A Body-Condition Index for Ursids

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A body-condition index for ursids

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Abstract: In this investigation a body-condition index (BCI) was developed for polar bears (*Ursus maritimus*), black bears (*Ursus americanus*), and grizzly bears (*Ursus arctos*), based on residuals from the regression of total body mass against a linear measure of size, straight-line body length (SLBL). Transformation of mass–length data from 1198 polar bears, 595 black bears, and 126 grizzly bears to natural logarithms resulted in a linear relationship between mass and length. However, the relationship in polar bears differed from that in black and grizzly bears. SLBL had a close positive relationship with skeletal (bone) mass in polar bears (n = 31) and black bears (n = 33), validating the use of SLBL as an accurate index of body size. There was no correlation between SLBL and BCI for polar bears (r = 0.005, p = 0.87, n = 1198) or for black bears and grizzly bears (r = 0.04, p = 0.30, n = 721), indicating that the BCI was independent of body size. The BCI had a close positive relationship with true body condition, measured as the standardized residual of the combined mass of fat and skeletal muscle against SLBL, in polar and black bears that were dissected to determine individual tissue masses. The BCI also had a close positive relationship with the standardized residual of fat mass against SLBL. Estimation of BCI values for polar bears, or for black bears and grizzly bears, is facilitated by prediction equations that require measurement of total body mass and SLBL for individual animals.

Résumé : Cette recherche nous a permis de développer un coefficient d'embonpoint (BCI) pour l'ours blanc (*Ursus maritimus*), l'ours noir (*Ursus americanus*) et l'ours brun (*Ursus arctos*) basé sur les résidus de la régression de la masse totale en fonction d'une mesure linéaire de la taille, la longueur du corps mesurée en ligne droite (SLBL). La transformation des données masse–longueur obtenues chez 1198 ours blancs, 595 ours noirs et 126 ours bruns en logarithmes naturels a donné lieu à une relation linéaire entre la masse et la longueur. Chez l'ours blanc cependant, cette relation s'est avérée différente de celle des deux autres espèces. La longueur du corps mesurée en ligne droite est en relation positive étroite avec la masse squelettique (osseuse) chez l'ours blanc (n = 31) et chez l'ours noir (n = 33), ce qui justifie l'utilisation de SLBL comme mesure juste de la taille. Il n'y a pas de corrélation entre la longueur SLBL et le coefficient BCI ni chez l'ours blanc (r = 0,005, p = 0,87, n = 1198), ni chez les ours noir ou brun (r = 0,04, p = 0,30, n = 721), ce qui indique que le coefficient est indépendant de la taille du corps. Le coefficient BCI est en corrélation positive étroite avec la condition physique réelle définie comme le résidu standardisé de la régression entre les masses combinées de gras et de muscle squelettique et la longueur SLBL chez des ours blancs et des ours noirs qui ont été disséqués pour permettre de mesurer la masse des tissus. Il y aussi une forte corrélation entre le coefficient BCI et le résidu standardisé de la régression entre la masse de graisse et SLBL. L'estimation des coefficients BCI pour les trois espèces est rendue plus facile par des équations prédictives qui nécessitent la mesure de la masse totale du corps et de la longueur SLBL des individus.

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Introduction

Body condition is an important determinant of an individual animal's health. Techniques for assessing body condition among many animals are used to monitor long-term trends in the fluctuation of food availability in a given habitat (Thomas et al. 1976; Costa et al. 1989; Hellgren et al. 1993; Stirling et al. 1999) and address questions of animal ecology (Messier and Crête 1984; Ryg et al. 1990; Atkinson and Ramsay 1995). They are also used in physiological and biochemical investigations to control for the potentially confounding effect of body condition on other measures (Verrillo et al. 1988; Lewis et al. 1990; Vansant et al. 1991).

Body condition of bears has been assessed using morphometric measurements (Cattet 1990; Farley and Robbins 1994; Stirling et al. 1999), blood analyses (Schroeder 1987; Hellgren et al. 1993; Gau and Case 1999), chemical analyses of the entire carcass (Watts and Hansen 1987), measurement of fat

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in bone marrow and muscles (Cattet 1988; Cattet 1990), bioelectrical impedance (Farley and Robbins 1994; Hilderbrand et al. 1998, 2000), and isotope dilution (Arnould and Ramsay 1994; Farley and Robbins 1994; Atkinson and Ramsay 1995; Atkinson et al. 1996; Hilderbrand et al. 1998, 2000). Although easy to measure, morphometrics are often imprecise because of variation in the measurement of linear dimensions and compounding of the resulting error by prediction equations (Cattet 1990; Eason et al. 1996; Cattet et al. 1997). Blood chemistry is affected by many factors aside from body condition and, in general, appears to have little association with quantitative measurements of body composition (Hellgren et al. 1993; Gau and Case 1999). Chemical analyses of the entire carcass and measurement of fat in bone marrow and among muscles are time-consuming techniques that require dead bears and laboratory analysis. In contrast to other techniques, bioelectrical impedance and isotope dilution have been advocated as useful and reliable methods to determine the body composition and condition of living bears (Farley and Robbins 1994; Hilderbrand et al. 1998), but making accurate and repeatable estimates of body composition by bioelectrical-impedance analysis requires considerable training and experience, and isotope dilution is time-consuming and requires laboratory analysis.

Although residuals from the regression of mass against a linear measure of size have been used widely to separate the effects of body condition from the effects of body size in a variety of species (Reist 1985; Krebs and Singleton 1993; Jakob et al. 1996), they have not been used to assess body condition in ursids. Nevertheless, residuals potentially offer a practical and reliable index of true body condition that could be measured easily and used to compare individual bears within species regardless of sex, age, reproductive state, geographical population, or date of capture. In this investigation a body-condition index (BCI) was developed for polar bears (*Ursus maritimus*), black bears (*Ursus americanus*), and grizzly bears (*Ursus arctos*), based on residuals from the regression of mass against a linear measure of size. True body condition was defined as the combined mass of fat and skeletal muscle in an animal relative to its body size. Although fat is often regarded as the only tissue that yields a significant amount of potential energy, skeletal muscle also represents a major source of stored energy, and change in the mass of one tissue is generally paralleled by change in the mass of the other (Ryg et al. 1990; Atkinson et al. 1996).

Materials and methods

Total body mass (TBM) and straight-line body length (SLBL) values were extracted from the records of 1198 captures of free-ranging polar bears that occurred from 1984 to 2001 in Ontario, Manitoba, and the central Canadian Arctic (Cattet et al. 1997). Mass and length values were also extracted from the records of 595 captures of black bears that occurred in Ontario between 1989 and 1998 and 126 captures of grizzly bears that occurred in Alberta between 1974 and 2002. For all captures, regardless of species, TBM was determined by suspending the bear from a spring-loaded weigh scale or an electronic load scale, and SLBL was determined as the straight-line distance from the tip of the nose to the end of the last tail vertebra, using a measuring tape extended above the bear in ventral (sternal) recumbency. The use of any unpublished data was authorized by provincial government wildlife agencies; details are provided in the Acknowledgements.

Mass and length values from all captures were transformed to natural logarithms and the relationship between the ln-transformed variables was described using ordinary least squares linear regression analysis (SPSS® 10.0 for Windows®, SPSS Inc., Chicago, Illinois, U.S.A.). The curvilinear relationship between TBM and SLBL is described as follows:

$$[1]\qquad \mathrm{TBM} = e^{\beta_0} \cdot \mathrm{SLBL}^{\beta_1}$$

where e is the base of the natural logarithm and β_0 and β_1 are the intercept and slope of the fitted line, respectively. Transformation of the mass and length data to their natural logarithms resulted in the following equation:

$$[2]\qquad \ln \mathrm{TBM} = \beta_1 \cdot \ln \mathrm{SLBL} + \beta_0$$

Initially, species-specific regression equations were calculated from subsets of each species' data over a range of SLBL values (110–194 cm) that were shared among the three species. Slopes and intercepts were then compared using large-sample *Z* tests for parallelism and common intercept to determine if the mass and length data for the three species could be pooled for further analysis (Kleinbaum and Kupper 1978). Logarithmic, inverse, quadratic, cubic, power, compound, S-curve, logistic, growth, and exponential regression models were also applied to the transformed data and compared against the least squares linear regression model to verify the assumption that TBM increased linearly with SLBL.

The standardized residuals (Zar 1996) of TBM against SLBL were used as the BCI for bears. To verify that SLBL was a reliable index of body size, least squares linear regression was used to assess the relationship between SLBL and skeletal (bone) mass in polar bears ($n = 31$) and black bears ($n = 33$). To determine if the BCI was independent of body size, correlation analysis was used to measure the strength of association between the BCI and SLBL. To determine if the BCI was related to true body condition (the combined mass of fat and skeletal muscle in an animal relative to its body size), standardized residuals of the combined mass of fat and skeletal muscle against SLBL were calculated for the same sample of polar bears and black bears. Least squares linear regression was then used to assess the relationship between the standardized residuals of true body condition and the BCI. The methods of collecting and dissecting killed polar bears and black bears have been described by Cattet (1990). Similar morphological data from grizzly bears were not available for analysis.

To facilitate estimation of the BCI for individual bears, a prediction equation was developed that is based on the following relationship:

$$[3]\qquad \mathrm{TBM} = e^{(a\mathrm{BCI}+b)} \cdot \mathrm{SLBL}^{(w\mathrm{BCI}+z)}$$

where *a*, *b*, *w*, and *z* are constants determined from simple linear regression of fixed BCI values against respective intercepts (to derive *a* and *b*) and slopes (to derive *w* and *z*). For this, 11 different equations for BCI values fixed at –2.5, –2.0, –1.5, –1.0, –0.5, 0, +0.5, +1.0, +1.5, +2.0, and +2.5 were calculated by ordinary least squares regression analysis

Fig. 1. Relationship between ln-transformed total body mass (TBM) and ln-transformed straight-line body length (SLBL) for 1198 polar bears, *Ursus maritimus* (●), 595 black bears, *Ursus americanus* (○), and 126 grizzly bears, *Ursus arctos* (□). Solid lines indicate the best fitting lines determined by ordinary least squares regression analysis and are described as follows: $\ln TBM = 3.08 \cdot \ln SLBL - 10.81$ ($R^2 = 0.94$, SEE = 0.22) for polar bears and $\ln TBM = 3.21 \cdot \ln SLBL - 11.62$ ($R^2 = 0.91$, SEE = 0.20) for black bears and grizzly bears.

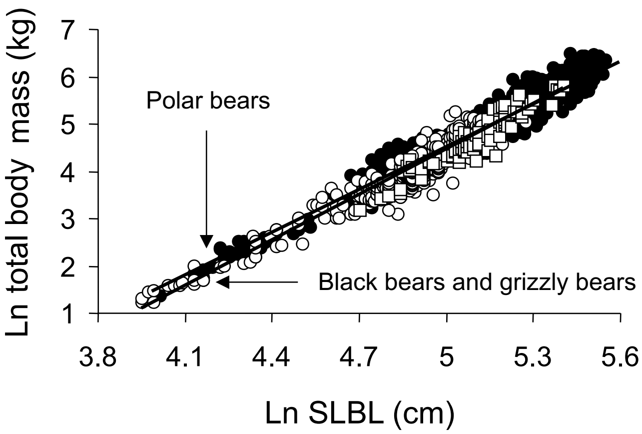
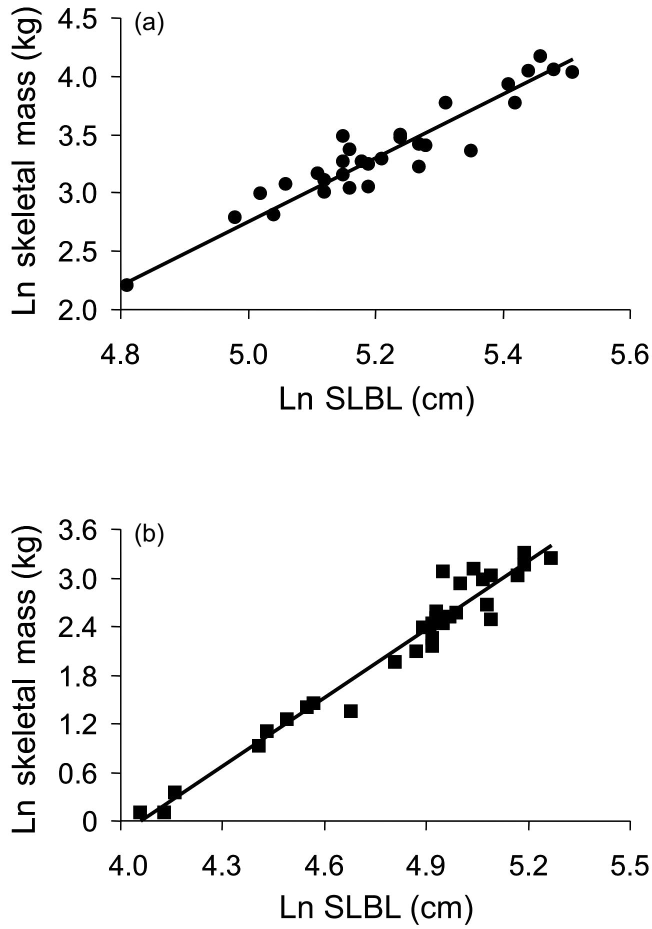


Fig. 2. Relationship between ln-transformed skeletal mass and ln-transformed SLBL for 31 polar bears (*a*) and 33 black bears (*b*). Solid lines indicate the best fitting lines determined by ordinary least squares regression analysis and are described as follows: $\ln(\text{skeletal mass}) = 3.70 \cdot \ln SLBL - 10.75$ ($R^2 = 0.90$, SEE = 0.16) for polar bears and $\ln(\text{skeletal mass}) = 2.81 \cdot \ln SLBL - 11.43$ ($R^2 = 0.95$, SEE = 0.20) for black bears.



of subsets of mass–length data in which BCI values were similar among bears, i.e., BCI values for the –2.5 group were >–2.75 and ≤–2.25, those for the –2.0 group were >–2.25 and ≤–1.75, …, and those for the +2.5 group were >+2.25 and ≤+2.75. Then, from simple linear regression of fixed BCI values against intercepts and slopes, the BCI could be estimated as follows:

$$[4] \qquad BCI = (\ln TBM - z \cdot \ln SLBL - b) \div (a + w \cdot \ln SLBL)$$

Results

The mass–length data obtained from 1919 captures of free-ranging bears were analyzed by a range of curve-estimation regression models, but it was determined that the logarithmic model provided the best fit. Transformation of the mass–length data to natural logarithms resulted in a linear relationship between mass and length (Fig. 1). Further support for the assumption that the relationship between TBM and SLBL was curvilinear was provided by the observation that no systematic trends were apparent in the scatter plots of standardized residuals (BCI values) against SLBL (Fig. 3).

A comparison of intercepts and slopes between species-specific equations calculated over a shared range of SLBL values (110–194 cm) indicated no differences between black bears and grizzly bears ($Z_{\beta_0} = 0.91$ and $Z_{\beta_1} = 0.99$, $p > 0.05$). There were, however, differences between polar bears and black bears ($Z_{\beta_0} = 10.34$ and $Z_{\beta_1} = 10.04$, $p \le 0.001$) and between polar bears and grizzly bears ($Z_{\beta_0} = 4.22$ and $Z_{\beta_1} = 4.40$, $p \le 0.001$). On this basis, the complete mass–length data for black bears and grizzly bears were combined and reanalyzed to give the following relationship:

$$[5] \qquad \ln TBM = 3.21 \cdot \ln SLBL - 11.62,\ R^2 = 0.91,\ \text{standard error of the estimate (SEE)} = 0.20,\ n = 721 \text{ (Fig. 1)}$$

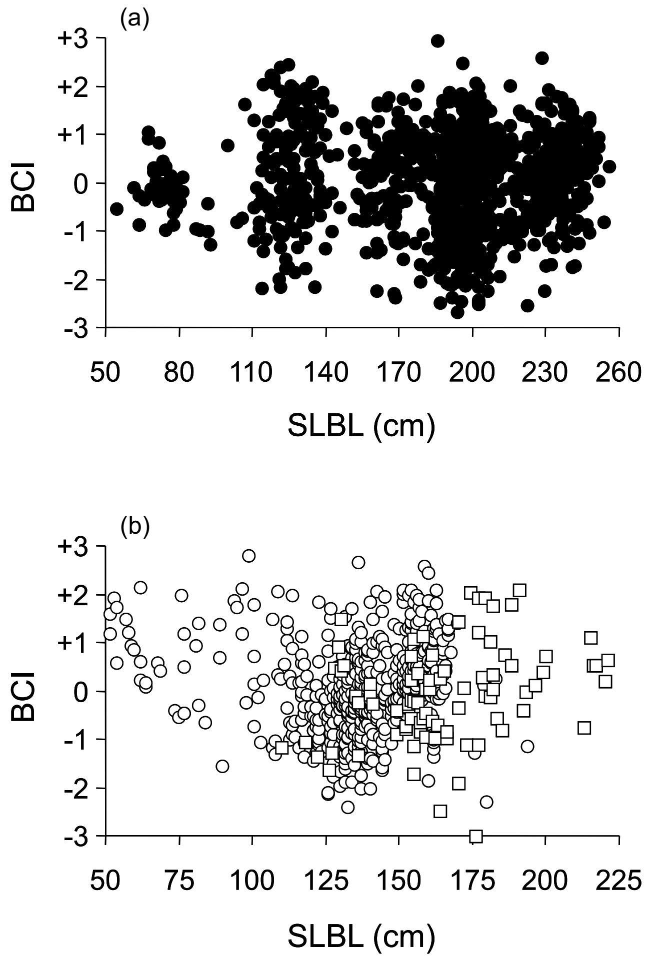
The complete data for polar bears were analyzed to give the following relationship:

$$[6] \qquad \ln TBM = 3.08 \cdot \ln SLBL - 10.81,\ R^2 = 0.94,\ SEE = 0.22,\ n = 1198 \text{ (Fig. 1)}$$

The relationship between SLBL and skeletal mass was highly significant ($p < 0.001$) for polar bears ($n = 31$) and black bears ($n = 33$), supporting the assumption that SLBL could be used as a reliable measure of body size. Linear regression models for the two species are as follows:

$$[7] \qquad \text{Polar bears: } \ln(\text{skeletal mass}) = 3.70 \cdot \ln SLBL - 10.75,\ R^2 = 0.90,\ SEE = 0.16 \text{ (Fig. 2)}$$

Fig. 3. Lack of association between the body condition index (BCI) and SLBL in polar bears (*a*) and in black bears (○) and grizzly bears (□) (*b*). Pearson's correlation values were r = 0.005 (p = 0.87, n = 1198) for polar bears and r = 0.04 (p = 0.30, n = 721) for black bears and grizzly bears.



$$[8]\quad \text{Black bears: } \ln(\text{skeletal mass}) = 2.81 \cdot \ln \text{SLBL} - 11.43,\ R^2 = 0.95,\ \text{SEE} = 0.20 \text{ (Fig. 2)}$$

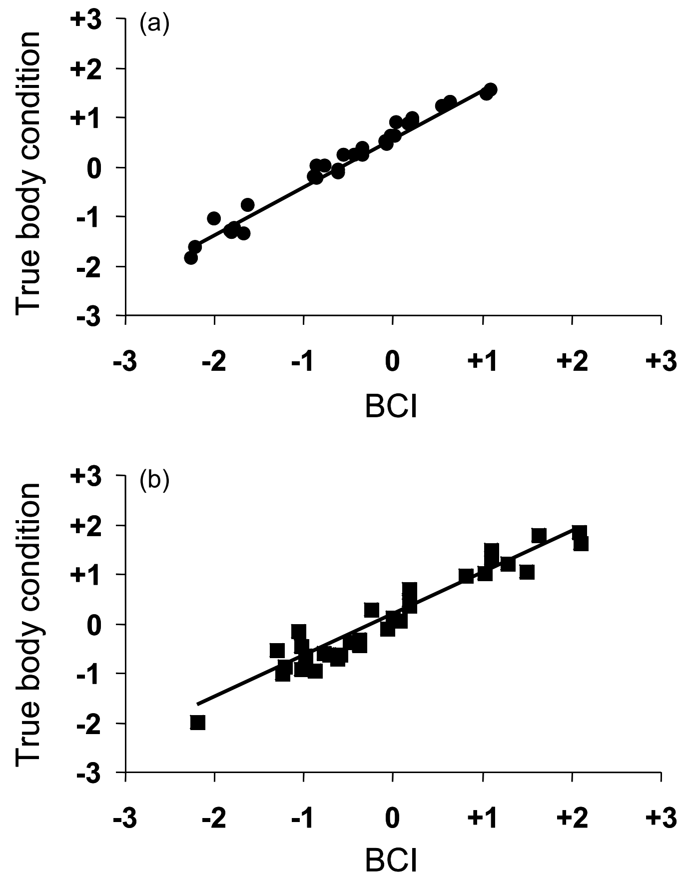
There was no correlation between SLBL and the BCI for polar bears (r = 0.005, p = 0.87, n = 1198) or for black bears and grizzly bears (r = 0.04, p = 0.30, n = 721), indicating that the BCI was independent of body size (Fig. 3).

True body condition of polar bears (n = 31) and black bears (n = 33) was measured as the standardized residual of the combined mass of fat and skeletal muscle (range = 13.8–362.5 kg for polar bears and 2.0–114.4 kg for black bears) against SLBL (range = 122–247 cm for polar bears and 58–194 cm for black bears). The relationship between true body condition and the BCI was highly significant (p < 0.001) in both species. Linear regression models for the two species are as follows:

$$[9]\quad \text{Polar bears: true body condition} = 1.01 \cdot \text{BCI} + 0.63,\ R^2 = 0.98,\ \text{SEE} = 0.15 \text{ (Fig. 4)}$$

$$[10]\quad \text{Black bears: true body condition} = 0.86 \cdot \text{BCI} + 0.17,\ R^2 = 0.93,\ \text{SEE} = 0.28 \text{ (Fig. 4)}$$

Fig. 4. Relationship between true body condition (the standardized residual of the combined mass of fat and skeletal muscle) and the BCI for 31 polar bears (*a*) and 33 black bears (*b*). Solid lines indicate the best fitting lines determined by ordinary least squares regression analysis and are described as follows: true body condition = 1.01 · BCI + 0.63 (R^2 = 0.98, SEE = 0.15) for polar bears and 0.86 · BCI + 0.17 (R^2 = 0.93, SEE = 0.28) for black bears.



Further, the relationship between the standardized residual of fat mass, SR_{fat} (range = 2.3–163.4 kg for polar bears and 0.2–47.5 kg for black bears) against SLBL and skeletal muscle mass (range = 2.3–163.4 kg for polar bears and 1.8–80.3 kg for black bears) against SLBL was positive and significant in both species (polar bears: F = 26.0, p < 0.001; black bears: F = 6.0, p = 0.02). Lastly, the relationship between SR_{fat} against SLBL and the BCI also was significant (p < 0.001), and is described by the following linear regression models:

$$[11]\quad \text{Polar bears: } SR_{fat} = 0.94 \cdot \text{BCI} + 0.58,\ R^2 = 0.83,\ \text{SEE} = 0.40$$

$$[12]\quad \text{Black bears: } SR_{fat} = 0.72 \cdot \text{BCI} + 0.18,\ R^2 = 0.63,\ \text{SEE} = 0.61$$

To facilitate estimation of the BCI for polar bears or for black bears and grizzly bears, the following models were developed:

$$[13]\quad \text{Polar bears: BCI} = (\ln \text{TBM} - 3.07 \cdot \ln \text{SLBL} + 10.76) \div (0.17 + 0.009 \cdot \ln \text{SLBL})$$

$$[14]\quad \text{Black bears and grizzly bears: BCI} = (\ln \text{TBM} - 3.21 \cdot \ln \text{SLBL} + 11.64) \div (0.29 - 0.017 \cdot \ln \text{SLBL})$$

The correlation between measured and estimated BCI values was highly significant in both groups (polar bears: $r = 1.0$, $p < 0.001$, $n = 1198$; black bears and grizzly bears: $r = 1.0$, $p < 0.001$, $n = 721$)

Discussion

In this investigation a BCI was developed for polar bears, black bears, and grizzly bears, based on residuals from the regression of TBM against SLBL. Although residuals from the regression of mass against a linear measure of size have been used in a wide variety of species to separate the effects of body condition from the effects of body size (Reist 1985; Krebs and Singleton 1993; Jakob et al. 1996), they had not been used previously to assess body condition in ursids. Nevertheless, residuals cannot be accepted as a valid index of condition until proof is provided that certain key criteria are met (Green 2001). First, the relationship between mass and length (following any transformations) must be linear. Second, the indicator of body size must be an accurate index of overall structural size, e.g., skeletal mass. Third, the residuals that represent the BCI must be independent of body size. If any of these criteria are violated, it is unlikely that residuals will reflect true body condition.

The criterion of a linear relationship between mass and length was met in this study. The mass–length data obtained from 1919 captures of free-ranging bears were analyzed using a range of curve-estimation regression models, but it was determined that the logarithmic model provided the best fit. Transformation of the mass–length data to natural logarithms resulted in a linear relationship between mass and length (Fig. 1).

The criterion that the indicator of body size must be an accurate measure of overall structural size was met in this study. SLBL had a strong positive relationship with skeletal mass in polar bears and black bears that were dissected to determine individual tissue masses (Fig. 2). Although comparable data for grizzly bears were not available, there was no reason to expect that the relationship between SLBL and skeletal mass in this species would not be similarly close.

The criterion that the BCI must be independent of body size was met in this study. No significant association could be found between the BCI and SLBL in either polar bears or in black bears and grizzly bears (Fig. 3).

In addition to meeting all criteria, the BCI was demonstrated to reflect true body condition, defined as the combined mass of fat and skeletal muscle in a bear relative to its body size. The BCI had a strong positive relationship with the standardized residual of the combined mass of fat and skeletal muscle in polar bears and black bears that were dissected to determine individual tissue masses (Fig. 4). Again it is expected that the relationship between the BCI and true body condition in grizzly bears would be close.

Although true body condition is defined in this study as the combined mass of fat and skeletal muscle in a bear relative to its body size, in other studies body condition has been determined on the basis of some measure of fat only, e.g., percent body fat (Thomas et al. 1976; Cattet 1990; Atkinson and Ramsay 1995; Hilderbrand et al. 2000). Nevertheless, the BCI was also demonstrated to have a strong positive relationship with the mass of fat in bears relative to their body size. Further, when body size was controlled for, the relationship between fat and skeletal muscle mass in polar bears and black bears was significant and positive, suggesting that energy storage and use in these species is dependent on both tissues.

The relationship between mass and length and the resultant residuals in polar bears differed from that found in black bears and grizzly bears (Fig. 1). This likely reflects differences in body form between polar bears and the other two species, rather than being a sampling artifact. Large numbers of all three species were captured, exhibiting a wide range of body condition. Black bears and grizzly bears were captured from the time of den emergence (March to May), when body condition is poorest, to the time of den entry (October), when body condition peaks. Similarly, polar bears were captured during most months of the year, including the entire period of their annual fast, from July to November.

In conclusion, the development of a BCI for ursids based on the residuals from the regression of TBM against SLBL meets the criteria necessary for a valid index of body condition: (*i*) the relationship between TBM and SLBL is linear; (*ii*) SLBL is an accurate index of body size; and (*iii*) the BCI is independent of body size. Further, the BCI has been demonstrated to reflect true body condition measured either as the combined mass of fat and skeletal muscle or as the mass of fat only, independent of body size. The BCI can be measured easily and used to compare individual bears within species, regardless of sex, age, reproductive state, geographical population, or date of capture. Estimation of BCI values for polar bears, or for black bears and grizzly bears, is facilitated by prediction equations that require measurement of TBM and SLBL for individual animals.

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