The influence of body size on measurements of overall cardiac function

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Chantler, Paul D., R. E. Clements, L. Sharp, K. P. George, L.-B. Tan, and D. F. Goldspink. The influence of body size on measurements of overall cardiac function. Am J Physiol Heart Circ Physiol 289: H2059–H2065, 2005.—The purpose of this study was to determine the best scaling method to account for the effects of body size on measurements of overall cardiac function and subsequently the interpretation of data based on cardiac power output (CPO). CPO was measured at rest (CPOrest) and at maximal exercise (CPOmax) on 88 and 103 healthy but untrained men and women, respectively, over the age range of 20–70 yr. Cardiac reserve (CR) was calculated as CPOmax – CPOrest, body surface area (BSA), and lean body mass (LBM). The linear regression model failed to completely normalize these measurements. In contrast, the allometric model produced size-independent values of CPO. Furthermore, all the assumptions associated with the allometric model were achieved. For CPOrest, mean body size exponents were BM0.33, BSA0.60, and LBM0.47. For CPOmax, the exponents were BM0.41, BSA0.81, and LBM0.71. For CR, mean body size exponents were BM0.44, BSA0.87, and LBM0.79. LBM was identified from the root-mean-squares errors of the separate regression models as the best physiological variable (based on its high metabolic activity) to be scaled in the allometric model. Scaling of CPO to LBMb (where b is the scaling exponent) dramatically reduced the between-gender differences with only a 7% difference in CPOrest and CPOmax values. In addition, the gender difference in CR was completely removed. To avoid erroneous interpretations and conclusions being made when comparing data between men and women of different ages, the allometric scaling of CPO to LBMb would seem crucial.

MAP is one of the two components of CPO. However, this particular physiological variable has been reported to be independent of body size (10). In contrast, the other component, blood flow (CO), is known to be influenced by body size (3, 7, with a larger body mass creating a greater demand for oxygen. In fact, de Simone et al. (7) concluded that normalizing CO to body surface area (BSA) raised to the power of 0.71 was essential to identify the effects of obesity on cardiac function. Because CO is an integral component of CPO, it seems probable that body dimensions will impact on CPO and hence the interpretation of such measurements. If a relationship does exist, it will be important to allow for the potential confounding influences of body size/composition when comparing data sets on CPO between intra- and intergroups of heart failure patients or normal subjects (1).

The most frequently used method of scaling simply divides a physiological variable (y) by body mass (x). However, this approach does not allow for the fact that the relationship between body size and physiological functions are often complex and nonlinear (23). When nonlinear, the linear regression standards model (RES) of $y = a + bx + \varepsilon$ will either underestimate or overcorrect for the impact of body size. This can lead to erroneous interpretations and conclusions, with possible therapeutic consequences in treating patients. In addition, RES assumes that the spread of scores around the regression line is constant throughout the range of x and y variables. This assumption of homoscedasticity is unlikely to be valid in subjects who vary greatly in body size (23). Therefore, normalizing physiological data using RES may not be appropriate, even when the least-squares regression line provides a better fit to the data. In contrast, the allometric model of $y = ax^b + \varepsilon$ has been reported to be theoretically, physiologically, and statistically superior to RES and other methods of scaling (12, 23, 36).

It is also important to identify the most appropriate scaling variable, as well as the correct scaling model. Body mass (BM), BSA, and lean body mass (LBM) have all been used as scaling variables (5, 7, 26). Choosing the most appropriate variable should be based on its biological relevance and the accuracy of its measurement. For example, in cardiology, BSA, which incorporates both height and BM, is routinely used to scale for left ventricular mass (8, 11, 25). Despite the fact that BSA seems appropriate, its use has been criticized on both theoretical (14) and mathematical grounds (32).

George et al. (13) have indicated that the best scaling variable for cardiac dimensions would be one that represents the most metabolically active tissues in the body, i.e., muscle or LBM. Although easily and accurately measured in exercise...
physiology, the use of BM to normalize physiological function [e.g., maximal oxygen consumption (V\O_2\max), CO, etc.] will often be invalid, as the proportion of muscle mass to total BM will not be constant across different populations of subjects (13). It has been suggested that LBM (6, 13, 26, 27) and the allometric model (13, 23) represent the most appropriate normalization for cardiac structures and functions. Scaling for LBM will allow the independent isolation of a body dimension that relates to high levels of metabolic activity and blood flow (33). Given that CO and CPO are known to respond to the body’s demands for oxygen, it would seem theoretically sensible to scale both to LBM. However, establishing that LBM is the best dimension will depend on the accuracy with which it is measured. The emergence of dual-energy X-ray absorptiometry (DXA) provides a potentially accurate method of determining LBM, as well as the proportions of adipose tissue and bone (16).

To date, the relationship between CPO, body size, and composition has not been investigated. If measurements of CPO are influenced by body dimensions, then the most appropriate scaling variable and modeling technique need to be identified before comparing and interpreting data between inter- and intragroups of subjects or patients. This study illustrates the impact and importance of normalizing data for differences in body composition before interpreting measurements of overall cardiac function (i.e., CPO) between different populations of subjects or patients.

**METHODS**

**Subjects**

Healthy subjects were recruited from the Merseyside community through the use of local media. Eighty-eight untrained healthy men and 103 women ranging from 20–70 yr of age were enrolled. All subjects underwent a medical history/lifestyle questionnaire and a treadmill ECG-exercise stress test. Subjects with any history of coronary heart disease, hypertension (blood pressure >160/90 mmHg), diabetes, or neuromuscular problems or taking prescribed medications known to affect cardiovascular or respiratory function were excluded. To eliminate possible confounding influences due to obesity, only subjects with a body mass index <35 kg/m^2^ were included in the study. The study was approved by the Liverpool John Moores University Ethics Committee, and all subjects gave their written informed consent.

**Power Analysis**

The authors chose a prior power of 90% and a correlation coefficient of 0.3 as being of potential clinical relevance. This required a sample size of ~105 subjects. This target was readily met, and indeed surpassed, with 191 subjects eventually being studied, and thereby promoting adequate statistical power.

**Protocol for Measuring CPO**

Before attending the laboratory for exercise testing, all subjects refrained from consuming food, alcohol, or caffeine for 3 h and from undertaking any exercise (24 h). Measurements of CPO involved two stages separated by a 24-h recovery period.

**Stage 1: aerobic capacity (V\O_2\max).** This stage involved an incremental exercise-stress test on a treadmill to uncover any asymptomatic cardiovascular problems and the V\O_2\max of each subject. For this, we used a ramping protocol, consisting of a preliminary 2-min warm-up stage at 2.2 km/h with no incline, followed by increments in both the speed and gradient of the treadmill at 1-min intervals until reaching volitional exhaustion. The V\O_2\max achieved by the subjects will be subsequently used in stage 2 of the protocol to ensure that they were exercising at their physiological limit when CPO\max was measured.

A 12-lead ECG was monitored throughout, and the subject’s heart rate (HR) was obtained from this. Blood pressure (BP) was measured at rest and at 2-min intervals up to, and including, maximal exercise by manual auscultation and sphygmomanometry. Breath-by-breath analysis of oxygen consumption (\V\O_2\), carbon dioxide production (\V\CO_2\), end-tidal partial pressure of carbon dioxide, tidal ventilation, and respiratory rate were all measured using the Medgraphics CPX-D system (Medgraphics, St. Paul, MN). V\O_2\max was considered to have been reached when a minimum of two of the three following criteria were satisfied: a plateau in V\O_2 despite further increases in workload, a HR > 95% of the age-predicted maximal value (220 - age), and a respiratory exchange ratio > 1.10.

**Stage 2: measurements of CPO_{rest} and CPO_{max}.** Resting CPO involved measuring both BP and CO in a seated position. CO at rest was measured using the CO\_2 rebreathing technique of Collier (2) and calculated using the indirect Fick method. The concentrations of gases in the mixture that were rebreathed were 10% CO\_2-35% O\_2-55% N\_2, and the volume was twice that of the subject’s resting tidal volume. Mean CO and MAP were calculated from triplicate measurements, separated by 4 min to allow for CO\_2 washout from the circulation.

All subjects then exercised on the treadmill to 100% of their V\O_2\max. When V\O_2\max, maximal \V\CO_2, and maximal HR were reached (as established in stage 1), maximal BP was measured and a CO\_2 rebreathing maneuver was performed to determine maximal CO. This time, the Defares (9) method and gas concentrations of 5% CO\_2-35% O\_2-60% N\_2 were employed.

**Calculations.** CPO (in W) was calculated from the averaged CO (l/min) and MAP (mmHg), i.e., by using

\[
CPO = (CO \times MAP) \times K
\]

where K is the conversion factor (2.22 \times 10^{-3}) into watts (4). MAP was calculated as

\[
MAP = DBP + 0.412(SBP - DBP)
\]

where SBP and DBP are systolic and diastolic blood pressures, respectively, measured in millimeters Hg (21).

**Body composition.** DXA (Hologic, Horizon Park, Levenssteenweg, Belgium) was used to provide whole body, bone, adipose tissue, and lean body mass.

**Scaling of physiological measurements.** The relationship between various variable components of body size (e.g., total mass, surface area, lean mass) and CPO were examined using Pearson’s correlation.

**Examination of Scaling Models**

**RES model.** For the RES model, the physiological measurements (y) were normalized using the equation (23)

\[
y = a + bx + \varepsilon
\]

where b represents the slope of the line of best fit, a the intercept on the y-axis, and \varepsilon the additive residual error term.

**Allometric model.** The allometric equation can be represented as

\[
y = ax^b\varepsilon, \text{where } y \text{ represents the physiological variable (e.g., CPO}_{max}, x \text{ represents the body size variable (e.g., BM), } a \text{ represents the proportionality coefficient or constant multiplier, } b \text{ is the power function exponent, and } \varepsilon \text{ represents the multiplicative residual error term (23). The equation can be linearized by taking natural logarithms of both sides, giving}

\[
\ln y = \ln a + b \ln x + \ln \varepsilon
\]

To evaluate whether a single allometric scaling model would apply to both genders, we sought to investigate whether a size-independent term, yax^b\varepsilon, exists and is applicable to either gender. With this scaling
Gender-related differences in cardiac variables

Table 2. Gender-related differences in cardiac variables at rest and maximal exercise

<table>
<thead>
<tr>
<th>Variables</th>
<th>Men (n = 88)</th>
<th>Women (n = 103)</th>
<th>Difference in Women Relative to Men, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>COrest, l/min</td>
<td>4.8±0.1</td>
<td>3.8±0.1†</td>
<td>−21</td>
</tr>
<tr>
<td>COmax, l/min</td>
<td>19.6±0.3</td>
<td>15.1±0.2†</td>
<td>−23</td>
</tr>
<tr>
<td>CPOrest, W</td>
<td>1.0±0.02</td>
<td>0.8±0.02†</td>
<td>−20</td>
</tr>
<tr>
<td>CPOmax, W</td>
<td>5.3±0.09</td>
<td>4.0±0.06†</td>
<td>−25</td>
</tr>
<tr>
<td>CR, W</td>
<td>4.3±0.08</td>
<td>3.2±0.06†</td>
<td>−26</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 191. COrest and COmax, cardiac output at rest and at maximal exercise; CPOrest and CPOmax, cardiac power output at rest and at maximal exercise; CR, cardiac reserve. *P < 0.05, †P < 0.001, significant differences between men and women.

Table 3. Direct comparisons of the correlation coefficients for all relationships between cardiac power and body size

<table>
<thead>
<tr>
<th></th>
<th>CPOrest</th>
<th>CPOmax</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>0.43*</td>
<td>0.59*</td>
<td>0.55*</td>
</tr>
<tr>
<td>BSA</td>
<td>0.46*</td>
<td>0.65*</td>
<td>0.61*</td>
</tr>
<tr>
<td>LBM</td>
<td>0.52*</td>
<td>0.75*</td>
<td>0.71*</td>
</tr>
</tbody>
</table>

Male and female data were pooled, with n = 191. Significant Pearson’s correlations: *P < 0.01.

that was not constant throughout the range of values. In addition, the ability of the linear or allometric model to provide a size-independent mass exponent was evaluated by correlating the scaled CPO values, obtained from the RES or allometric model, with the variables of body size. This correlation would not be significantly different from zero if the influence of body size has been fully accounted for (1).

Information regarding the most appropriate body dimension was obtained by comparing the model $R^2$ (i.e., the ratio of the variance due to treatment and the total variance) and root-mean-squares-error from separate regression models, together with the relative width of the confidence intervals surrounding the mean size exponents.

All the above analyses were carried out using the SPSS 11.0 for Windows statistical package (SPSS, Chicago, IL).

RESULTS

Anthropometric Details

Significant ($P < 0.05$) gender-related differences in body composition were found (Table 1). On average, men were 7% taller and possessed larger BM, LBM, and BSA by 18%, 28%, and 15%, respectively, compared with women (Table 1).

Cardiovascular Differences Between Men and Women

The sedentary men also possessed significantly greater hemodynamic values, both at rest and at maximal exercise, than their female counterparts (Table 2). The largest differences between men and women were found in maximal cardiac function with men possessing significantly ($P < 0.001$) 25% and 26% greater CPOmax and CR values, respectively, than the sedentary women.

Relationship Between Body Size and CPO

Pearson’s correlations ($r$) were significant ($P < 0.01$) for all variables of CPO and body dimensions (Table 3). However, LBM presented the strongest correlation with CPOrest ($r = 0.52$), CPOmax ($r = 0.75$), and CR ($r = 0.71$) compared with other body dimensions.

Scaling Model

RES model. Significant ($P < 0.05$) correlations were obtained between the absolute residuals and the independent variables of the log-linear relationships (28) between variables of body size. That is, there is no significant gender difference in the slopes of the log-linear relationships between men and women.

Clearly, this is possible only if similar regression slopes were compared separately according to gender but can be compared together. For example:

$$CPI_{\text{rest}} = \frac{CPO_{\text{rest}}}{BM^a}$$

where CPIrest represents CPOrest scaled allometrically to body mass (BMa). Direct gender comparisons could then be made with respect to appropriately scaled CPO values, to evaluate the reduction in between-gender variability due to each scaling model or scaling variable of body size.

All exponents were calculated as means, with 95% confidence intervals (CI). Statistical significance of the coefficients was tested at an α-level of 0.05.

Regression Diagnostics

To examine the data for heteroscedasticity and identify which scaling model, RES or allometric, provided the best statistical fit for these data, residuals (predicted − observed CPO) from the linear and log-linear models were converted to absolute values and then correlated with the predictor variable (e.g., BM, LBM, or BSA). A significant correlation indicated heteroscedasticity, with error variance obtained by introducing increment terms to the constants, $\Delta a$ to $a$ and $\Delta b$ to $b$, giving $y = (a + \Delta a)x^{b+\Delta b}$. For the size-independent term, $y/a^b$, to be applicable irrespective of gender, then the delta term, $\Delta b$, will need to be negligible and the difference between $b$ and $(b + \Delta b)$ will need to be statistically not significant.

The scaled version of CPO was achieved by dividing the physiological variable by body size raised to the power function ratio (as determined above). For example

$$CPI_{\text{rest}} = \frac{CPO_{\text{rest}}}{BM^a}$$

was the relationship between the absolute residuals and the independent variables.
variables for the relationships analyzed between CPOmax, CR, and all variables of body size by the RES model (Table 4). These indicated that the error around the regression line was not constant. Therefore, the assumption of homoscedasticity was not satisfied. Instead, the error around the regression line increased as the independent variable increased (i.e., homoscedasticity). However, no such significant correlations were identified between the absolute residuals and the independent variables, together with the allometric model residuals, were revealed that the log-transformed dependent and independent variables for resting CPO (Table 4).

**Alloometric model.** Kolmogorov-Smirnov one-sample test revealed that the log-transformed dependent and independent variables, together with the allometric model residuals, were normally distributed. In addition, no significant correlations were identified between the absolute residuals and the predictor variable (e.g., natural logs of LBM, BM, or BSA) (Table 5), implying that there was homoscedasticity. The absence of correlation between residuals from the log-linear analysis of covariance confirmed the appropriate fit provided by the allometric model.

Analyses on the effects of gender on the relationships between body size and CPO showed that the slopes of the regression lines for male and female values were quantitatively similar. The exponents, b, for body size factors between the male and female subjects were not statistically significantly different (all P > 0.05), and the Δb values were negligible. This allows common exponents to be calculated for both genders and thus direct comparisons irrespective of gender can be made (Table 6).

To check whether the allometric model completely provided size-independent values, Pearson’s correlations were performed between the power functions and the various variables of body size. No significant correlations were found, indicating that the allometric model produced size-independent values of CPO (Table 7). In addition, examination of the model residuals revealed no size-related distribution pattern, indicating that the log-linear model was correctly specified, with the residuals randomly scattered around zero, thus confirming the appropriate fit provided by the allometric model.

**Scaling variables.** As the allometric model successfully provided dimensionless size exponents, theoretically all body dimensions could be used to scale measurements of CPO. However, when examining the strength of the b exponents, scaling to LBMb gave the highest R² and lowest root-mean-squares error. Also, the width of the CIs was relatively narrow for CPO values measured at rest and at maximal exercise. By comparison, values were less precise when using either BMb or BSBa (Table 6).

The CPO data derived from men and women were reanalyzed by scaling to either BMb, BSBa, or LBMb, with the aim of providing data that were independent of body size (Table 8). Highly significant (P < 0.001) gender-related differences (22–25%) remained for all values of CPO, scaled for BMb or BSBa (Table 8). The least differences were found when CPOs were normalized with LBMb, although the CPOrest and CPOmax scaled to LBMb showed 7% difference, with men still showing higher values than women, which remained significant (P < 0.05). In contrast, only when values of CR were scaled to LBMb were the gender differences nonsignificant (Table 8).

**DISCUSSION**

More often than not, when cardiac function is assessed in exercise physiology or medical research, indexes of either blood flow (e.g., ejection fraction or cardiac output) or pressure (e.g., wedge pressure), but not both, are measured. As a hydraulic pump, the heart generates both blood pressure and

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**Table 5. Correlation coefficients of the absolute residuals from the allometric model and the independent variables**

<table>
<thead>
<tr>
<th></th>
<th>CPOrest</th>
<th>CPOmax</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln BM</td>
<td>−0.09</td>
<td>0.10</td>
<td>−0.09</td>
</tr>
<tr>
<td>ln BSA</td>
<td>−0.06</td>
<td>−0.07</td>
<td>−0.08</td>
</tr>
<tr>
<td>ln LBM</td>
<td>−0.09</td>
<td>−0.03</td>
<td>−0.02</td>
</tr>
</tbody>
</table>

The independent variables are ln BM, ln BSA, and ln LBM; n = 191.

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**Table 6. Exponents of body dimension derived from log-linear allometric models**

<table>
<thead>
<tr>
<th>Size Variable, x</th>
<th>b Exponent (95% CI)</th>
<th>ln a</th>
<th>Model R²</th>
<th>Model RMSE</th>
<th>P Value for Size Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Female</td>
<td>Male</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPOrest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BM</td>
<td>0.33 (0.11–0.54)</td>
<td>0.201</td>
<td>0.239</td>
<td>0.278</td>
<td>0.043</td>
</tr>
<tr>
<td>BSA</td>
<td>0.60 (0.20–1.01)</td>
<td>0.566</td>
<td>0.664</td>
<td>0.277</td>
<td>0.043</td>
</tr>
<tr>
<td>LBM</td>
<td>0.47 (0.22–0.73)</td>
<td>0.143</td>
<td>0.134</td>
<td>0.275</td>
<td>0.040</td>
</tr>
<tr>
<td>CPOmax</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BM</td>
<td>0.41 (0.25–0.57)</td>
<td>0.714</td>
<td>0.872</td>
<td>0.504</td>
<td>0.023</td>
</tr>
<tr>
<td>BSA</td>
<td>0.81 (0.52–1.10)</td>
<td>2.532</td>
<td>3.013</td>
<td>0.513</td>
<td>0.022</td>
</tr>
<tr>
<td>LBM</td>
<td>0.71 (0.53–0.89)</td>
<td>0.272</td>
<td>0.285</td>
<td>0.567</td>
<td>0.020</td>
</tr>
<tr>
<td>CR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BM</td>
<td>0.44 (0.25–0.62)</td>
<td>0.505</td>
<td>0.620</td>
<td>0.435</td>
<td>0.032</td>
</tr>
<tr>
<td>BSA</td>
<td>0.87 (0.53–1.22)</td>
<td>1.946</td>
<td>2.319</td>
<td>0.445</td>
<td>0.032</td>
</tr>
<tr>
<td>LBM</td>
<td>0.79 (0.57–1.00)</td>
<td>0.164</td>
<td>0.170</td>
<td>0.501</td>
<td>0.030</td>
</tr>
</tbody>
</table>

RMSE, root-mean-squares error; ln a, point estimate of constant term. 95% confidence intervals (CI) are shown in parentheses.
flow, and as such, both components need to be determined if a comprehensive measure of overall cardiac function is to be obtained (4, 29, 35). This is one advantage derived by measuring CPO. Also, because CPO is measured both at rest and during maximal exercise, the functional reserve capacity of the heart can be determined by subtraction of these two values.

This is the first study that has examined the relationship between CPO and various body dimensions and composition. It is clear from the strong positive correlations (Table 2) that body size affects both peak and resting values of CPO. These novel findings highlight the importance of normalizing data appropriately before making comparisons between different populations of individuals or patients.

For data on CPO to become independent of body size, the correct scaling technique must be selected and applied. Frequently when attempting to normalize various physiological variables for differences in body size, many investigators routinely use the linear regression model. The assumption that this model adequately corrects for differences in body size is not always true. Although the use of the allometric scaling model for normalizing cardiac dimensions and functions has become more popular within recent years, its advantages have not yet become widely appreciated. In this study we have shown that the allometric model is superior to the RES model, as only the former fully accounts for differences in body size when comparing data on CPO between men and women (Table 7). In contrast, significant correlations still remained when using the RES model. Hence, it is highly likely that the use of the RES model for scaling CPO data will lead to less precise and possibly erroneous conclusions (e.g., with smaller individuals receiving an arithmetic advantage over larger ones). By way of example, if a man and woman possess the same CPOmax (e.g., 5 W) and BM (e.g., 60 kg), but the man has 10% body fat (LBM = 63 kg) and the woman 25% body fat (LBM = 52.5 kg), the RES model results in a gender difference of 25% in CPOmax. In contrast, when scaled allometrically to the power of 0.71, the difference in CPOmax is only 14%. That is, the RES model produces an error of 11% compared with the allometric model for scaling CPOmax and when comparing these values in men and women. Therefore, for data on CPO to be independent of body size, the correct scaling technique must be selected and applied.

In addition to the scaling model, it is important to establish the body size variable that is the most relevant to normalize CPO. Although for convenience in exercise physiology BM is routinely used as a variable, the contribution that LBM makes toward BM will vary between individuals and between different populations. BM is therefore likely to be less satisfactory as a scaling factor than LBM (13). In contrast, in a clinical setting BSA continues to be the choice of scaling variable for normalizing cardiac structures and function. Its popularity, however, does not necessarily mean that it represents the best method. Here we have examined BSA along with other body size variables. We have clearly shown that LBM is the main determinant of CPO, whether measured at rest or during exercise. In addition, the statistical evidence highlights that LBM was the best variable of body size to scale CPO. Furthermore, like BM, changes in BSA failed to distinguish between differences in body composition, (e.g., as caused by changes in muscularity or obesity). Hence, it is probably an inappropriate scaling variable, especially in populations where changes in body composition occur. Other authors have shown that BSA is not the best variable for normalizing cardiac variables (34). Thus, scaling CPO to LBM effectively reduced the between-gender variability in CPO and CR in particular (Table 8). However, in the absence of research tools such as DEXA that accurately measure LBM, BM or BSA may be used in a clinical or field setting to generate body size-independent CPO data. These can provide alternatives to scaling to LBM, but the limitations of these approaches should be appreciated and noted. However, in a purely experimental setting, we would strongly encourage the determination of LBM, if possible by DEXA.

We are only aware of one previous study in which the relationship between body size and component aspects of cardiac function was examined using the allometric scaling model. In that study, de Simone et al. (7) examined the relationship between CO and body size. However, CO was only measured using M-mode echocardiography and cubing unidimensional measurements under resting conditions, and not during exercise. With a similar subject population to that used here, de Simone et al. (7) scaled CO at rest for BM to the power of 0.41. They concluded that this normalization of CO was essential to establish the effects of obesity on cardiac function. The value of their $b$ exponent was higher than that calculated here for CPOrest, when scaled to either BM ($b = 0.33$) or LBM ($b = 0.47$).

According to the theory of geometric similarity, CPO should be related to BM (and therefore to LBM) to the power of 0.67 (15). In our study, CPOrest, CPOmax, and CR were scaled against LBM raised to the power 0.67, 0.71, and 0.79, respectively. Although the exponents $b$ for CPOmax and CR differed slightly, the 95% confidence limits suggest that they were not significantly different from 0.67 (Table 6). The exponent 0.67 was also included in the 95% confidence limits for CPOrest. However, unlike maximal exercise, where all relevant body functions are working close to their limits, it is difficult to attain a uniform basal state. Hence more scatter is often found

### Table 8. Gender-related comparisons of normalized cardiac power output

<table>
<thead>
<tr>
<th>Age, yr</th>
<th>Men</th>
<th>Women</th>
<th>Difference in CPOrest Relative to Men, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45.4±1.8</td>
<td>44.3±1.4</td>
<td>-2</td>
</tr>
<tr>
<td>Absolute data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPOrest, W</td>
<td>1.0±0.02</td>
<td>0.8±0.02*</td>
<td>-20</td>
</tr>
<tr>
<td>CPOmax, W</td>
<td>5.3±0.09</td>
<td>4.0±0.06*</td>
<td>-25</td>
</tr>
<tr>
<td>CR, W</td>
<td>4.3±0.08</td>
<td>3.2±0.06*</td>
<td>-26</td>
</tr>
<tr>
<td>CPO Scaled to BM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPOrest, W/kg BM1/3</td>
<td>0.24±0.01</td>
<td>0.21±0.01†</td>
<td>-13</td>
</tr>
<tr>
<td>CPOmax, W/kg BM0.44</td>
<td>0.88±0.01</td>
<td>0.72±0.01†</td>
<td>-18</td>
</tr>
<tr>
<td>CR, W/kg BM0.44</td>
<td>0.63±0.01</td>
<td>0.51±0.01†</td>
<td>-19</td>
</tr>
<tr>
<td>CPO Scaled to BSA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPOrest, W/m2 BSA0.60</td>
<td>0.7±0.01</td>
<td>0.6±0.01†</td>
<td>-14</td>
</tr>
<tr>
<td>CPOmax, W/m2 BSA0.81</td>
<td>3.1±0.05</td>
<td>2.6±0.04†</td>
<td>-16</td>
</tr>
<tr>
<td>CR, W/m2 BSA0.87</td>
<td>2.4±0.04</td>
<td>2.0±0.03†</td>
<td>-17</td>
</tr>
<tr>
<td>CPO Scaled to LBM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPOrest, W/kg LBM0.47</td>
<td>0.15±0.003</td>
<td>0.14±0.003*</td>
<td>-7</td>
</tr>
<tr>
<td>CPOmax, W/kg LBM0.71</td>
<td>0.29±0.004</td>
<td>0.27±0.004*</td>
<td>-7</td>
</tr>
<tr>
<td>CR, W/kg LBM0.79</td>
<td>0.17±0.003</td>
<td>0.17±0.003</td>
<td>0</td>
</tr>
</tbody>
</table>

Data are expressed as means ± SE; $n = 191$. *P < 0.05, †P < 0.001, significant differences between men and women.
in resting measures. Thus it was not surprising that the $b$
exponent for $CPO_{\text{rest}}$ was lower than that for $CPO_{\text{max}}$ or $CR$.
Although we have calculated specific power function ratios for
$CPO$, whether at rest or at maximal exercise, it is important that
further empirical studies determine their own scaling exponents
as by their nature they are specific to the population from
which they are determined.

Although the use of $LBM$ represents an improvement on the
conventional approaches of scaling physiological functions to
$BM$ or $BSA$, it is not perfect because $LBM$ is composed of both
metabolically active (e.g., skeletal and cardiac muscle, etc.)
and less active (e.g., tendons, ligaments, etc.) tissues or organs.
Although under basal conditions, the liver, kidneys, and
gastrointestinal tract possess high metabolic rates (22), during
vigorous exercise the demands of striated muscles predominate.
Therefore, an ideal scaling variable for $CPO$ would be
one that solely takes into account the most metabolically active
tissues under defined physiological conditions (e.g., skeletal
and cardiac muscles during exercise).

The use of $LBM$ is further dependent on the accuracy by
which it can be measured. In this study, DEXA was used as a
precise technique for measuring various elements of body
composition (17–19). Unfortunately, in practical terms, the
scaling of $CPO$ data to $LBM$ may be limited by the availability of
appropriate equipment and hence the accuracy with which
$LBM$ can be measured. Calipers have been used extensively to
measure skinfold thickness, and bioelectrical impedance has
been used to measure adipose mass. However, although more
readily available, these methods possess more inherent errors
and do not measure the body’s bone content.

In conclusion, this study has yielded novel findings that
highlight the fact that $CPO$ is significantly affected by body
size and composition, particularly the amount of metabolically
active lean tissue. If differences in body size, specifically
$LBM$, are not accounted for before data between inter-and
intragroups of subjects or patients are compared and interpreted,
erroneous conclusions are likely to be made. Therefore,
whenever practically possible, measurements of $CPO$ should
be scaled for differences in body size, specifically to $LBM$, and
the allometric model of scaling used. However, further re-
search is required to test the applicability of these findings to
diverse samples of the population to establish the normal range
of exponents has been determined for the diverse
populations (i.e., heart failure), then $CPO$ can be scaled allo-
metrically on an individual basis.

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