.6)	0.72	5 (2.0)	5 (2.0)	0.59
Male	47 (18.8)	47 (18.8)	0.82	3 (1.2)	3 (1.2)	1.00
C+W						
Female	43 (17.2)	65 (26.0)	0.53	4 (1.6)	10 (4.0)	0.42
Male	46 (18.4)	52 (20.8)	0.72	2 (0.8)	2 (0.8)	1.00
Age ≥ 60 years						
Chest						
Female	78 (31.2)	83 (33.2)	0.84	12 (4.8)	12 (4.8)	0.91
Male	69 (27.6)	69 (27.6)	0.88	15 (6.0)	15 (6.0)	1.00
Hip						
Female	82 (32.8)	98 (39.2)	0.76	21 (8.4)	32 (12.8)	0.73
Male	84 (33.6)	82 (32.8)	0.95	27 (10.8)	27 (10.8)	0.96
Umbilical						
Female	96 (38.4)	98 (39.2)	0.61	24 (9.6)	25 (10.0)	0.75
Male	75 (30.0)	70 (28.0)	0.85	3 (3.6)	10 (4.0)	0.84
Waist						
Female	91 (36.4)	103 (41.2)	0.50	22 (8.8)	38 (15.2)	0.66
Male	74 (29.6)	77 (30.8)	0.71	10 (4.0)	12 (4.8)	0.71
C+Hp						
Female	64 (25.6)	76 (30.4)	0.64	10 (4.0)	15 (6.0)	0.71
Male	62 (24.8)	65 (26.0)	0.88	9 (3.6)	10 (4.0)	0.84
C+U						
Female	78 (31.2)	97 (38.8)	0.43	15 (6.0)	18 (7.2)	0.51
Male	48 (19.2)	56 (22.4)	0.81	7 (2.8)	5 (2.0)	0.66
C+W						
Female	83 (33.2)	82 (32.8)	0.67	14 (5.6)	20 (8.0)	0.75
Male	47 (18.8)	65 (26.0)	0.47	9 (3.6)	6 (2.4)	0.52

Notes: [a]Number of error (%), *kappa agreement *P* value <0.001 all of parameters.
Abbreviations: Kappa, kappa agreement probability; C+Hp, chest + hip circumference; C+U, chest + umbilical level circumference; C+W, chest + waist circumference.

33.2%) and original hip Sco (32.8%) in the older female could be included. Third, for Cco, all predicted formulas had this acceptable performance except in the C+U simple equation in the elderly female (38.8%). Of these results and quantitative error to actual body weight in Table 6 as well as error tolerance in Table 7, at the overall aspect, the appropriate chest containing equations of Sco in both sex and age groups had higher accuracy than other Sco in terms of error tolerance. (Chest versus non-Chest [95% CI] 10%: 73.4 [69.7–77.1] versus 69.3 [67.0–71.6]; $P = 0.03$. 20%: 95.3 [93.2–95.8] versus 94.3 [92.6–96.0]; $P = 0.25$). In addition, the Sco using chest covariate equations had the highest kappa agreement between the original and simple formula. For the Cco equation, error and error tolerance were comparable (Tables 6, 7, and

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Table 7 Mean error tolerance threshold with 95% confidence interval classified by sex, age groups, and types of equations

Parameters Mean (95% CI)	Sex			Age group			Type			All
	Female	Male	*P*	Younger	Older	*P*	Original	Simple		
10% threshold										
Chest	73.4	73.4	1.00	76.7	70.1	0.02	74	72.8	0.73	73.4
	(63.0–83.8)	(71.3–75.5)		(72.3–81.1)	(65.7–74.5)		(66.7–81.3)	(65.2–80.4)		(69.7–77.1)
Hip	66.6	70.5	0.23	71.7	65.4	0.03	69.4	67.7	0.62	68.55
	(60.3–72.9)	(63.6–77.4)		(67.0–76.4)	(60.5–70.3)		(63.4–75.4)	(59.2–76.2)		(64.9–72.2)
Umbilical	66.6	71.2	0.26	71.7	66.1	0.16	69.7	68.1	0.71	68.9
	(56.6–76.6)	(65.1–77.3)		(65.6–77.8)	(57.0–75.2)		(60.2–79.2)	(59.3–76.9)		(64.4–73.4)
Waist	68.9	72.0	0.55	75.4	65.5	0.02	72.3	68.6	0.47	70.4
	(54.0–83.8)	(67.3–76.7)		(70.7–80.1)	(57.0–74.0)		(61.4–83.2)	(57.7–79.5)		(64.9–76.0)
C+Hp	76.5	79.0	0.56	82.2	73.3	<0.01	79.7	75.8	0.35	77.6
	(66.6–86.4)	(70.7–87.3)		(76.9–87.5)	(69.3–77.3)		(70.7–88.7)	(67.4–84.2)		(73.2–82.3)
C+U	73.9	80.2	0.29	82.0	72.1	0.07	78.5	75.6	0.64	77.0
	(56.8–91.0)	(77.4–83.0)		(80.4–83.6)	(58.0–86.2)		(68.1–88.9)	(60.0–91.2)		(70.5–83.6)
C+W	72.7	79.0	0.18	79.4	72.3	0.12	78.1	73.6	0.36	75.9
	(60.8–84.6)	(73.4–84.6)		(73.2–85.6)	(61.5–83.1)		(66.1–90.1)	(65.8–81.4)		(70.5–81.2)
All	71.2	75.0	0.03	77.0	69.3	<0.01	74.5	71.7	0.12	73.1
	(68.3–74.2)	(73.1–77.0)		(75.1–78.9)	(67.0–71.5)		(71.9–77.1)	(69.2–74.3)		(71.4–74.9)
20% threshold										
Chest	95.7	94.8	0.25	95.9	94.6	0.07	95.6	94.9	0.38	95.3
	(94.1–97.3)	(93.2–96.5)		(94.4–97.4)	(93.5–95.7)		(93.5–97.7)	(93.9–95.8)		(94.4–96.1)
Hip	93.4	93.5	0.98	97.6	89.3	<0.01	94.0	92.9	0.76	93.45
	(85.5–100)	(85.6–100)		(96.4–98.8)	(86.4–92.2)		(87.2–100)	(84.1–100)		(89.6–97.3)
Umbilical	93.7	95.9	0.33	96.4	93.2	0.14	95.3	94.3	0.67	94.8
	(87.2–100)	(94.2–97.6)		(94.2–98.6)	(87.7–98.7)		(90.0–100)	(89.5–99.1)		(92.3–97.3)
Waist	91.9	97.2	0.11	97.3	91.8	0.09	95.5	93.6	0.60	94.6
	(83.6–100)	(94.2–100)		(94.4–100)	(83.7–99.9)		(90.6–100)	(83.8–100)		(90.7–98.4)
C+Hp	96.3	97.4	0.38	98.1	95.6	0.01	97.4	96.3	0.38	96.8
	(93.4–99.2)	(95.2–99.6)		(96.7–99.5)	(93.9–97.3)		(95.2–99.6)	(93.4–99.2)		(95.5–98.2)
C+U	95.7	98.2	0.13	98.4	95.5	0.06	97.0	96.9	0.96	96.9
	(91.4–100)	(97.0–99.4)		(97.7–99.1)	(91.5–99.5)		(93.7–100)	(92.5–100)		(95.0–98.8)
C+W	95.2	98.1	0.10	98.2	95.1	0.08	97.1	96.2	0.65	96.6
	(90.9–99.5)	(95.9–100)		(95.8–100)	(91.2–99.0)		(93.7–100)	(91.3–100)		(94.5–98.7)
All	94.6	96.4	0.02	97.4	93.6	<0.01	96.0	93.6	0.26	95.5
	(93.2–95.9)	(95.4–97.4)		(96.9–98.0)	(92.3–94.9)		(95.0–97.0)	(94.6–96.4)		(94.7–96.3)

Note: Error tolerance (%) = 100 – error (%).
Abbreviations: C+Hp, chest + hip; C+U, chest + umbilical; C+W, chest + waist circumference.

Figure 4). Although there were no differences of error tolerance between the C+Hp and other Cco equations (C+Hp versus Non-C+Hp [95% CI] 10%: 77.8 [73.2–82.3] versus 76.5 [72.7–80.2]; $P = 0.65$. 20%: 96.9 [95.5–98.2] versus 96.8 [95.6–98.0]; $P = 0.96$), but C+Hp had more error tolerance. In addition, we observed that C+Hp had more precision and slightly higher mean error tolerance compared with other Cco in all subgroups (Figure 4, Table 7).

Discussion

Although weight scales are highly available, there were some limitations in special groups of people and many previous studies have suggested equations using anthropometric measurement to predict these parameters (Table 7).[10–12,14–16,18] However, all of the population studies were collected and generated formulas based on the Western population and there were no suggested equations in the Asian population. Therefore, the present study was a pioneering endeavor to develop equations to predict body weight by anthropometric circumferential measurements. The present study separated equations divided by age groups and sex due to previous reports of variations of body composition depending on the age spectrum and sex difference and possibly interference to equation validity.[17] These were demonstrated by differences of coefficient and intercepts at the same covariate equations in different age spectrums in the present study (Table 4). No differences were found in all of the measuring parameters between the modeling and validation groups (Table 1). In the selection process, stepwise regression analysis revealed multicollinearity between hip, umbilical level, and waist

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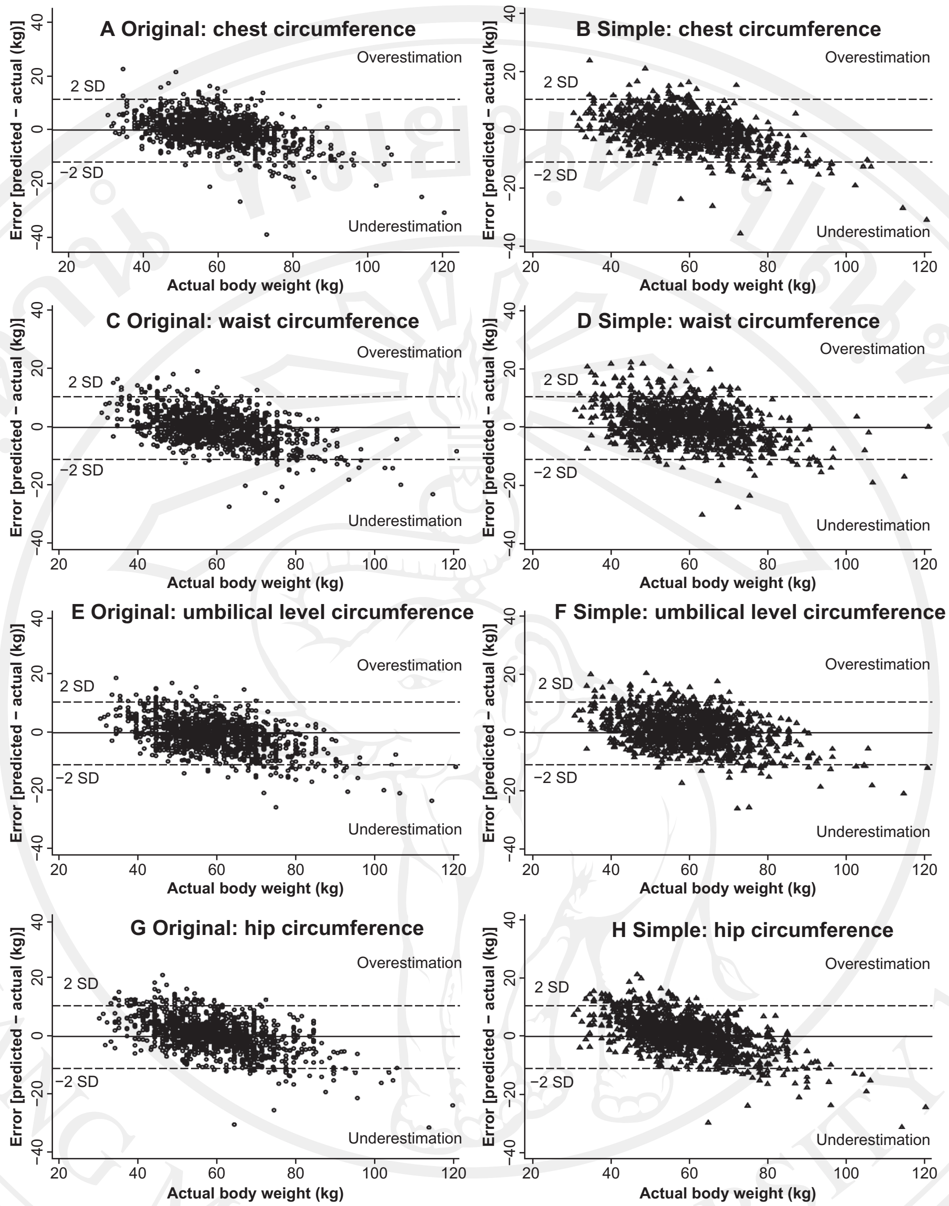

Figure 2 Bland–Altman plot between error of prediction and actual body weight in single covariate equations.
Abbreviation: SD, standard deviation.

variables. Therefore, these covariates were separated into individual equations in the present study and the fixed covariate parameter of the individual equations was body height. Differences of body somatotype effect and body shape might affect the predictive validity.[19–21] Although the authors did not detail body somatotype classifications due to the complexity of measurement, simple combinations between chest and one torso region were initiated by summation between the chest and abdominal region circumference (Cco) and these equations were tested for validation.

Previous studies using mid-arm and calf circumference together with skinfold thickness parameters in elderly people or using only arm circumference and height in obese people were proposed for body weight prediction.[11,14–16,18] However, with our criteria for covariate selection, the authors found that mid-arm, mid-thigh, and mid-calf circumference had fewer fitting properties using correlation coefficient, adjusted R-square, AIC, and BIC than the other covariates (Table 2). Therefore, these variables were not selected for our model creation and validation processes. The probable reasons of these differences might be explained by different ethnic groups having different body composition as well as weight distribution.[22] In addition, there were no comparisons between different circumferences of anthropometric measurements in previous studies.[11,14–16,18] There were some concerns about the measurement difficulties of these torso

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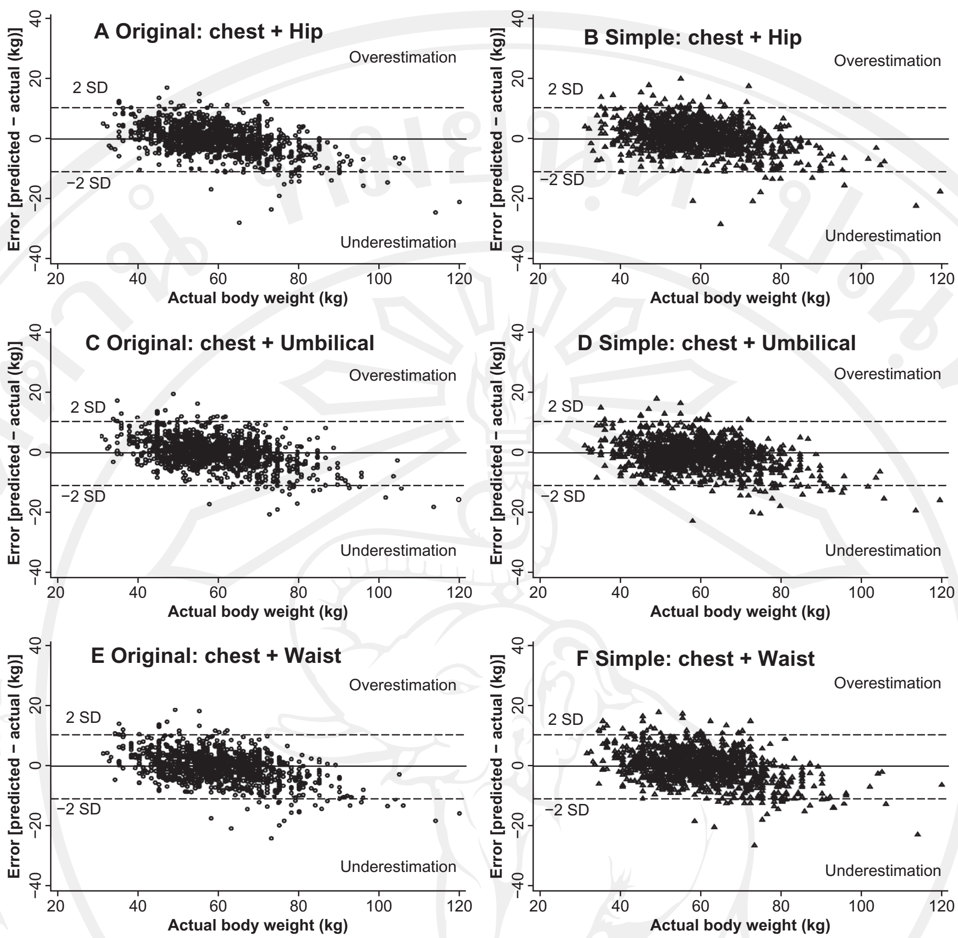

Figure 3 Bland–Altman plot between error and actual body weight in combination covariate equations.
Abbreviation: SD, standard deviation.

parameters, but these parameters might be collected and are feasible to perform during health care processes. The author divided the proposed models into two groups as mentioned previously: Sco equations and Cco equations. To simplify our equation for the purpose of bedside use, the covariate coefficients and constant intercepts were adjusted to simple numbers (Table 4). Both original and simple models were verified for validity to the other samples in the validation groups.

For the validation results in Table 5, both original and simple formulas had significant correlation coefficients of more than 0.75 ($P < 0.01$). Of these, the original and simple equations were comparable in correlation coefficients. Although there were comparable numbers of significant differences when comparing between CC and SS pairs, CS pairs had significant differences (Figure 1). When considered together with Tables 5 and 6, these findings demonstrated that combination covariate equations had more precision than the single covariate equation. These might be explained by different somatotypes in volunteers. Somatotype patterns of endomorphic, mesomorphic, or ectomorphic body types are the important factor to determine different body circumference proportions and body stature. Different gender, age, and lifestyles lead to these somatotype distinctions.[19,21] In the authors' opinion, summation of chest and one of torso circumference might simply be a method to decline the somatotype effect and these resulted in higher error tolerance in combination covariate equations. For the Sco equation (Tables 5, 6, and Figure 2) and Cco equation (Tables 5, 6, and Figure 3), even though chest-containing equations and the summation of chest and hip did not have the least predictive error in all age groups and sex, they had acceptable performance compared with all of the others. In addition, both equations had the better error tolerance when comparing the same type of equation in Figure 4. Therefore, the authors proposed these two equations to predict the actual body weight. The background reason to explain these findings was unknown, but the authors suspected that these variables had less variation and conformed alterations to body weight, body composition, and stature throughout life span.[17,19]

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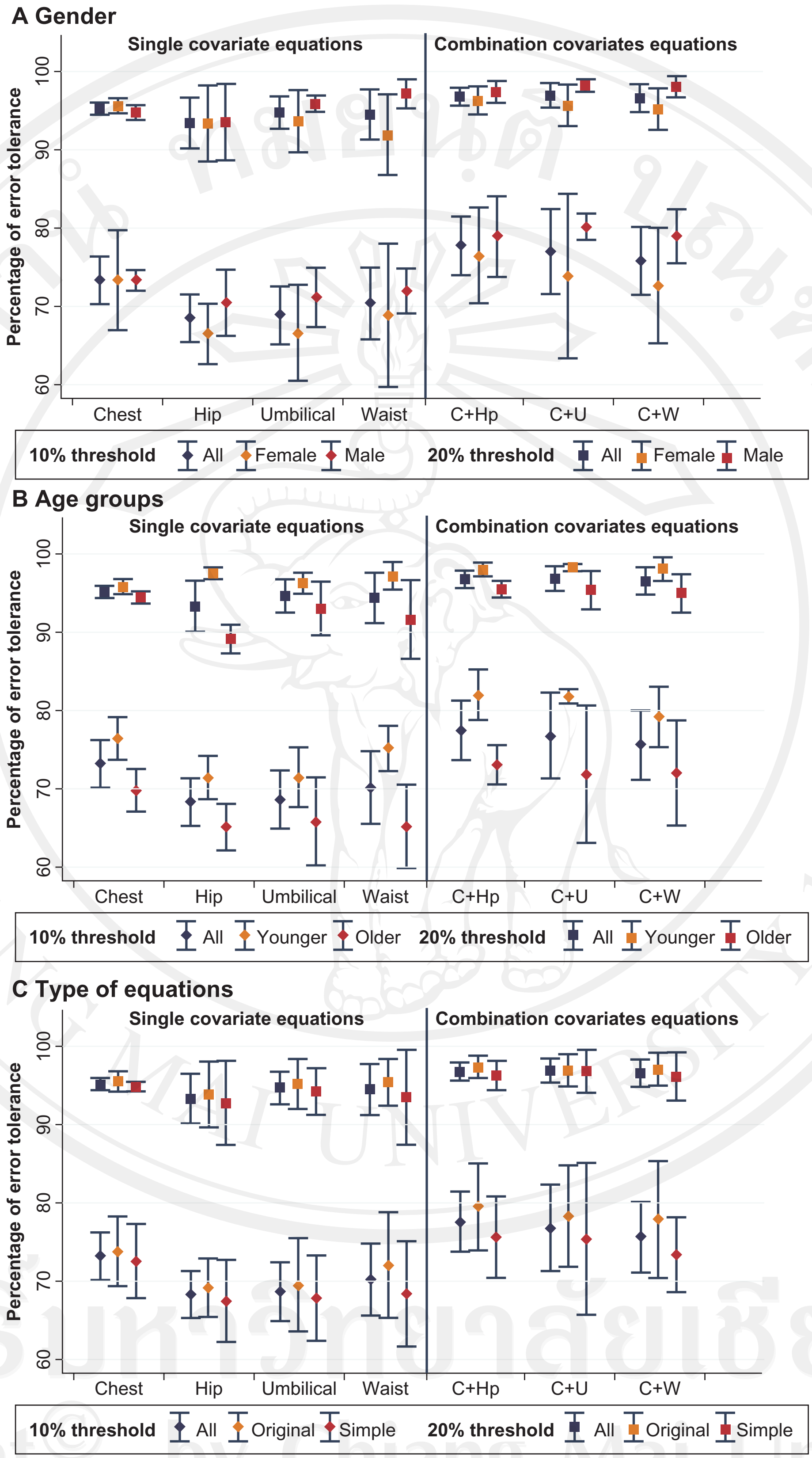

Figure 4 Percentage of error tolerance comparison in 10% and 20% error threshold in each covariate equation classified by the subgroups (**A**) sex (**B**) age groups, and (**C**) type of equations.

Note: Error tolerance (%) = 100 – error (%).

Abbreviations: C+Hp, chest + hip; C+U, chest + umbilical; C+W, chest + waist.

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Table 8 Summary of previous body weight predicted equation and validation

Author	Population	Equation	Model	Validation
Chumlea[16]	228 elderly (P, USA)	Female: WT = 0.98 (MAC) + 1.27 (CC) + 0.40 (SST) + 0.87 (KH) – 62.35 Male: WT = 1.73 (MAC) + 0.98 (CC) + 0.37 (SST) + 1.16 (KH) – 81.69	Female R^2 = 0.85 Male R^2 = 0.90	Mean signed differences 0.1 – 1.8 kg
Donini[14]	285 elderly (H, Italy)	Female: WT = 1.41 (MAC) + 1.11 (CC) + 0.47 (SST) + 1.0 (KH) – 67.37 Male: WT = 36.2 (ln MAC) + 42.47 (ln CC) + 6.91 (ln SST) + 0.8 (KH) – 253.7	Female R^2 = 0.83 Male R^2 = 0.89	95% error range Woman: ±6.1 kg Male: ±4.9 kg
Jung[18]	300 elderly (P+H, Hong Kong)	Female: WT = 1.01 (KH) + 2.81 (MAC) – 66.04 Male: WT = 1.10 (KH) + 3.07 (MAC) – 75.81	See note[a]	Difference (95% CI) Female: 2.7 (2.3/3.6) Male: 0.4 (–0.5/1.4)
Miyatake[13]	2635 adults (H, Japan)	Female: ↓3 kg ≈ ↓2.85 waist (cm) Male: ↓3 kg ≈ ↓3.45 waist (cm)	NA	NA
Crandall[11]	1471 Obese (P+H, USA)	Female: WT = 2.15 (MAC) + 0.54 (HT) – 64.6 Male: WT = 3.29 (MAC) + 0.43 (HT) – 93.2	R^2 = 0.55 R^2 = 0.59	Error 10%: 30%–35% Error 20%: 8%–10%
Lin[10]	235 adults (P, USA)	Female: WT = 1.01 (KH) +2.81 (MAC) – 66.04 Male: WT = 1.10 (KH) + 3.07 (MAC) – 75.81	See note[a]	Error 10%: 31% (95% CI: 25%/37%)[b]
Fawzy[12]	50 young male (H, Egypt)	Male: WT = 9.05 (FBBL) + 11.53	R^2 = 0.27	NA
Bernal-Orozco[15]	95 elderly female (P, Mexico)	Female: WT = 1.599 (KH) + 1.135 (MAC) + 0.735 (CC) + 0.621 (TSF) – 83.123	R^2 = 0.90	Difference error in three samples: –0.02 ± 4.3; –0.7 ± 4.2; 1.9 ± 3.2

Notes: [a]Study used Ross Laboratories equation (Columbus, OH) for body weight prediction. These formulas were generated based on Caucasian population; [b]calculated from error tolerance.
Abbreviations: H, healthy volunteers; P, patients; WT, predicted body weight; HT, height; FBBL, left foot breadth at ball (measured by foot print method); KH, knee height; MAC, mid arm circumference; CC, calf circumference; TSF, triceps skinfold thickness; SST, subscapular skinfold thickness; ln, natural logarithm; NA, not available.

The most common body weight prediction method is visual estimation. However, many previous studies demonstrated that this was a poor estimation method and it was estimator-dependent.[6,7,23] One prospective study in an intensive care unit demonstrated that body weight errors estimation of ≥10% and ≥20% of actual body weight were as much as 47% and 19%, respectively.[23] Although there were differences in the setting and population in the previous study, the single (Chest) and combination (C+Hp) proposed equations in this present study could decrease evidence errors predictions compared to a previous study (≥10% and ≥20% error [95% CI]: Chest 26.6 [22.9–35.1] and 4.7 [3.9–5.6]. C+Hp 22.4 [17.7–29.5] and 3.2 [1.8–4.5], respectively; Table 6).

There were a number of potential strengths and weakness in the present study. The major strengths in the present study were a large sample size which was divided by gender and age groups. In addition, the modeling or development of the equation and validation groups were comparable in all basic demographics and measured data and different circumferences have been compared and demonstrate model fitting in the present study. However, there were a number of inevitable limitations for the study weakness. First, almost all of the participants in the present sample resided in the northern region of Thailand. Although all were the same ethnic background, the differences in lifestyle and living patterns between regions and Asian countries might affect the average body composition resulting in a validity distortion. However, the mixed ethnicity in the northern region of Thailand results from its geographic location between multiple nationalities. This might be the supportive factor to reduce ethnic differences when prediction results are extrapolated to other Asian countries. Second, nearly 80% of the volunteers had a body mass index of less than 25 kg/m², which is the criterion threshold of obesity diagnosis. Violations of linearity were performed before the model creation, but the authors found that underestimation might have occurred in volunteers with an actual body weight of more than 90 kg (Figures 2 and 3). Therefore, using the proposed prediction equation on this special population might include a caution for underestimating body weight. However, the present study demonstrated that using a combination covariate equation might alleviate these effects. The mathematic method to take the logarithm of covariate parameters before substitution of these values in the equations might diminish these effects and these methods have been proposed in a previous report (Table 7).[14]

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However; simple formulation and general clinical bedside calculation were our primary aims. Therefore, logarithm-based models were not proposed in the present study. Third, although the authors attempted to decrease the somatotype effect by a simplifying method using the summation of chest and one torso circumference as one covariate in the equations, the actual somatotype-detailing anthropometric measurement data was not collected in the present study. Therefore, the correlation between these simplified methods and actual somatotype could not be demonstrated. However, the authors observed that these methods could reduce performance error when comparing individual covariate-predicted equations and further study might be performed to reveal the relationship between combination covariate and somatotypes. Fourth, because of internal validity concerns, the study population was collected only in healthy volunteers. Therefore, the equation results might be distorted when equations are extrapolated to diseased patients. However, there were inconsistent population recruitments in the previous studies of body weight prediction (Table 7). In addition, the actual body weight in diseased patients might deviate from functional body weight in healthy volunteers by body composition alternations.[24,25] However, most phase I clinical trials were performed in healthy volunteers to determine the metabolic and pharmacological actions and the maximally tolerated dose. Of these backgrounds, in the authors' opinions, functional body weight from healthy volunteers might be applied to general clinical practice. Because of these limitations, further validation studies should be performed using these equations in the special clinical situations of the emergency department, intensive care units, or with immobilized patients. Finally, the authors proposed simple formulas which could be used in both sexes in the same age group. Although the authors endeavored to titrate the regression coefficient and intercept by substitution covariates with the mean value of the modeling sample as well as comparable correlation coefficients, the performance error of these equations was higher than the original ones. However, error tolerances of simple and original equations had comparable evidences of accuracy in the 10% error threshold range from one-fourth to one-third of the total sample. Therefore, these methods should be used only in situations in which a direct measurement is unavailable.

Conclusion

Body weight might be predicted by height and circumferential covariates equations. Cco had more error tolerance than Sco. Original and simple equations had comparable validity. Chest- and C+Hp-containing covariate equations had more precision between Sco and Cco equations, respectively.

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Disclosure

The authors report no conflicts of interest in this work. This study was a part of thesis in the clinical epidemiology PhD project of Assistant Professor Kaweesak Chittawatanarat.

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Appendix D

Chittawatanarat K, Pruenglampoo S, Kongsawasdi S, Chuatrakoon B, Trakulhoon V, Ungpinitpong W, Patumanond J. The variations of body mass index and body fat in adult Thai people across the age spectrum measured by bioelectrical impedance analysis Clin Interv Aging 2011;6:285-94.

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ORIGINAL RESEARCH

The variations of body mass index and body fat in adult Thai people across the age spectrum measured by bioelectrical impedance analysis

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Background: The measurements of body mass index (BMI) and percentage of body fat are used in many clinical situations. However, special tools are required to measure body fat. Many formulas are proposed for estimation but these use constant coefficients of age. Age spectrum might affect the predicted value of the body composition due to body component alterations, and the coefficient of age for body fat prediction might produce inconsistent results. The objective of this study was to identify variations of BMI and body fat across the age spectrum as well as compare results between BMI predicted body fat and bioelectrical impedance results on age.

Methods: Healthy volunteers were recruited for this study. Body fat was measured by bioelectrical impedance. The age spectrum was divided into three groups (younger: 18–39.9; middle: 40–59.9; and older: ≥60 years). Comparison of body composition covariates including fat mass (FM), fat free mass (FFM), percentage FM (PFM), percentage FFM (PFFM), FM index (FMI) and FFM index (FFMI) in each weight status and age spectrum were analyzed. Multivariable linear regression coefficients were calculated. Coefficient alterations among age groups were tested to confirm the effect of the age spectrum on body composition covariates. Measured PFM and calculated PFM from previous formulas were compared in each quarter of the age spectrum.

Results: A total of 2324 volunteers were included in this study. The overall body composition and weight status, average body weight, height, BMI, FM, FFM, and its derivatives were significantly different among age groups. The coefficient of age altered the PFM differently between younger, middle, and older groups (0.07; $P = 0.02$ vs 0.13; $P < 0.01$ vs 0.26; $P < 0.01$; respectively). All coefficients of age alterations in all FM- and FFM-derived variables between each age spectrum were tested, demonstrating a significant difference between the younger (<60 years) and older (≥60 years) age groups, except the PFFM to BMI ratio (difference of PFM and FMI [95% confidence interval]: 17.8 [12.8–22.8], $P < 0.01$; and 4.58 [3.4–5.8], $P < 0.01$; respectively). The comparison between measured PFM and calculated PFM demonstrated a significant difference with increments of age.

Conclusion: The relationship between body FM and BMI varies on the age spectrum. A calculated formula in older people might be distorted with the utilization of constant coefficients.

Keywords: fat mass, fat free mass, age, body mass index, Thai

Introduction

Body mass index (BMI) is widely used for nutritional assessment, obesity classification, and as a prognostic variable for mortality.[1] However, there are many limitations. First, the BMI could potentially produce an inaccurate diagnosis of "overweight" and "obese" in some special populations such as athletes, body builders, and elderly patients.[2–4] Second, BMI-associated mortality in specific situations is controversial.[1,5,6] A large

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retrospective study in critically ill patients demonstrated that only underweight was associated with poor outcomes in contrast with overweight and obesity.[7] These results are similar to a large prospective study of nonbariatric surgical patients.[8] This difference might be explained by the fat mass (FM) and fat free mass (FFM) proportions in the patients. The decrease of FFM and increase of FM had a negative impact on the overall mortality in an epidemiologic study, especially in males.[5,6] Therefore, the combination of BMI and FM might be useful as a clinical prognostic indicator as well as diagnostic criterion for obesity. However, the percentage of FM (PFM) could be predicted with a variety of formulas using BMI, gender, ethnic differences, and age. All of these generate a model based on linear assumption with constant individual variable coefficients.[9,10] Although ethnic and gender differences have a proven effect on the relationship between FM and BMI, these have not been analyzed in relation to the age spectrum.[4,11,12] The authors, however, suspected that age spectrum might distort this relationship and the coefficient of age might be inconsistent throughout the life span as opposed to gender and race. Therefore, the objectives of this study were to demonstrate the alteration and variation of the relationship between FM and its derivatives and BMI over each age group in the same ethnicity, and to compare this study's measured FM with previously estimated formulas.

Materials and methods

The authors enrolled healthy Thai volunteers by way of invitation at the Faculty of Medicine, Chiang Mai University, between May 2010 and May 2011. Volunteers were people from the general community. Four research assistants were trained in the measurement of bioelectrical impedance analysis (BIA). Body weight was measured using the same digital weighing apparatus each time (TCA-200 A-RT; Zepper, Bangkok, Thailand) and recorded in kilograms to one decimal point. Height was measured using a standard measuring board; the subjects' body positions ensured their head, shoulder blades, buttocks, and heels were touching the board during measurement. Height was recorded in centimeters. BMI was calculated by dividing the body weight in kilograms by square height in meters (BMI = body weight [kg]/height [m^2]). Volunteers who exhibited any characteristics that might interfere with measured parameters were excluded. These included: subjects <18 years old; pregnant women; persons with any implanted electronic device; those exhibiting signs of chronic steroid use; persons with amputated limb(s), or limited ambulation, inability to lie down, or edematous limb(s); and those with chronic diseases such as liver cirrhosis, renal failure, and heart failure. This study was approved by the Faculty of Medicine, Chiang Mai University Ethics Committee. All volunteers gave informed consent before their enrollment into the study.

A bioelectrical impedance analyzer (Biodynamics BIA 310e™; Biodynamics Corporation, Seattle, WA) was used to analyze body composition. This machine is a single frequency BIA (SF-BIA) that generates a 50 kHz current, which passes between surface electrodes placed on the hand and foot.[13] The machine's sensor measures the reactance and resistance range up to 300 and 1500 Ohms, respectively. Input data were calculated using the machine's software and output was reported as PFM, percentage of FFM (PFFM), FM, FFM, and total body water. The machine was always tested by two research assistants to verify accuracy before use. One assistant tested the machine by measuring the BIA results of the other assistant at least twice. The result was considered valid if it did not have an error $>5\%$. Fat mass index (FMI) and fat free mass index (FFMI) were calculated by dividing the fat mass and fat free mass by square height in meters (ie, FMI = FM/height^2 [m^2]; FFMI = FFM/height^2 [m^2]).

Because single frequency bioelectrical impedance analysis is not valid under conditions of significantly altered hydration,[14] before analysis all volunteers were asked to observe the following pretest guidelines: (1) no alcohol consumption within 24 hours; (2) no exercise, caffeine, or food within 4 hours prior to taking the test, (3) drink two to four glasses of water 2 hours before examination. During the examination, two pairs of sensor electrocardiograph pads were placed on the patient, one on the right wrist and hand and the other on the right foot and ankle. At least 75% of the electrode was required to be in contact with the patient's skin. Patient data, including gender, age, height, and weight, were entered into the machine's software before each test. Results of the measurements were recorded and printed.

Comparison of percentage body fat with other fat prediction formulas

The predicted percentage of fat by sex, BMI, and age was calculated using the formulas proposed by Gallagher et al.[9] These formulas were selected for three reasons. First, the formulas were generated based on two standard measurements: dual energy X-ray absorptiometry (DXA) and the four compartment model (4C). Second, the formulas considered ethnic differences and integrated ethnic parameters. Finally, the formulas considered the interaction among the

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parameters involved. The equations were demonstrated as follows:[9]

1. DXA model: PFM = 76.0 – 1097.8 (BMI^{-1}) – 20.6 (Sex) + 0.053 (Age) + 95.0 (Asian) (BMI^{-1}) – 0.044 (Asian)(Age) + 154 (Sex) (BMI^{-1}) + 0.034 (Sex) (Age)
2. 4C model: PFM = 63.7 – 864 (BMI^{-1}) – 12.1 (Sex) + 0.12 (Age) + 129 (Asian) (BMI^{-1}) – 0.091 (Asian) (Age) + 0.03 (African American) (Age)

These formulas reported a correlation coefficient of about 0.90 and standard error of estimation of about 4%. Variables were defined as sex = 1 for male and 0 for female; Asian = 1 for Asian and 0 for other races.[9]

Statistical analysis

Volunteers were categorized according to age into three groups: younger (18–39 years), middle (40–59 years), and older (≥60 years). Each group was further divided into four, using 5-year intervals – except in the first group, which ranged from 18 to 24 years, and the last group, which began at ≥75 years. Weight status was based on BMI using the World Health Organization diagnostic criteria and categorized into four groups: underweight (<18.5 kg/m^2), normal (18.5–24.9 kg/m^2), overweight (25–29.5 kg/m^2), and obese (≥30 kg/m^2).[15]

Differences among the groups were tested depending on data types. Categorized data were tested by chi square. All of the continuous variable data were reported as mean ± standard deviation. The difference among age groups was tested for equal variances using Bartlett's test and Bonferroni comparison. Group differences were calculated using one-way analysis of variance test for equal variance and the Kruskal–Wallis test for unequal variance. A comparison was made between PFMs to verify the previously used Gallagher et al formulas,[9] and paired Student's *t*-test was calculated to demonstrate differences in each quartile of each age group. A Bland–Altman plot was performed to demonstrate the error between the predicted PFM formula and the measured PFM for age.

A multivariate regression model was used to test the association between the PFM and independent variables (age, gender, BMI, and status). Weight status was categorized by BMI criteria as previous mentioned and was adjusted for gender and age. The coefficient of age spectrum in older volunteers (≥60 years) was compared with younger (<60 years) by multivariate linear regression, and the interaction between age and age spectrum was tested. Data were analyzed by STATA (v 11.0; STATA Inc, College Station, TX) software. A statistically significant difference was defined as a *P* value of <0.05.

Results

During this 13-month study, 2324 volunteers (1324 females and 1000 males) were included. The number of females was slightly higher in this study (female 57%; male 43%). The most common three occupations were worker, farmer, and officer, with different proportions in each age group. Ninety-six percent of the study population resides in the northern region of Thailand (Table 1). Body weight, height, and BMI were significantly different between age groups and gender. Nearly 60% of the population had a normal weight status. Approximately one quarter of the study population was overweight (24% of females and 26.8% of males) and <10% were underweight or obese (Table 1). Although the overall proportion of weight status between genders was comparable, there was a higher percentage of obesity in females in the older age group (Table 1).

Using a BIA to analyze body fat and FFM as shown in Table 2, the volunteers of both genders had significant differences ($P < 0.05$) between younger, middle, and older age groups of FM, FFM, PFM, PFFM, FMI, FFMI, PFMR (percentage fat mass ratio = PFM:BMI), and PFFMR (percentage fat free mass ratio = PFFM:BMI). However, after subgroup analysis by weight status and gender, differences could be observed in two groups. First, in the under, normal, and overweight status groups there were significant differences between age groups of both genders for all previous parameters mentioned except FM. In the overweight group a significant difference in FM and PFFMR was found only among females in the underweight volunteers. Second, in the obese group, no parameter had significant differences for either gender, but all parameters except for FM and PFFMR were statistically different among the females. The relationships between the PFM, PFFM, BMI PFMR, and PFFMR over the age spectrum in each gender are shown in Figures 1 and 2. These figures show that PFM and BMI initially increased in parallel with age, diverged at middle age, and separated significantly for those aged >60 years, while the percentage of FFM decreased (Figure 1). These findings corresponded that the PFMR remained steady over time until 50 years of age when it increased in both genders, while the PFFMR was rather stable into older ages (Figure 2).

Multivariate regression coefficients adjusted for age, gender, BMI, and weight status of PFM are shown in Table 3. Of these, all of the parameters had significantly different coefficients in each age group except in the underweight volunteers. The females had higher body fat than males, by approximately 7.44%, which lowered in the middle age

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Table 1 Demographic data of volunteers in each age group

Parameters	Younger (n = 459)	Middle (n = 862)	Older (n = 1003)	Total (n = 2324)	*P* value
Gender (%)					<0.01
Female	311 (67.8)	510 (59.2)	503 (50.2)	1324 (57.0)	
Male	148 (32.2)	352 (40.8)	500 (49.8)	1000 (43.0)	
Occupation (%)					<0.01
Farmer	33 (7.2)	181 (21.0)	169 (16.8)	383 (16.5)	
Officer†	52 (11.3)	145 (16.8)	157 (15.6)	354 (15.2)	
Private	55 (12.0)	150 (17.4)	61 (6.1)	266 (11.5)	
Worker	174 (37.9)	239 (27.7)	88 (8.8)	501 (21.6)	
Unemployed	110 (24.0)	79 (9.2)	59 (5.9)	248 (10.7)	
Other	35 (7.6)	68 (7.9)	469 (46.8)	572 (24.6)	
Habitats (%)					0.55
Northern	437 (95.2)	827 (96.0)	967 (96.4)	2231 (96)	
Other	22 (4.8)	35 (4.0)	36 (3.6)	93 (4.0)	
Body weight (kg)‡					
Female	56.5 ± 10.7	57.9 ± 10.0	54.3 ± 10.9	56.2 ± 10.6	<0.01
Male	67.3 ± 12.7	68.0 ± 12.1	59.7 ± 11.0	63.7 ± 12.3	<0.01
Height (cm)‡					
Female	156.3 ± 5.7	154.3 ± 5.3	151.9 ± 6.5	153.9 ± 6.1	<0.01
Male	167.5 ± 6.6	165.5 ± 5.7	162.1 ± 7.2	164.1 ± 6.9	<0.01
BMI (kg/m²)‡					
Female	23.1 ± 4.2	24.3 ± 3.8	23.5 ± 4.1	23.7 ± 4.1	<0.01
Male	23.9 ± 4.1	24.8 ± 4.0	22.6 ± 3.4	23.6 ± 3.9	<0.01
Status (%)					
Female					<0.01
Underweight	29 (9.3)	15 (2.9)	54 (10.7)	98 (7.4)	
Normal	206 (66.2)	311 (61.0)	294 (58.5)	811 (61.3)	
Overweight	53 (17.0)	152 (29.8)	113 (22.3)	318 (24.0)	
Obese	23 (7.4)	32 (6.3)	42 (8.4)	97 (7.3)	
Male					<0.01
Underweight	10 (6.8)	10 (2.8)	47 (9.4)	67 (6.7)	
Normal	84 (56.8)	189 (53.7)	345 (69.0)	618 (61.8)	
Overweight	42 (28.4)	130 (36.9)	96 (19.2)	268 (26.8)	
Obese	12 (8.1)	23 (6.5)	12 (2.4)	47 (4.7)	

Notes: †Includes retired officers; ‡mean ± standard deviation.
Abbreviation: BMI, body mass index.

group. The coefficient of BMI was 0.5, which was highest in middle age (0.66; $P < 0.01$) but lowest in older age (0.42; $P < 0.01$). The relationship between increasing age and body composition showed an orderly increase of PFM over each additional year of aging (0.07%, 0.13%, and 0.26% in the younger, middle, and older groups, respectively). PFM changes in underweight, overweight, and obese groups (compared with normal weight status) had the highest alteration in middle age and the lowest in the older age – except in the underweight category, which was comparable to the younger group (Table 3).

To confirm the coefficient alteration of age spectrums on all FM and FFM variables, the authors compared the age spectrum effects between older age volunteers (≥60 years) and younger ages (<60 years) based on the previously mentioned findings and Figures 1 and 2. The results are shown in Table 4. Of these, PFM, PFFM, FMI, and FFMI had significant differences in coefficient alteration among age spectrums ($P < 0.01$). However, there were no differences in coefficient change between groups in PFFMR ($P = 0.11$).

To demonstrate how the age spectrum affected the validity of PFM prediction, the authors compared PFM between measured PFM by BIA and calculated PFM[9] on each age spectrum (Figure 3) as well as error of PFM between BIA measurements and calculated PFM (Figure 4).[9] BIA measured as PFM was comparable only in the age range of 30 and 45 years. Differences started at 45–50 years ($P < 0.01$) and showed significance after that age ($P < 0.001$). Errors of PFM prediction from BMI-based formulas using four compartments and the DXA model were demonstrated using the Bland–Altman

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Table 2 Mean and standard deviation of weight, percentage, and ratio to BMI of fat mass and lean body mass in each age group and status

	Younger		Middle		Older		Total	
	Female	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
FM (kg)								
Overall**	18.1 ± 5.4	16.4 ± 5.5	19.8 ± 5.8	18.4 ± 6.0	20.1 ± 5.8	17.5 ± 5.1	19.5 ± 5.7	17.7 ± 5.5
Underweight*	12.1 ± 2.5	10.1 ± 2.6	12.4 ± 2.5	11.5 ± 3.7	13.6 ± 2.6	12.7 ± 3.6	13.0 ± 2.7	12.1 ± 3.6
Normal**	16.4 ± 2.9	13.9 ± 3.0	17.1 ± 3.0	15.7 ± 3.2	18.4 ± 3.3	16.7 ± 3.9	17.4 ± 3.2	16.0 ± 3.7
Overweight	22.8 ± 3.3	19.7 ± 3.4	23.3 ± 3.3	21.0 ± 3.5	23.6 ± 3.4	21.1 ± 3.8	23.3 ± 3.3	20.8 ± 3.6
Obese	29.5 ± 6.1	28.2 ± 4.3	32.3 ± 8.8	29.1 ± 12.8	31.3 ± 7.4	29.3 ± 11.3	32.2 ± 7.6	28.9 ± 10.7
FFM (kg)								
Overall**	38.5 ± 6.3	50.8 ± 8.3	38.1 ± 5.5	49.6 ± 7.8	34.2 ± 6.8	42.2 ± 8.6	36.7 ± 6.5	46.1 ± 9.2
Underweight**	30.1 ± 5.1	39.6 ± 3.9	29.6 ± 3.0	36.4 ± 6.0	25.5 ± 4.8	31.1 ± 6.0	27.5 ± 5.1	33.2 ± 6.5
Normal**	37.1 ± 4.1	47.7 ± 5.6	36.2 ± 4.1	46.3 ± 5.4	32.7 ± 5.0	41.0 ± 6.5	35.2 ± 4.8	43.6 ± 6.7
Overweight**	43.3 ± 4.2	55.7 ± 5.9	40.9 ± 4.0	53.2 ± 6.0	38.9 ± 5.5	50.0 ± 7.7	40.6 ± 4.8	52.4 ± 6.9
Obese*	50.0 ± 5.3	64.7 ± 7.1	47.0 ± 7.1	62.0 ± 9.7	43.0 ± 5.3	57.7 ± 6.1	46.0 ± 6.5	61.6 ± 8.5
PFM(%)								
Overall**	31.6 ± 4.7	24.0 ± 4.5	33.7 ± 5.0	26.8 ± 5.0	36.9 ± 5.9	29.4 ± 6.6	34.4 ± 5.7	27.7 ± 6.1
Underweight**	28.9 ± 6.6	20.4 ± 5.4	29.5 ± 5.2	24.4 ± 8.7	35.1 ± 7.3	29.3 ± 8.8	32.4 ± 7.4	27.2 ± 8.9
Normal**	30.6 ± 3.7	22.5 ± 3.6	32.0 ± 4.4	25.3 ± 4.5	36.0 ± 5.6	29.1 ± 6.3	33.1 ± 5.2	27.0 ± 6.0
Overweight**	34.4 ± 3.8	26.1 ± 3.6	36.2 ± 3.8	28.3 ± 4.4	37.9 ± 4.8	30.0 ± 6.0	36.5 ± 4.3	28.6 ± 5.1
Obese*	36.9 ± 4.9	30.3 ± 3.1	40.5 ± 3.9	31.2 ± 5.1	41.9 ± 5.3	33.0 ± 8.6	40.2 ± 5.1	31.4 ± 5.8
PFFM(%)								
Overall **	68.4 ± 4.7	76.0 ± 4.5	66.3 ± 5.0	73.2 ± 5.0	63.2 ± 5.9	70.6 ± 6.6	65.6 ± 5.7	72.6 ± 6.6
Underweight**	71.1 ± 6.6	79.6 ± 5.4	70.5 ± 5.2	75.6 ± 8.7	64.9 ± 7.3	70.7 ± 8.8	67.6 ± 7.4	72.8 ± 8.9
Normal**	69.4 ± 3.7	77.5 ± 3.6	68.0 ± 4.4	74.7 ± 4.5	64.0 ± 5.2	70.9 ± 6.3	66.9 ± 5.2	73.0 ± 6.0
Overweight**	65.6 ± 3.8	73.9 ± 3.6	63.8 ± 3.8	71.7 ± 4.4	62.1 ± 4.8	70.0 ± 6.0	63.4 ± 4.4	71.4 ± 5.1
Obese*	63.1 ± 4.9	69.7 ± 3.1	59.5 ± 3.9	68.8 ± 5.1	58.1 ± 5.4	67.0 ± 9.0	59.8 ± 5.1	68.6 ± 5.7
FMI (kg/m^2)								
Overall**	7.4 ± 2.2	5.9 ± 1.9	8.3 ± 2.4	6.7 ± 2.1	8.7 ± 2.4	6.7 ± 1.9	8.2 ± 2.4	6.6 ± 2.0
Underweight**	5.0 ± 1.1	3.6 ± 1.1	5.2 ± 1.0	4.3 ± 1.6	6.1 ± 1.3	4.9 ± 1.4	5.6 ± 1.3	4.6 ± 1.5
Normal**	6.7 ± 1.1	4.9 ± 1.0	7.2 ± 1.3	5.7 ± 1.1	8.0 ± 1.5	6.4 ± 1.5	7.3 ± 1.4	6.0 ± 1.4
Overweight**	9.4 ± 1.3	7.0 ± 1.0	9.8 ± 1.3	7.6 ± 8.0	10.1 ± 1.4	8.0 ± 1.6	9.8 ± 1.3	7.7 ± 1.4
Obese*	12.3 ± 2.7	9.9 ± 1.4	13.5 ± 3.6	10.7 ± 4.5	13.6 ± 2.7	10.8 ± 3.4	13.3 ± 3.0	10.8 ± 3.4
FFMI(kg/m^2)								
Overall**	15.7 ± 2.4	18.1 ± 2.5	16.0 ± 1.9	18.1 ± 2.5	14.7 ± 2.4	16.0 ± 2.7	15.4 ± 2.3	17.0 ± 2.8
Underweight**	12.4 ± 1.3	13.9 ± 0.8	12.4 ± 0.8	13.3 ± 1.6	11.2 ± 1.3	12.1 ± 1.9	11.7 ± 1.4	12.5 ± 1.8
Normal**	15.1 ± 1.3	17.0 ± 1.4	15.2 ± 1.2	16.9 ± 1.5	14.1 ± 1.6	15.5 ± 1.8	14.8 ± 1.4	16.1 ± 1.8
Overweight**	17.8 ± 1.2	19.7 ± 1.4	17.2 ± 1.1	19.3 ± 1.4	16.6 ± 1.5	18.7 ± 1.9	17.1 ± 1.3	19.2 ± 1.6
Obese*	20.8 ± 1.9	22.7 ± 1.3	19.6 ± 2.2	22.9 ± 2.9	18.7 ± 1.5	21.8 ± 2.7	19.5 ± 2.0	22.6 ± 2.5
PFMR								
Overall**	1.4 ± 0.2	1.0 ± 0.2	1.4 ± 0.2	1.1 ± 0.2	1.6 ± 0.3	1.3 ± 0.4	1.5 ± 0.3	1.2 ± 0.3
Underweight**	1.7 ± 0.4	1.2 ± 0.3	1.7 ± 0.3	1.4 ± 0.5	2.0 ± 0.4	1.7 ± 0.6	1.9 ± 0.4	1.6 ± 0.6
Normal**	1.4 ± 0.2	1.0 ± 0.2	1.4 ± 0.2	1.1 ± 0.2	1.6 ± 0.3	1.3 ± 0.3	1.5 ± 0.2	1.2 ± 0.3
Overweight**	1.3 ± 0.1	1.0 ± 0.1	1.3 ± 0.1	1.0 ± 0.2	1.4 ± 0.2	1.1 ± 0.2	1.4 ± 0.2	1.1 ± 0.2
Obese*	1.1 ± 0.1	0.9 ± 0.1	1.2 ± 0.1	0.9 ± 0.1	1.3 ± 0.1	1.0 ± 0.2	1.2 ± 0.1	1.0 ± 0.1
PFFMR								
Overall**	3.1 ± 0.6	3.3 ± 0.7	2.8 ± 0.5	3.0 ± 0.5	2.8 ± 0.6	3.2 ± 0.6	2.9 ± 0.6	3.1 ± 0.6
Underweight*	4.1 ± 0.4	4.6 ± 0.4	4.0 ± 0.4	4.3 ± 0.6	3.8 ± 0.5	4.2 ± 0.5	3.9 ± 0.5	4.2 ± 0.5
Normal**	3.2 ± 0.3	3.6 ± 0.4	3.1 ± 0.3	3.3 ± 0.3	2.9 ± 0.4	3.3 ± 0.4	3.0 ± 0.4	3.3 ± 0.4
Overweight**	2.4 ± 0.2	2.7 ± 0.2	2.4 ± 0.2	2.7 ± 0.2	2.3 ± 0.2	1.9 ± 0.3	2.4 ± 0.2	2.6 ± 0.2
Obese	1.9 ± 0.3	2.1 ± 0.2	1.8 ± 0.3	2.1 ± 0.3	1.8 ± 0.2	2.1 ± 0.3	1.8 ± 0.3	2.1 ± 0.3

Notes: *$P < 0.05$ only in females; **$P < 0.05$ in both males and females.

Abbreviations: FM, fat mass; FFM, fat free mass; PFM, percentage of fat mass; PFFM, percentage fat free mass; FMI, fat mass index; FFMI, fat free mass index, PFMR, percentage fat mass to BMI ratio; PFFMR, percentage fat free mass to BMI ratio.

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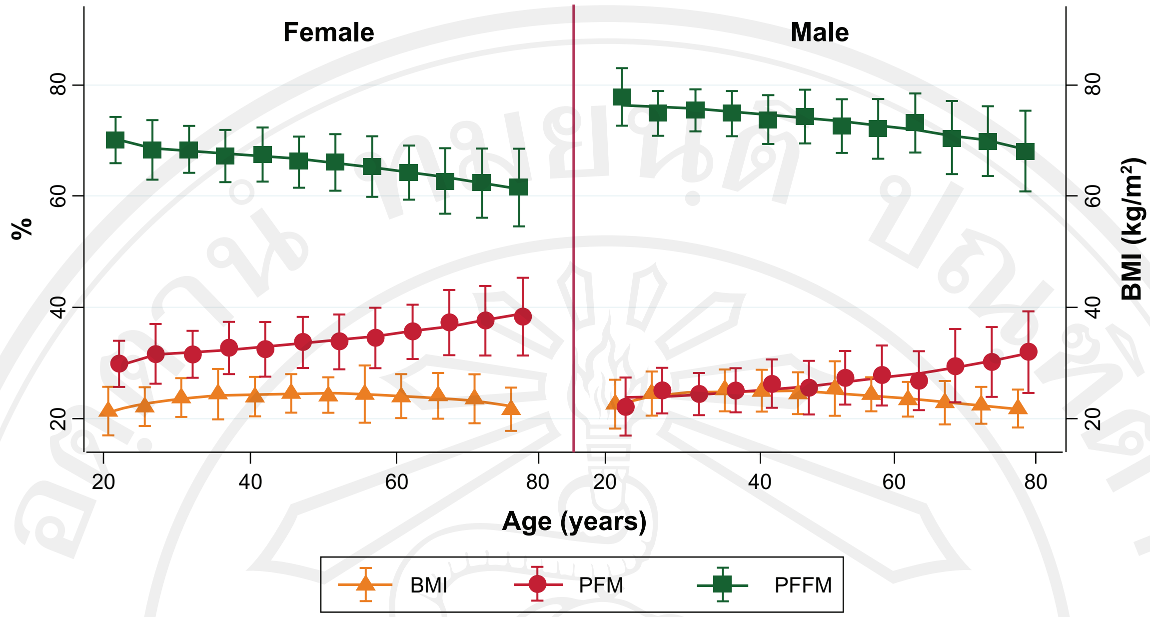

Figure 1 Relationship of BMI, percentage body fat, and percentage lean body mass demonstrated by mean ± standard deviation over age in each gender.
Abbreviations: BMI, body mass index; PFM, percentage of fat mass; PFFM, percentage of fat free mass.

plot in Figure 4. The predicted error line in these two curves revealed that underestimation might occur in older people using calculated PFM prediction by BMI results.

When taking into account age group, gender, and ethnicity difference, one multinational study of a Japanese-based population suggested that the PFM in that population was associated with a BMI of >30 (obesity diagnosis according to BMI criteria). The results for males and females were PFM (Asian criteria) of 28–29 and 40–41, respectively.[9] However, the cutoff point for determining obesity was different from the previous Thai adults study, where obesity was defined using PFM (Thai criteria) cutoff points of 25 for males and 35 for females.[10] Using the BMI status definition for obesity diagnosis in this study, the lower cutoff point of PFM

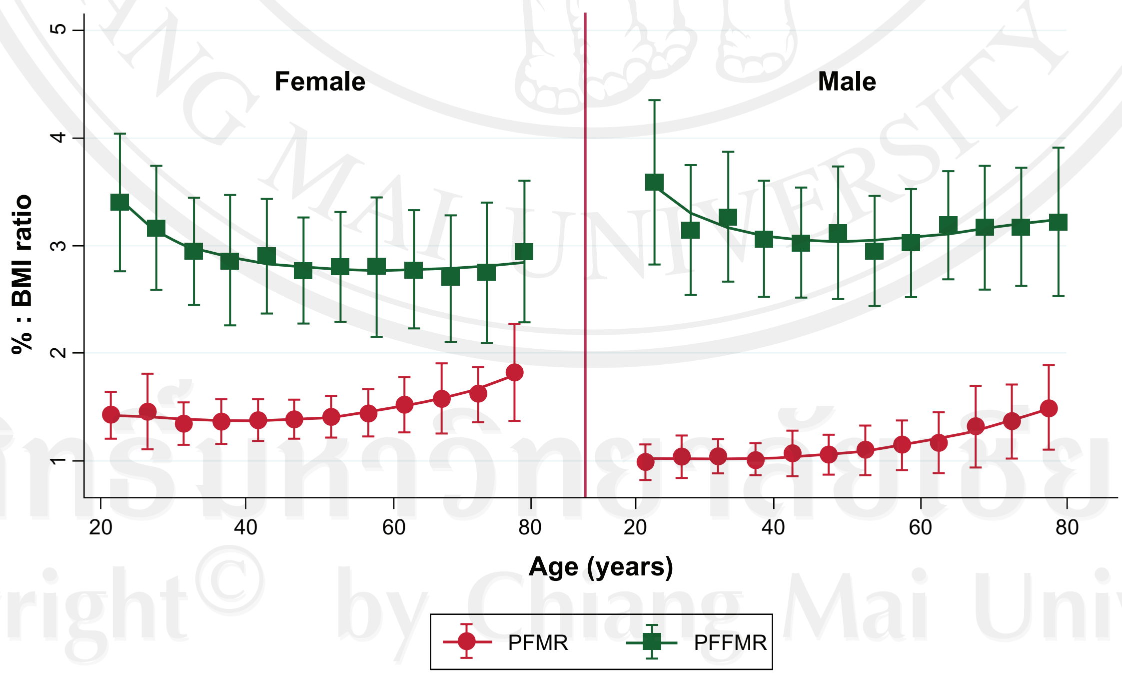

Figure 2 Relationship of PFMR with PFFMR demonstrated by mean ± standard deviation over age in each gender.
Abbreviations: PFMR, percentage of fat mass to BMI ratio; PFFMR, percentage of fat free mass to BMI ratio.

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Table 3 Multivariate regression coefficient of parameters associated with percentage fat mass measured by bioelectrical impedance analysis

Parameters	Younger†	*P*	Middle†	*P*	Older†	*P*	Total†	*P*
Female	7.92 (7.14/8.69)	<0.01	7.41 (6.83/7.98)	<0.01	7.61 (6.88/8.35)	<0.01	7.44 (7.02/7.85)	<0.01
Age (year)	0.07 (0.01/0.12)	0.02	0.13 (0.08/0.18)	<0.01	0.26 (0.21/0.31)	<0.01	0.15 (0.14/0.17)	<0.01
BMI	0.57 (0.48/0.66)	<0.01	0.66 (0.59/0.74)	<0.01	0.42 (0.32/0.52)	<0.01	0.50 (0.45/0.55)	<0.01
Underweight‡	–1.41 (–0.06/–2.77)	0.04	–2.29 (–4.05/–0.53)	0.11	–1.46 (–2.72/–0.20)	0.02	–1.04 (–1.86/–0.22)	0.13
Overweight‡	3.48 (2.54/4.42)	<0.01	3.68 (3.04/4.32)	<0.01	1.85 (0.93/2.78)	<0.01	2.75 (2.26/3.24)	<0.01
Obese‡	6.59 (5.19/8.00)	<0.01	7.50 (6.28/8.71)	<0.01	5.68 (4.02/7.32)	<0.01	6.48 (5.62/7.35)	<0.01

Notes: †Regression coefficient (95% confidence interval: lower/upper value); ‡compared with normal status as reference.
Abbreviations: BMI, body mass index; BIA, bioelectrical impedance analysis.

Thai criteria was reasonable for obesity classification as it gave less false negative rates of obesity diagnosis (Asian vs Thai criteria; 47.4% [46/97] vs 7.22% [7/97] in females and 21.28% [10/47] vs 8.51% [4/47] in males).

Discussion

The authors stratified weight status into four groups based on previous studies.[9,15] In Table 1 the average body weight, height, and BMI were significantly different between age groups. However, the sample in this study is not a representative sample of the overall proportion of the population by weight status in Thailand: nearly 60% of the volunteers had a normal weight status, 25% were overweight, and <10% were in the extreme weight status groups (underweight or obese). However, referral or sampling bias from the selection process might be of concern due to the enrollment site being a tertiary hospital. Although each weight status classified by BMI was not a prospective cohort, the BMI was an indicator of mortality risk.[11] In addition, BMI changed according to variations in body fat.[2,16] The BMI criteria were also used for weight status classification. However, the criteria may have been subject to spectrum bias when they were compared with the body fat measurement criteria.[15,16] Because of these reasons, consideration of both BMI and fat mass together in each gender and by ethnicity might be more precise when predicting death as well as when diagnosing obesity.

The standard ways of measuring FM and FFM need special investigation. Five commonly used methods for body fat detection as standard references are: body density via underwater weighing, DXA, three- and four-compartment models, deuterium dilution techniques, and bioelectrical impedance.[9,10,17,18] Along with the limitations to determining body fat, there are many proposed formulas for the calculation of percentage of body fat that use basic anthropometric parameters (BMI, age, gender, and ethnic differences). These generated prediction formulas are based on previously devised standard measurements;[9,10,19,20] they have differences in coefficients regarding age, gender, and ethnic differences. However, gender and ethnicity were categorized data, while age was a continuous variable. In addition, the predictive coefficient of age in these formulas use constant values throughout the life span in the same ethnic group,[3,9,10,19] which may have distorted and produced prediction errors from different spectrums in the age groups

Table 4 Coefficient alteration between age group quarters adjusted by gender and BMI

Parameter	<60 years†	≥60 years†	Difference†	*P* value
PFM	0.09 (0.07/0.11)	0.26 (0.21/0.31)	0.18 (0.13/0.23)	<0.01
PFFM	–0.09 (–0.11/–0.07)	–0.26 (–0.31/–0.21)	–0.18 (–0.23/–0.13)	<0.01
FMI	0.02 (0.01/0.02)	0.06 (0.05/0.07)	0.04 (0.03/0.06)	<0.01
FFMI	–0.02 (–0.02/–0.01)	–0.06 (–0.07/–0.05)	–0.05 (–0.06/–0.03)	<0.01
PFMR ($\times 10^{-2}$)	0.32 (0.23/0.41)	1.20 (0.95/1.46)	0.97 (0.73/1.21)	<0.01
PFFMR ($\times 10^{-2}$)	–0.61 (–0.73/–0.49)	–0.87 (–1.13/–0.60)	–0.22 (–0.49/0.04)	0.11

Note: †Regression coefficient (95% confidence interval: lower/upper value).
Abbreviations: PFM, Percentage of fat mass; PFFM, Percentage fat free mass; FMI, Fat mass index; FFMI, Fat free mass index; PFMR, Percentage fat mass to BMI ratio; PFFMR, Percentage fat free mass to BMI ratio.

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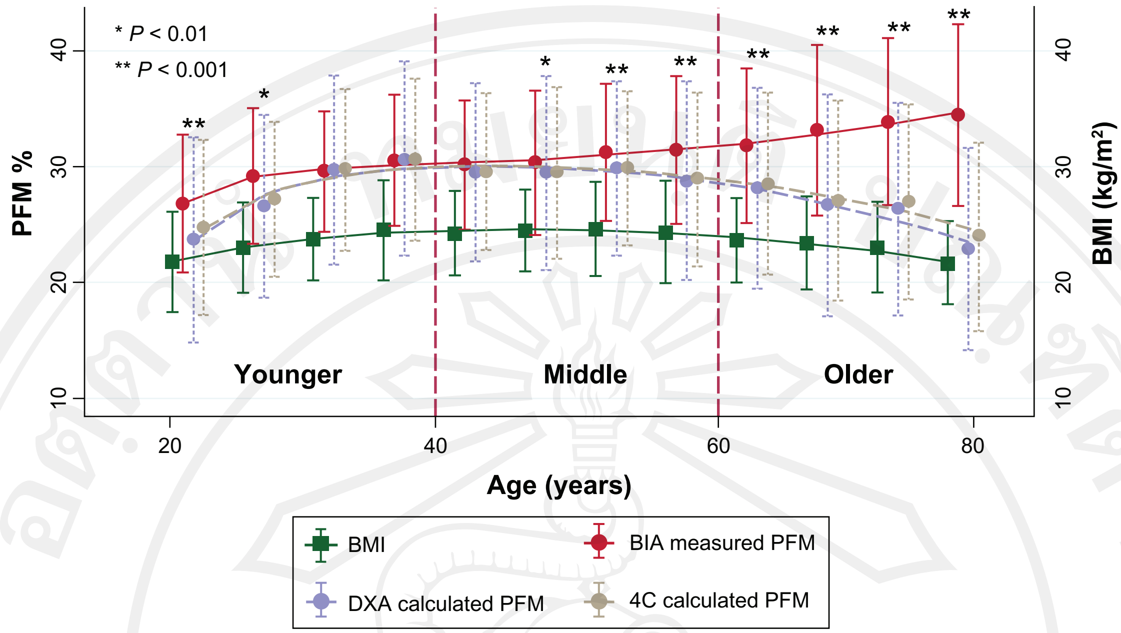

Figure 3 Comparing measured BIA, calculated PFM and BMI demonstrated by mean ± SD in each age group.
Abbreviations: BMI, body mass index; BIA, bioelectrical impedance analysis; PFM, percentage of fat mass; DXA, dual energy X-ray absorptiometry; 4C, four-compartment method; SD, standard deviation.

due to biological distinctions in metabolic synthesis in older people.[21] These hypotheses were confirmed in this study, and the age spectrum played an important role in fat mass. To reduce the interaction of BMI differences in each age group in this study, stratified weight status and gender were analyzed (shown in Table 2 with mean percentage body fat for each). Of these, there were significant differences in PFM and PFFM as well as FMI and FFMI at the same weight status for both males and females, except in the obese volunteers, where age showed a reduced influence in females.

The definition of the percentage of body fat for obesity classification is controversial.[9,10] However, in this study the obesity PFM cutoff points of 25 for males and 35 for females had a lower false negative rate than PFMs of 28 and 40, respectively. The changes in PFM, PFFM, and BMI are shown in Figure 1. With increasing age, BMI and PFM diverged, especially in older volunteers. These contrasted with PFFM, which decreased in parallel with the BMI. To confirm these variables with the age spectrums, multivariate analysis (shown in Table 3) was performed, and this revealed an increased age coefficient in older volunteers. To verify the alteration of the coefficient, the authors analyzed PFMR and PFFMR against age change, as shown in Figure 2. The age spectrum effected significant differences in all of the FM and FFM variables except the PFFMR. This might be explained by the increase of PFM concurrent with the slightly decreasing PFFM caused by the physiological alterations of aging.[19]

The authors demonstrated an error of formula for estimating the PFM in terms of constant coefficient of age compared with measured body fat by BIA in Figures 3 and 4. The overall difference was comparable in the younger and middle-aged groups, but the graph began to diverge at 50 years of age, with the difference increasing as age increased. In all of the findings in this study, the formula predicted that the PFM should be stratified in each age group with different coefficients.

There were a number of potential strengths and weaknesses in this study. The major strength was a large sample size when compared with previous studies and this study's samples were distributed across all groups of weight status in each subgroup. Also, the bioelectrical impedance analyzer is noninvasive, portable, and is reported to have acceptable validity and accuracy.[22] It is widely used in Thailand due to being an inexpensive and portable instrument. However, the criterion validity using the Biodynamics BIA 310e is unknown for Thai people, and the authors noticed a wide range of measurement error if the researcher did not adhere strictly to the examination guidelines. Therefore, thorough checking of the location of the electrocardiograph pads had to be performed and strict following of screening pretest protocols needed to be verified before performing the measurements.

There were a number of inevitable limitations to the study. First, measurement error could occur for some volunteers who did not fully follow the strict pretest preparation. Second,

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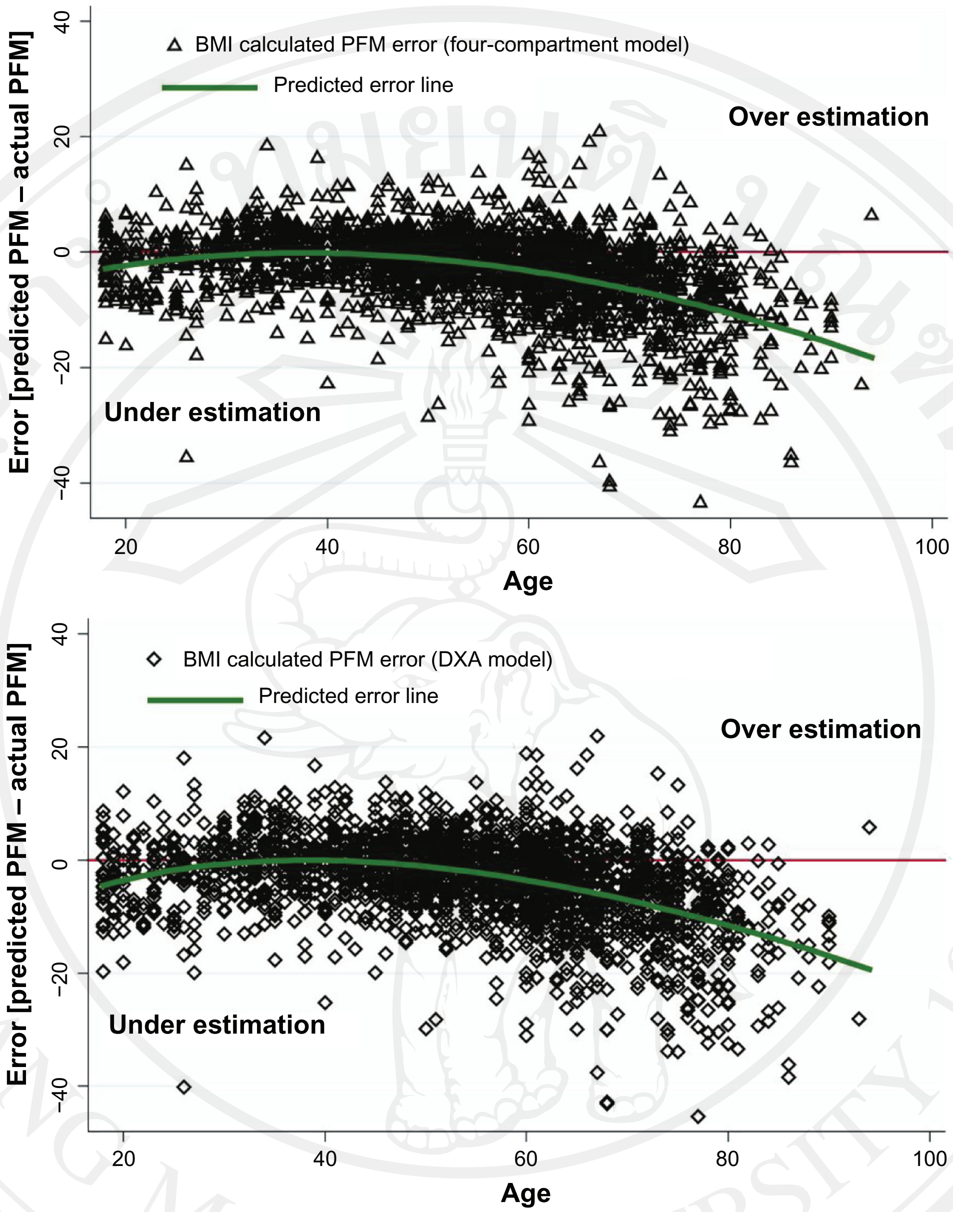

Figure 4 Bland–Altman plot demonstrated error of PFM prediction using BMI in four compartment and DXA model over age.
Abbreviations: BMI, body mass index; PFM, percentage of fat mass; DXA, dual energy X-ray absorptiometry.

nearly 96% of the volunteers lived in the northern region of Thailand. Even though there are similarities in body type and environment across most rural areas in Thailand, extrapolating these results to other populations should be done with caution due to the differences in lifestyles and eating patterns in each population. Third, the method for screening volunteers was by interview. Some of the volunteers, especially older patients, may have had an unknown health history, such as undetected disease, which may have resulted in selection errors. Fourth, the authors could not control for the volunteers' occupations, which might have changed throughout their lives. There may have been differences in the amount of vigorous physical activity they engaged in due to their occupation, which may have changed their body composition, but this was not measured in this study. However, it should be noted that none of the volunteers included in the present study were athletes or body builders. Finally, the authors compared measurement results using the BIA to formulas that were created by the DXA and four-compartment methods. Using a different method might have yielded distinctly different results; however, the authors observed that the correlation of measured and calculated PFM intersected in younger volunteers and this might explain the validity of the formula difference in each age spectrum.

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Conclusion

The relationship between PFM and BMI shows variation on the age spectrum. A calculated formula in older people might be distorted with the utilization of constant coefficients throughout the life span. Therefore, it is concluded that older people should be considered a special population and a prediction formula should be performed separately.

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Disclosure

The authors have no conflicts of interest in this work. This study was a part of Assistant Professor Kaweesak Chittawatanarat's PhD thesis project in clinical epidemiology.

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