To weigh or not to weigh: conditions for the estimation of body mass by morphometry

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Abstract: The objective of this study was to define the conditions under which the body mass of polar bears (*Ursus maritimus*) can be estimated by morphometry with acceptable accuracy (high precision and low bias). Morphometric and body mass values from 563 polar bears captured and handled in southern Hudson Bay during 1984–86 and 2000–03 were analyzed to determine the effects of sample size and time on the accuracy of estimated body mass (EBM) and to determine the effect of using EBM versus observed body mass (OBM) to calculate body condition index (BCI) values. When sample size was small ($\leq$25), variation around the difference between OBM and EBM was large. However, precision improved markedly with increasing sample size, stabilizing within approximately 3% for sample sizes $\geq$100. Morphometric–body mass relationships developed for southern Hudson Bay polar bears in the mid-1980s consistently overestimated body masses of bears handled since 2000 by approximately 4%, suggesting relationships within the population had changed over time (increased bias). This was verified by new prediction equations developed for each period that showed the EBM of polar bears captured in 2000–03 is 7–18% less than that for bears captured in the mid-1980s when morphometric values are held constant. Accuracy was reduced when EBM, instead of OBM, was used as a predictor variable for calculation of the BCI. This was caused by both loss of precision and increase in bias as a result of compounding the error associated with the EBM. Although body mass can be estimated accurately by morphometry under specific conditions, we recommend that investigators routinely weigh a proportion of bears captured per field season to ensure and maintain accuracy. The OBM values can be used to both verify the accuracy of EBM values and to calculate BCI values for representative bears.

Key words: accuracy, bias, body condition, estimated body mass, morphometry, observed body mass, Ontario, polar bear, precision, *Ursus maritimus*

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Body mass is an important biological attribute that provides a measure of health in individual animals and, when measured across many animals, insight into the status of populations. However, weighing large animals can be difficult, requiring equipment, staff, and time. Consequently, estimation of body mass through the measurement of form (morphometry) is common practice. Nevertheless, opinions differ regarding the utility of morphometry to estimate body mass. Some advocate that estimation of body mass using morphometric measurements is accurate enough for many population-level studies (Kolenosky et al. 1989, Durner and Amstrup 1996, Derocher and Wiig 2002). Others conclude the accuracy of this method is too low to be reliable (Eason et al. 1996, Cattet et al. 1997, Bassano et al. 2003).

Cattet et al. (1997) assessed the usefulness of morphometry to predict body mass in polar bears and concluded the accuracy of this approach was too low to be useful. This conclusion was based primarily on the finding that 95% prediction intervals were large ($\pm$17% of measured body mass) despite a large sample size ($n = 914$) and use of various combinations of predictor variables for each animal. However, this assessment may have been too limiting because prediction intervals were used instead of confidence intervals. In other words, the analyses focused on estimating the error associated with individual predictions instead of the error associated with

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population means. To follow-up this earlier work, we examined the effects of sample size and time on the accuracy of estimating body mass in polar bears of the Southern Hudson Bay population.

Accuracy has 2 components: bias and precision (Snedecor and Cochran 1989). Bias measures whether a statistic is consistently too low or too high, and precision reflects the variation in repeated measurements of the same quantity. We also examine how the estimation of body condition is affected when estimated body mass is used as a predictor variable instead of observed body mass. Our objective in this effort is to clearly define the conditions under which estimated body mass can be used with acceptable accuracy.

Study area and methods

Morphometric, body mass, and age values were extracted from the records of 563 free-ranging polar bears captured and handled along the Hudson Bay coast of Ontario (52°00′–57°00′N and 80°00′–89°00′W) during the summer and fall months of 1984–86 and 2000–03. Body length was measured to the nearest cm as the dorsal straight-line distance from the tip of the nose to the end of the last tail vertebra. Chest or axillary girth was measured to the nearest cm as the circumference around the chest at the axilla. All bears were measured while ventrally recumbent with the back legs extended behind and the front legs forward. Body mass was measured to the nearest 500 g by suspending the bear from a spring-loaded weigh scale (1984–86) or an electronic load scale (2000–03) mounted below a tripod. During weighing, bears were placed in a semi-supportive sling and lifted by chain pulley until clear of the ground. Although gut fill has been identified as a potentially important factor affecting body mass (Derocher and Wiig 2002), it is unlikely to have been a significant factor in this study because all bears were captured during summer and fall when food intake is typically low and many bears are fasting.

Body mass for all bears was also estimated using a long standing morphometric–body mass relationship developed for polar bears in southern Hudson Bay by Kolenosky et al. (1989) that is applied to polar bears in this region today (Lunn et al. 2004). Age of bears was determined from counts of cementum growth layers in a vestigial premolar tooth extracted at capture (Calvert and Ramsay 1998). All capture and handling procedures were approved annually by the Animal Care Committee of the Ontario Ministry of Natural Resources.

The effects of sample size and time on differences between observed and estimated body mass values were evaluated by splitting the dataset into 2 groups, one representing 1984–86 ($n = 298$) and the other 2000–03 ($n=265$). Confidence intervals for the difference between observed (OBM) and estimated body mass (EBM) values for subsets within each group, increasing in size by 5 from 5 to the total group size, were estimated from 1500 bootstrap samples drawn from each subset (Davison and Hinkley 1997). Paired t-tests were performed on all bootstrap samples to compare mean values for OBM and EBM (Zar 1996, Steidl and Thomas 2001).

Because the morphometric–body mass relationships developed by Kolenosky et al. (1989) consistently overestimate the body mass of female and male bears captured in 2000–03, it was necessary to develop new models to estimate body mass. For this, the natural log of EBM (kg) was calculated using a multiple linear regression model of the form:

$$\begin{aligned} EBM = {} & \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 Z_1 + \beta_4 Z_2 \\ & + \beta_5 X_1 Z_1 + \beta_6 X_1 Z_2 + \beta_7 X_2 Z_1 + \beta_8 X_2 Z_2 \quad [1] \end{aligned}$$

where $X_1 =$ the natural log of chest girth (cm), $X_2 =$ the natural log of body length (cm), $Z_1 =$ sex (0 if female, 1 if male), and $Z_2 =$ time (0 if 1984–86, 1 if 2000–03). This model enabled testing whether sex and time were significant factors affecting the relationship between the morphometric measurements and body mass (Kleinbaum and Kupper 1978).

After calculating EBM values for both periods, a power analysis was performed to examine the effect of changing the desired level of precision (±2.5, 5, and 10%) on the sample size required for 95% power with alpha = 0.05 (Steidl and Thomas 2001).

Body condition index (BCI) was calculated using a model of the form:

$$\begin{aligned} BCI = {} & (BM - 3.07 \cdot BL + 10.76) \\ & \div (0.17 + 0.009 \cdot BL) \quad [2] \end{aligned}$$

where BM is the natural log of observed or estimated body mass (kg) and BL is the natural log of body length (cm). This model predicts the standardized residual from the regression of body mass against body length, an index of body condition with a strong association with true body condition in polar bears, defined as the combined mass of fat and skeletal muscle relative to body size (Cattet et al. 2002). The indexing of body condition using standardized residuals has been criticized because the sequence of calculating standardized residuals using simple linear regression, and then comparing the residuals with a t-test or analysis of variance (ANOVA), is an *ad hoc* sequential procedure that results in a number

Table 1. Age, sex, and physical characteristics of polar bears captured in southern Hudson Bay during the summer and fall months of 1984–86 and 2000–03.

Characteristic	1984–86 (*n* = 298)	2000–03 (*n* = 265)
Age, years (SD)	6 (5.5)	6 (6.2)
Range	0.8–22	0.8–25
Number by sex and age class[a]		
subadult females (<5 yrs)	82	83
adult females (≥5 yrs)	61	74
subadult males (<5 yrs)	87	70
adult males (≥5 yrs)	68	38
Observed body mass, kg (SD)	287.0 (153.00)	213.5 (122.08)
Range	55.0–654.0	50.5–613.0
Straight line body length, cm (SD)	191 (39.1)	183 (35.6)
Range	115–256	116–254
Chest girth, cm (SD)	135 (30.7)	123 (28.4)
Range	78–201	70–199

[a]Bears ≥5 yrs were classified as adults according to Lunn et al. (1997).

of statistical errors such as overestimated degrees of freedom and incorrect regression coefficient. (Garcia-Berthou 2001). These errors are avoided, however, if body mass is simply compared by analysis of covariance (ANCOVA) with body length used as a covariate. Given the statistical problems of the residual index, it is important to consider BCI values for polar bears not as standardized residuals, but as estimates of standardized residuals calculated from equation [2]. It follows that statistical errors identified by Garcia-Berthou (2001) do not apply in this case because BCI values are not computed as residuals from simple linear regression.

The associations between OBM and EBM, and between BCI values calculated using OBM (BCI_{OBM}) and BCI values calculated using EBM (BCI_{EBM}), were evaluated by simple linear regression and Pearson correlation analysis (Zar 1996). The slopes for each regression line were compared against a slope of 1 (isometry) using a *Z*-test for parallelism, and correlation coefficients were compared for equality (Kleinbaum and Kupper 1978).

Unless indicated otherwise, statistical significance was assigned when the probability (*P*) of Type I error was ≤0.05. All data were analyzed using SPSS® 11.5 for Windows® (SPSS Inc., Chicago, Illinois, USA).

Results

In both periods, the sample of polar bears analyzed broadly represented polar bears by age, sex, body mass, and morphometric measurements (Table 1).

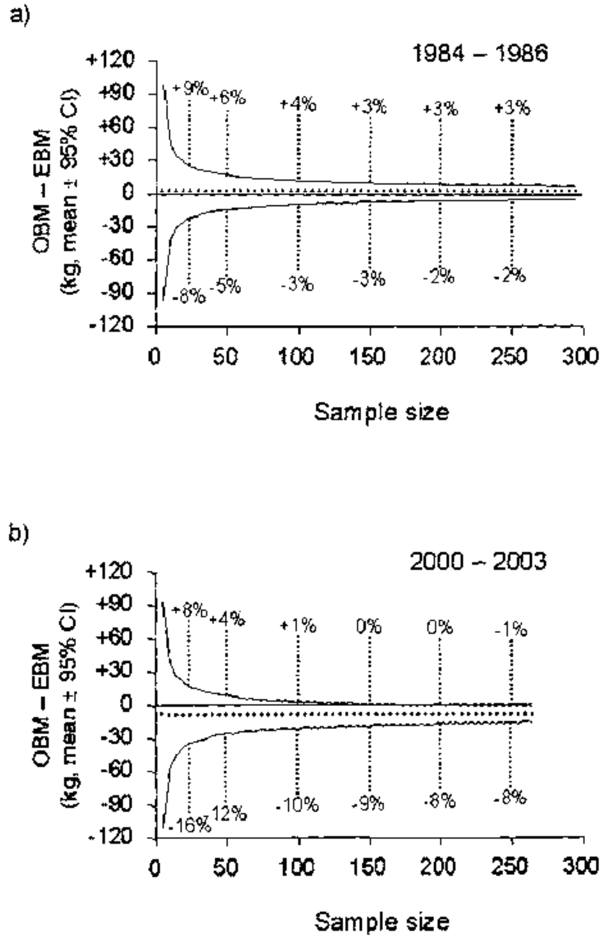

Fig. 1. The effect of sample size on the difference between observed (OBM) and estimated body mass (EBM) for polar bears in the Hudson Bay region of Canada for 1984–86 (a) and 2000–03 (b). Body mass was estimated for bears using morphometric–body mass equations developed by Kolenosky et al. (1989). Mean differences and confidence limits for subsets within each period, increasing in size by 5 from 5 to the total group size, were estimated from 1500 bootstrap samples from each subset.

The precision of estimating body mass was affected most by sample size, whereas bias was affected mostly by time (Fig. 1). In both periods, precision as reflected by the 95% confidence interval for the difference between observed (OBM) and estimated body mass (EBM) was low and variable at sample sizes ≤50, but improved and stabilized by the time sample sizes reached 100. At samples ≥100, the precision was approximately 3% for 1984–86 with the bias toward slightly underestimating OBM (Fig. 1a). In contrast, the precision was lower and the bias considerably larger for 2000–03 with body mass overestimated by approxi-

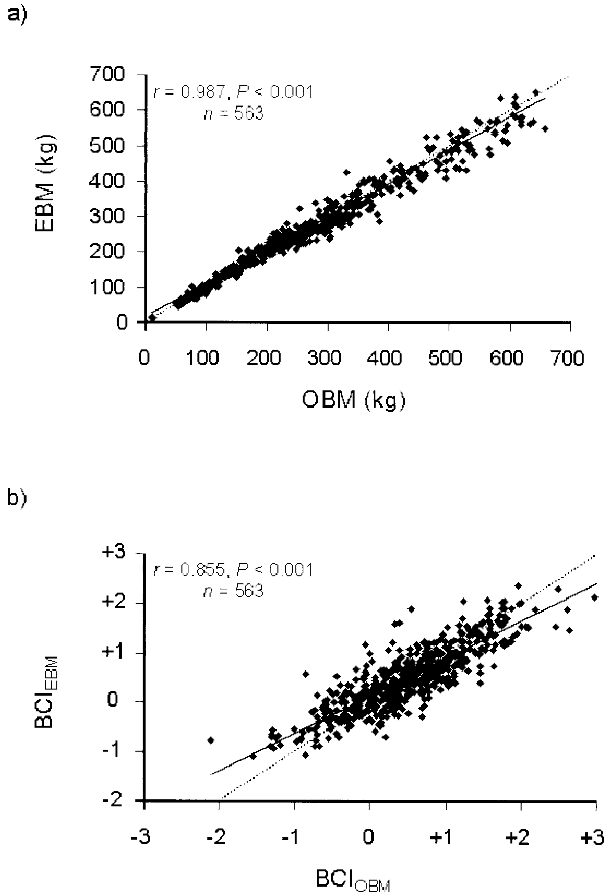

Fig. 2. (a) The association between estimated (EBM) and observed body mass (OBM), and (b) between body condition index (BCI) values calculated using EBM (BCI_{EBM}) and BCI values calculated using OBM (BCI_{OBM}) for polar bears in the Hudson Bay region of Canada for 1984–86 and 2000–03. BCI values were calculated using the model developed by Cattet et al. (2002). Lines presented are the line of isometry (······) and the best-fitting line determined by simple linear regression (——).

mately 4% (Fig. 1b). The difference between OBM and EBM in the latter period was significant at sample sizes $\geq$125 (paired *t*-tests at sample size = 125, mean $t = 2.68$; 1499 df; mean $P = 0.047$).

Because the estimates of body mass differed in precision and bias between the periods, new models for estimating body mass were calculated as:

$$\text{For 1984–86: } \quad \text{EBM} = e^{-9.03} \times \text{body length}^{1.29} \times \text{chest girth}^{1.60}, \quad R^2 = 0.987, \quad n = 298 \qquad [3]$$

$$\text{For 2000–03: } \quad \text{EBM} = e^{-9.04} \times \text{body length}^{1.57} \times \text{chest girth}^{1.27}, \quad R^2 = 0.981, \quad n = 265 \qquad [4]$$

where EBM is in kg, *e* is the base of the natural logarithm, and body length and chest girth are in cm. A single model for all bears in both periods was not possible because time affected both body length ($F = 7.16$; 1, 562 df; $P = 0.008$) and axillary girth ($F = 11.35$; 1, 562 df; $P = 0.001$). However, neither morphometric measurement was affected by sex of bear (body length: $F = 0.34$; 1, 562 df; $P = 0.56$; chest girth: $F = 0.47$; 1, 562 df; $P = 0.49$).

A power analysis of the difference between OBM and EBM for the 563 bears, where EBM was calculated using equations [3] and [4], indicated minimum samples sizes of 172, 45, and 13 were required to ensure no more than 2.5, 5, and 10% difference, respectively, between OBM and EBM at 95% power.

To examine how the estimation of body condition is affected when EBM, instead of OBM, is used as a predictor variable, we calculated new EBM values for all bears using equations [3] and [4] and calculated body condition index (BCI) values using EBM (BCI_{EBM}) and OBM (BCI_{OBM}). Regression of EBM against OBM provided a slope of 0.969 that was less than isometry ($Z = 4.73$, 561 df, $P < 0.001$; Fig. 2a). Similarly, regression of BCI_{EBM} against BCI_{OBM} provided a slope of 0.738, which was less than isometry ($Z = 13.85$, 561 df, $P < 0.001$; Fig. 2b). However, comparison between these slopes indicated that disparity from isometry was greater for the regression of BCI_{EBM} against BCI_{OBM} than for the regression of EBM against OBM ($Z = 11.51$, 561 df, $P < 0.001$). Further, a comparison of correlation coefficients indicated the association between BCI_{EBM} and BCI_{OBM} was not as strong as that between EBM and OBM (Fig. 2; $Z = 20.74$, 1120 df, $P < 0.001$).

Discussion

The results of this study suggest morphometric measurements can be used to estimate body mass in polar bears with acceptable accuracy under the following conditions: (1) the sample size within the unit of comparison should be sufficiently large, and (2) the morphometric–body mass prediction equation must be time-specific. Further, researchers should be aware that the use of estimated body mass (EBM), instead of observed body mass (OBM), as a predictor variable for the calculation of body condition will diminish accuracy considerably. The following discussion describes these conditions in more detail.

Sample size affected the accuracy of estimating body mass largely through its influence on precision. When the sample size for the unit of comparison (population, cohort, or sex–age class) was small, the variation around the difference between OBM and EBM was large. However, as the sample size increased, the precision improved markedly and stabilized around 3% for sample sizes $\geq$100, which should be acceptable accuracy for most studies. It is difficult to recommend a minimum sample size for acceptable accuracy because "acceptable" will vary according to study needs. For example, if the need is to detect differences in body mass as small as 2.5% among groups, the minimum sample size required for 95% power is 172 bears. Conversely, if a level of detection of 5% or greater is sufficient, a minimum sample of 45 bears is required for similar power.

Time affected the accuracy of estimating body mass largely through its influence on bias. We found that the morphometric–body mass relationships developed by Kolenosky et al. (1989) for polar bears captured in the mid-1980s overestimated the body mass of polar bears captured from the same population from 2000–03 by approximately 4%. Further, comparison of estimated body mass values between the periods, calculated using equations [3] and [4], showed that the EBM for polar bears captured in 2000–03 was significantly less (7–18% less) than that for bears captured in the mid-1980s, when values for chest girth and body length are held constant. It would appear these relationships have changed with time and, although the importance of using population-specific equations has been emphasized (Swenson et al. 1987, Durner and Amstrup 1996), this is the first study to our knowledge to show that morphometric–body mass equations must also be time-specific. Accordingly, when estimating body mass in a population year after year, comparisons should be made between OBM and EBM values from a representative sample of bears every few years to ensure that bias has not changed substantially and, if it has, to modify the existing morphometric–body mass equation.

Accuracy was reduced considerably when EBM, instead of OBM, was used as a predictor variable for calculating body condition index (Cattet et al. 2002). The loss of accuracy was caused by both loss of precision and increase in bias relative to that associated with the EBM. In general, the use of EBM as a predictor variable in the calculation of body condition indices will result in the compounding of error and a consequent reduction in accuracy. This finding has direct implications for ongoing research on polar bears in southern Hudson Bay, where long-term monitoring of body condition has become a high priority amid growing concern that climatic warming may cause a gradual decline in the body condition of polar bears inhabiting Hudson Bay (Stirling et al. 1999). It suggests that some proportion of the bears handled each year should be weighed to reliably monitor body condition over time.

Management implications

The estimation of body mass using morphometric measurements has acceptable accuracy (high precision and low bias) for population-level studies of polar bears provided three conditions are met. First, the sample size should be sufficiently large to ensure moderate to high precision. Although the required sample size will vary according to study needs, a minimum of 172 bears is required to detect differences in body mass as small as 2.5%, and at least 45 bears for a level of detection of 5% or greater, at 95% power. Second, morphometric–body mass relationships must be validated by comparing observed and estimated body mass values periodically (e.g., every few years) to ensure that bias has not changed substantially and, if it has, to modify the existing morphometric–body mass equation. Third, estimated body mass should not be used as a predictor variable to calculate indices of body condition because the error associated with estimated body mass will be compounded and the accuracy of the body condition index will be reduced considerably. Although these conditions were determined from analysis of a single population of polar bears, we believe they are broadly applicable to large mammals in general for which morphometric measurements are often used to estimate body mass.

To balance the relative ease of estimating body mass using morphometric measurements with problems that may arise with accuracy, we recommend investigators handling large numbers of polar bears on a regular basis use morphometry to estimate body mass for all bears handled, but also weigh a representative proportion of the total number of bears handled. The availability of observed and estimated body mass values from the same bears will allow routine assessment of the accuracy of mass estimation and enable reliable monitoring of body condition.

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