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Using form analysis techniques to improve photogrammetric mass-estimation methods

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ABSTRACT

Numerical characterization of animal body forms using elliptical Fourier decomposition may be a useful analytic technique in a variety of marine mammal investigations. Using data collected from the Weddell seal (*Leptonychotes weddellii*), we describe the method of body form characterization using elliptical Fourier analysis and demonstrated usefulness of the technique in photogrammetric mass-estimation modeling. We compared photogrammetric mass-estimation models developed from (1) standard morphometric measurement covariates, (2) elliptical Fourier coefficient covariates, and (3) a combination of morphometric and Fourier coefficient covariates and found that mass-estimation models employing a combination of morphometric measurements and Fourier coefficients outperformed models containing only one covariate type. Inclusion of Fourier coefficients in photogrammetric mass-estimation models employing standard morphometric measurements reduced the width of the prediction interval by 24.4%. Increased precision of photogrammetric mass-estimation models employing Fourier coefficients as model covariates may expand the range of ecological questions that can be addressed with estimated mass measurements.

Key words: body mass, shape analysis, elliptical Fourier analysis, Weddell seal, *Leptonychotes weddellii*.

Body form analysis techniques are becoming increasingly important in many marine mammal investigations. Numerous cetacean investigations rely on identifying individual animals based on dorsal fin form, coloring, or scar patterns (Katona and Whitehead 1981, Würsig and Jefferson 1990, Rugh *et al.* 1992, Agler *et al.* 1993, Defran *et al.* 1999, Karczmarski *et al.* 1999, Forcada and Aguilar 2000), and numerous pinniped investigations estimate body mass based on morphometric forms (Haley *et al.* 1991, Castellini and Caulkins 1993, Bell *et al.* 1997, Ireland *et al.* 2006). Form analyses techniques may provide a repeatable, numeric method of characterizing animal forms and may improve the precision of photogrammetric mass-estimation models (Proffitt *et al.* 2007a).

Mass-estimation models employing standard morphometric measurements as model covariates have been developed for several large pinniped species (Castellini and Kooyman 1990, Haley *et al.* 1991, Castellini and Caulkins 1993, Bell *et al.* 1997), and recently, Ireland *et al.* (2006) developed photogrammetric mass-estimation methods for Weddell seals (*Leptonychotes weddellii*). Photogrammetric mass-estimation techniques are desirable because they are less intrusive than direct morphometric measurements or traditional weighing procedures, and once an animal is photographed, a variety of morphometric dimensions may be measured or form analysis techniques may be applied to the images. In applying photogrammetric mass-estimation methods (Ireland *et al.* 2006) in a new study investigating variation in Weddell seal body mass at parturition, we discovered that predicted mass did not correspond well to true mass for animals >400 kg (Fig. 1). We identified two potential reasons for the lack of precision in photo-estimation of body mass for the largest seals: (1) lack of sufficient sample sizes of animals >400 kg when developing the predictive equation, and (2) morphometric predictors employed as covariates in the mass-estimation model may have been insufficient in characterizing phocid body form. These results prompted us to conduct targeted sampling to increase sample sizes of larger seals for incorporation into the prediction equation and to investigate new analytical methods that more comprehensively describe body form.

Phocid mass-estimation models have been developed using geometrical models that calculate the volume of two intersecting cones, which approximate the shape of a prone phocid (Castellini and Kooyman 1990), and the volume index is then used to derive a predictive mass-estimation model. Although these models may provide ample mass-estimation precision, the girth measurement cannot be collected photogrammetrically and photogrammetric length calculations are highly variable (Ireland *et al.* 2006). Additionally, near parturition animals may be at their largest and body forms may be irregular, not conforming to standard cone shapes. Therefore, in this study, we explored new form analysis techniques allowing us to more precisely estimate a body volume index from photogrammetric images, and hence, estimate body mass.

The goals of this study were to investigate the use of elliptical Fourier analysis in characterizing marine mammal body form and to investigate the applicability of employing Fourier coefficients as covariates in photogrammetric mass-estimation models. Fourier form analysis techniques are commonly used in a number of fields including systematics and paleobiology. They have been used to characterize the form of such diverse objects as bivalve shells and insect wings, with goals of classifying animals into taxonomic groups based on the numerical characterization of shell or wing form (Rohlf and Archie 1984, Ferson *et al.* 1985). The outline of a closed polygon, such as the outline of an animal's body or dorsal fin, can be numerically characterized using elliptical Fourier decomposition (Kuhl and Giardina 1982, Rohlf and Archie 1984, Lestrel 1989). The method of elliptical Fourier approximation (Kuhl and Giardina 1982) fits a closed curve to an ordered set of datapoints (x–y coordinates defining the outline) in a two-dimensional plane. The procedure uses an orthogonal decomposition of a curve into a sum of harmonically related ellipses,

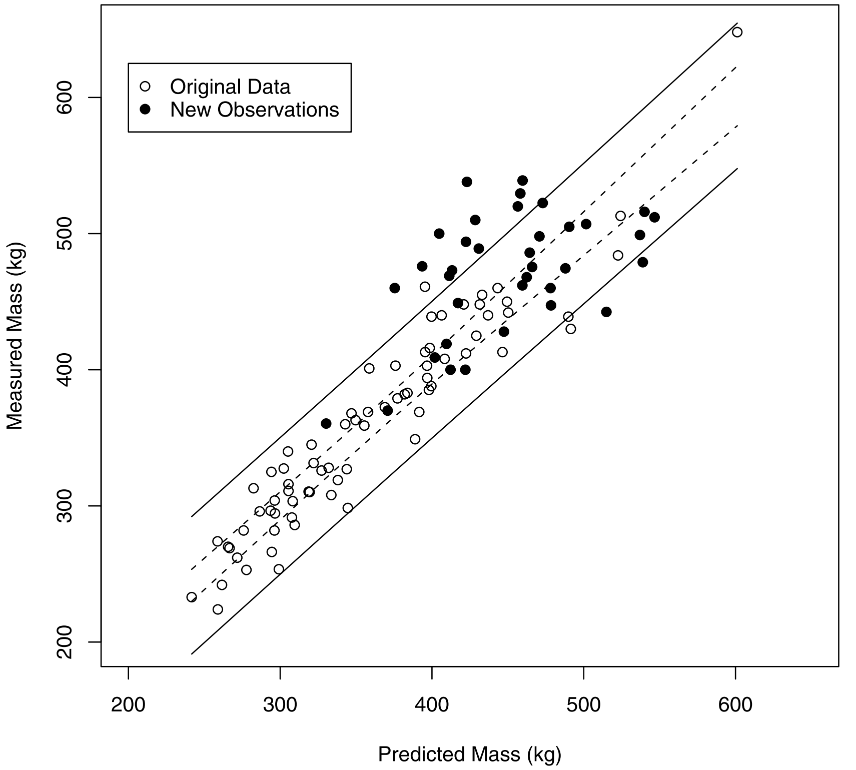

Figure 1. The original mass-estimation model developed using standard morphometric measurements overhead width (OW), side area (SA), and side height (SH) as model covariates (Ireland *et al.* 2006, Predicted mass = −134.1 + 3.6[OW] + 0.04[SA] − 2.5[SH]) did not precisely predict animal mass at the higher end of the predictive range. The 95% confidence interval is represented by the dashed line and the 95% prediction interval is represented by the outer solid lines. After the model was developed, new observations (solid circles, this study) of heavy animals frequently fell outside of the predictive range, and we had low confidence in the original models' predictive ability for animals above 400 kg.

yielding a series of coefficients over a defined number of harmonics that numerically characterize the form. The number of harmonics required to characterize the form is determined by the irregularity of the form (Fig. 2). The resulting coefficients that numerically quantify form can be used in multivariate form analyses. Individual Fourier coefficients do not have biological meaning. Rather, they provide a suite of coefficients that characterize overall form differences.

Using data collected on Weddell seals in McMurdo Sound, Antarctica, we first describe methods of performing elliptical Fourier analysis on animal body form. Next, we investigate the utility of Fourier analyses in photogrammetric mass-estimation modeling by comparing mass-estimation models employing traditional morphometric measurements as covariates with novel models employing Fourier coefficients as covariates. The applications of Fourier analysis in marine mammal science may be diverse, and these simple, widely applicable techniques merit exploration.

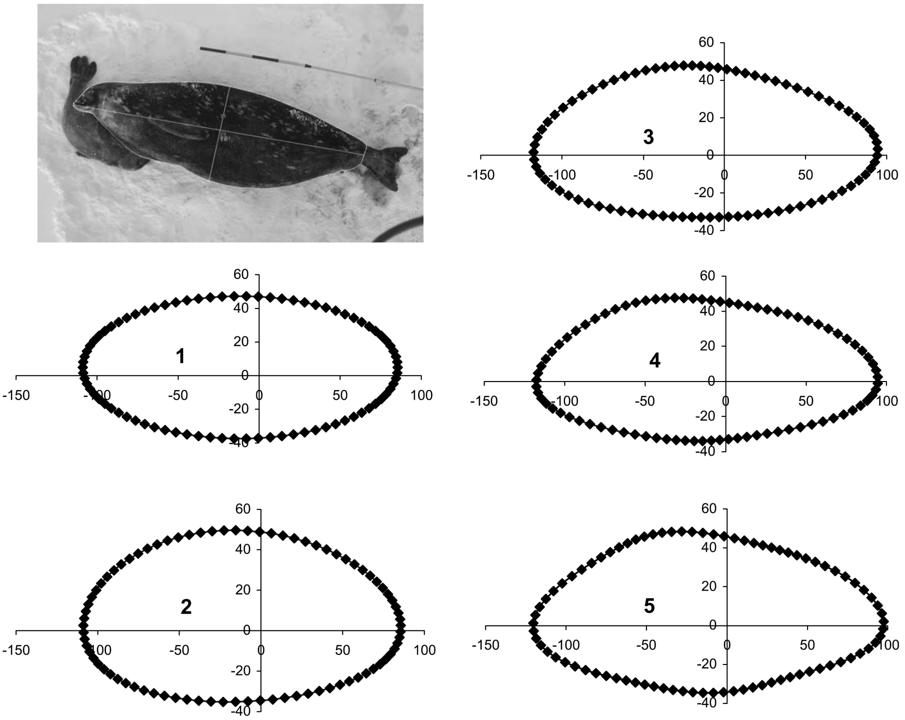

Figure 2. Overhead perspective seal image and reconstructions of the seal outline computed with various numbers of harmonics as indicated by the number within each outline. As the number of harmonics used to characterize the shape increased, the complexity of the reconstruction increased.

METHODS

Study System, Mass Measurements, and Photograph Acquisition

Mass measurements and photographic data were collected from Weddell seals in eastern McMurdo Sound, Antarctica (see Ireland *et al*. 2006 for details). Maternal postparturition masses were measured by coercing animals onto a mobile, digital weight platform (2002: San Diego Scale Company model number HP-4896-2K, 2003–2005: Maxey Manufacturing, Fort Collins, CO). Within 48 h, digital photographs of the animal in a standardized body position were collected from two perspectives: overhead and ground level side (Fig. 3). The standardized body position shown in Figure 3 was the position in which they were most commonly found while hauled out. Photographs were collected using specially designed, remotely operated, digital camera systems. The overhead perspective system consisted of a boom carrying the camera and facing perpendicular to the ground, and the side perspective system consisted of a boom carrying the camera near to the ground and facing parallel to the ground. A scaling pole was included in each photograph and used to digitally scale photographs prior to analysis. The scaled overhead and side perspective photographs were used to collect morphometric measurements and to perform elliptical Fourier analysis.

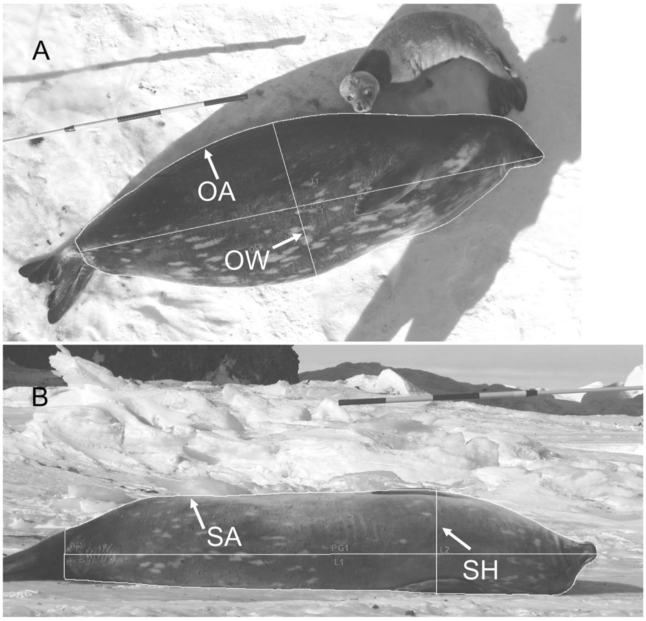

Figure 3. Image of a Weddell seal in standard body position from overhead (A) and side (B) perspectives. Morphometric measurements employed to estimate body mass included overhead area (OA), overhead width (OW), side area (SA), and side height (SH). The scaling pole used to calibrate the digital image is seen in the background.

Morphometric Covariates

Morphometric measurements were collected from the highest quality overhead and side perspective photographs following Ireland *et al*. (2006, Fig. 3). From overhead perspective photographs, a two-dimensional surface area (overhead area, OA) and width (overhead width, OW) were collected. From ground side perspective photographs, a two-dimensional surface area (side area, SA) and a maximum height (side height, SH) were collected. Caudal flippers and fore flippers were excluded from measurements because their position in each photograph was variable, and body length measurements were also excluded because of their high variability (Ireland *et al*. 2006). These four morphometric measurements (OA, OW, SA, and SH) were used as covariates in mass-estimation modeling exercises.

Elliptical Fourier Analysis and Fourier Coefficient Covariates

From each of the overhead and ground side images, the two-dimensional outline of the animal's body was digitized (MATLAB v 6.5, The Mathworks, Inc., Natick, MA, USA). Between 50 and 100 points were placed along the outline, and the *x*–*y* coordinates associated with these points were extracted. The number of points varied according to the shape of an animal, with a greater number of points being necessary to characterize the shape of the overhead perspective photographs. Elliptical Fourier analysis was performed on the set of *x*–*y* coordinates that defined the animal's body form. The coefficients for the first five harmonics were computed for each animal (on both the overhead and side perspective photographs). We chose to consider the first five harmonics from both the overhead and side perspective photographs (40 coefficients in total) because we did not want to over parameterize the model. Additionally, the two-dimensional body form of a phocid seal from both the overhead and side perspectives is roughly ellipsoid (Fig. 2), and we considered the first five harmonics acceptable in characterizing this body form. The resulting Fourier coefficients were evaluated as potential covariates in mass-estimation modeling exercises.

The algorithm for computing the elliptical Fourier coefficients is described in detail in Kuhl and Giardina (1982). This algorithm does not require data points to be spaced equally, allowing for images to be digitized by hand, and treats the x- and y-directional changes independently. The Fourier coefficients for the nth harmonic of the outline's x-axis projection are:

$$A_n = \frac{T}{2n^2\pi^2}\sum_{p=1}^{k}\frac{\Delta x_p}{\Delta t_p}\left[\left(\cos\frac{2\pi n t_p}{T}\right) - \left(\cos\frac{2\pi n t_{p-1}}{T}\right)\right] \text{ and}$$

$$B_n = \frac{T}{2n^2\pi^2}\sum_{p=1}^{k}\frac{\Delta x_p}{\Delta t_p}\left[\left(\sin\frac{2\pi n t_p}{T}\right) - \left(\sin\frac{2\pi n t_{p-1}}{T}\right)\right],$$

where p index's steps in the outline, k is the number of steps in the outline, Δx_p is the displacement along the x-axis of the contour between steps $p - 1$ and p, Δt_p is the length of the segment between steps $p - 1$ and p, t_p is the accumulated length of such segments at step p, and $T = t_k$ is the total length of the contour as approximated by the trace polygon (Kuhl and Giardina 1982). The coefficients for the y-coordinates of the nth harmonic, C_n and D_n, are found in the same manner using incremental changes in the y-direction. For each of n harmonics, four coefficients are computed (A_n, B_n, C_n, and D_n). Coefficients can be normalized to be invariant to size, orientation, and location in the digitization space. We normalized coefficients with respect to orientation and location in digitization space, thus eliminating information unrelated to mass estimation, but retaining information on size and shape that are crucial for mass-estimation modeling. Free software to perform the elliptical Fourier analysis is available (see Ferson *et al.* 1985 for description of methods).

Mass-Estimation Model Development and Comparisons

We developed three suites of competing mass-estimation models: one employing morphometric measurements derived from photographs as model covariates, one employing Fourier coefficients as model covariates, and one employing both morphometric measurements and Fourier coefficients as model covariates. The goal was to explore the applicability of Fourier coefficients in mass-estimation modeling. The Fourier coefficients from the first five harmonics of both the overhead and side perspective photographs and four morphometric measurements (OA, OW, SA, and SH) were employed as model covariates.

Within each suite of models, we performed all-subsets regression and used the prediction sum of squares ($PRESS_p$) to rank models in terms of their predictive ability (Neter *et al.* 1996). All-subsets regression was an acceptable methodology in this case because our goal in model building was prediction, not explanation or hypothesis testing. The $PRESS_p$ criterion measures a model's ability to predict observed response values of data points that were not used in the estimation of the model parameters. Models with the smallest $PRESS_p$ values have the smallest prediction error and were considered the top mass-estimation models. We performed a pseudo cross-validation analysis to assess the fit of the top-ranked models. The mass-estimation model was created with one observation left out, and this model was then used to predict the mass of the censured observation. We calculated what proportion of 95% prediction intervals for estimated female mass included or covered the known (or true) mass. We sought a model that generated prediction intervals with coverage levels matching the stated level (95%) and that achieved consistent coverage levels across the full range of female mass levels.

RESULTS

From 2002 to 2005, a total of 107 female Weddell seals were sampled and 106 were included in analyses. One outlier was censured from analyses because the measured body mass was more than 120 kg outside the range of masses observed in this or similar Weddell seal studies (Hill 1987, Wheatley *et al.* 2006, Proffitt *et al.* 2007b), and we suspected the measurement was inaccurate. Sampled animals were uniformly distributed over a wide range of masses representative of masses that would be expected for adult female seals from parturition to weaning (224.0–539.0 kg, $\bar{X} = 395.8$, SD = 85.9). By increasing the sample size of animals in the upper end of the predictive range and distributing sampling equally across the entire range of masses of interest, we corrected the problem that we had encountered with the previous mass-estimation model (compare Figs 1 and 4). The cross-validation analysis on the best model from the morphometric-measurements-only suite, model 13 (Table 1), produced 95% prediction intervals that included the actual mass 95.3%, that is, coverage levels were close to the stated level of 95%. Further, the coverage and precision were similar across the entire range of masses evaluated (Fig. 4).

We found that Fourier analysis techniques were an efficient method of reducing prediction error in photogrammetric mass estimation procedures, and the best overall mass-estimation model employed both morphometric and Fourier coefficients as model covariates (Table 1). In our mass-estimation models, the addition of Fourier coefficients as model covariates to models containing morphometric measurements reduced the width of the prediction interval by 24.4%, thus decreasing the prediction error by 12.2% (Fig. 5). The cross-validation analysis on the top model from the combined morphometric-measurements and Fourier coefficients suite, model 26 (Table 1), produced 95% prediction intervals that included the directly measured mass 96.3%, that is, the coverage level was slightly above the stated 95% level. Models containing only Fourier coefficients did not perform as well as models containing both Fourier coefficients and morphometric measurements as model covariates.

DISCUSSION

Here, we have presented a numerical method of photogrametrically estimating body mass using elliptical Fourier decomposition and demonstrated that Fourier analysis techniques may be useful in reducing prediction error in photogrammetric mass-estimation models. We found that photogrammetric mass-estimation models

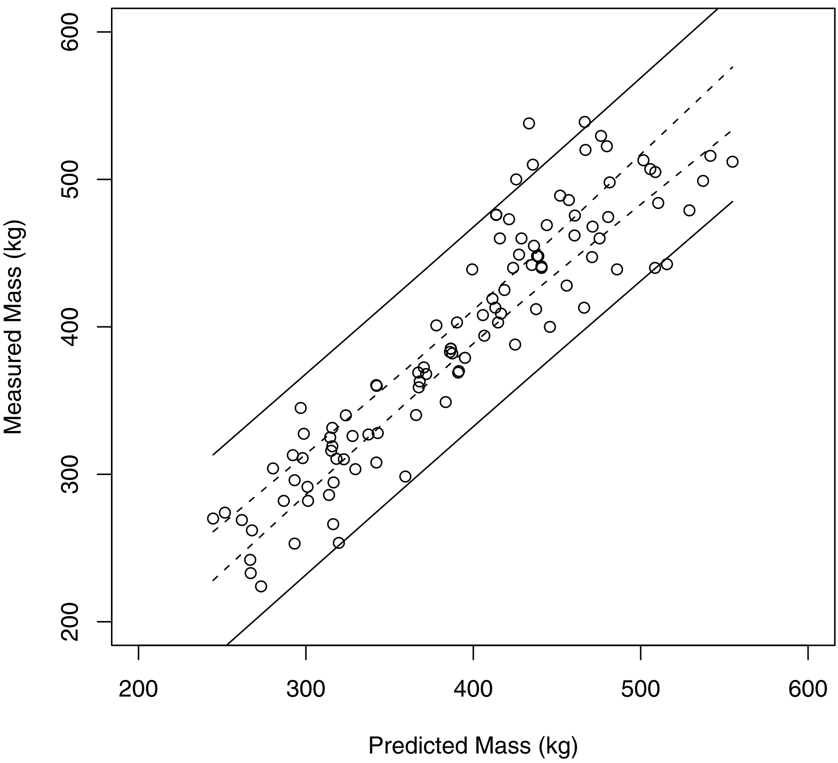

Figure 4. The relationship of the morphometric measurements to Weddell seal body mass (model 13, Predicted mass = −189.40 − 0.009[OA] + 6.51[OW] + 0.03[SA] − 1.90[SH]). The 95% confidence interval is represented by the dashed line and the 95% prediction interval is represented by the outer solid lines. The precision of the mass-estimation model developed using morphometric measurements as model covariates improved when sampling was distributed equally across the predictive range.

employing only standard morphometric measurements as model covariates may be improved upon by the addition of elliptical Fourier coefficients as covariates; however, these techniques do not replace the need to sample thoroughly across the range of masses of interest. These results have important implications for scientists employing photogrammetric mass-estimation techniques because the incorporation of Fourier form analyses has the potential to substantially enhance the power of photogrammetric mass-estimation procedures in addressing ecological questions important to our understanding of marine mammal ecology.

Although photogrammetric mass-estimation techniques have recently been refined (Ireland *et al.* 2006), more sophisticated analytical techniques may be employed to further improve photogrammetric mass-estimation methods by numerically characterizing an animal's body form. We found that in all suites of photogrammetric mass-estimation models, models that included covariates representing both the overhead perspective and side perspective body dimensions performed better than models containing covariates representing only one perspective. Additionally, we found models

Table 1. The top regression equations for the estimation of Weddell seal body mass, as determined by the smallest $PRESS_p$ value.

The $PRESS_p$ value and average prediction error (PE) are shown in the table. Morphometric predictors included overhead area (OA), overhead width (OW), side area (SA), and side height (SH). Fourier coefficient predictors are denoted using A*n*, B*n*, C*n*, and D*n*, where *n* represented the *n*th harmonic and the -side suffix represented coefficients from ground side perspective photographs.

Model	Covariates	$PRESS_p$	PE (kg)
Morphometric predictors suite			
13	OA + OW + SA + SH	127,616.7	34.4
12	OA + OW + SA	127,643.3	34.6
11	OW + SA + SH	137,107.9	35.9
10	OW + SA	137,878.1	36.0
7	AO + SA + SH	199,497.2	43.1
Fourier coefficient predictors suite			
18	A1 + D1 + C2 + A3 + D3 + C1side + D1side + B2side + C2side + A3side	196,767.6	43.2
17	A1 + D1 + C2 + B3 + D3 + A1side + C1side + D1side + B2side + C2side	197,768.5	43.3
16	A1 + D1 + C2 + A3 + B3 + D3 + D1side + B2side + C2side + A3side	203,520.0	43.3
14	A1 + D1 + C2 + D3 + A1side + B1side + D1side + B2side + C2side	204,141.6	43.6
15	A1 + D1 + C2 + D3 + B1side + D1side + B2side + C2side + A3side	207,536.4	43.6
Combined morphometric and Fourier coefficient predictors suite			
26	OA + OW + SA + SH + B1 + A2 + C2 + D2 + B3 + D1side + C2side	101,157.1	30.2
24	OW + SA + SH + A1 + A2 + C2 + D2 + B3 + D1side + C2side	103,396.7	30.2
23	OA + OW + SA + SH + B1 + C2 + D2 + A3 + D1side + C2side	103,703.3	30.2
21	OW + SA + A1 + A2 + C2 + D2 + B3 + D1side + C2side	105,124.4	30.2
22	OW + SA + SH + A1 + B1 + A2 + C2 + D2 + D1side + C2side	105,704.6	30.3

including both standard morphometric measurements as well as Fourier coefficients performed better than models containing only one covariate type. Interestingly, the Fourier coefficients included in the top models of the Fourier coefficient's only suite and the combined suite differed. The Fourier coefficients a1 and d1 that were included in each of the top-ranked models in the Fourier coefficients model suite were not included in the top models in the combined Fourier and morphometric model suite, most likely due to the correlation between a1 and OA and d1 and SA.

Comprehensive form analysis techniques, such as Fourier analyses, may compensate for contour information lost in mass-estimation models employing only conventional morphometric measurements as covariates. Contour information may be lost in the process of characterizing form using conventional linear measurements (Daegling and Jungers 2000). The advantage of incorporating Fourier coefficients into

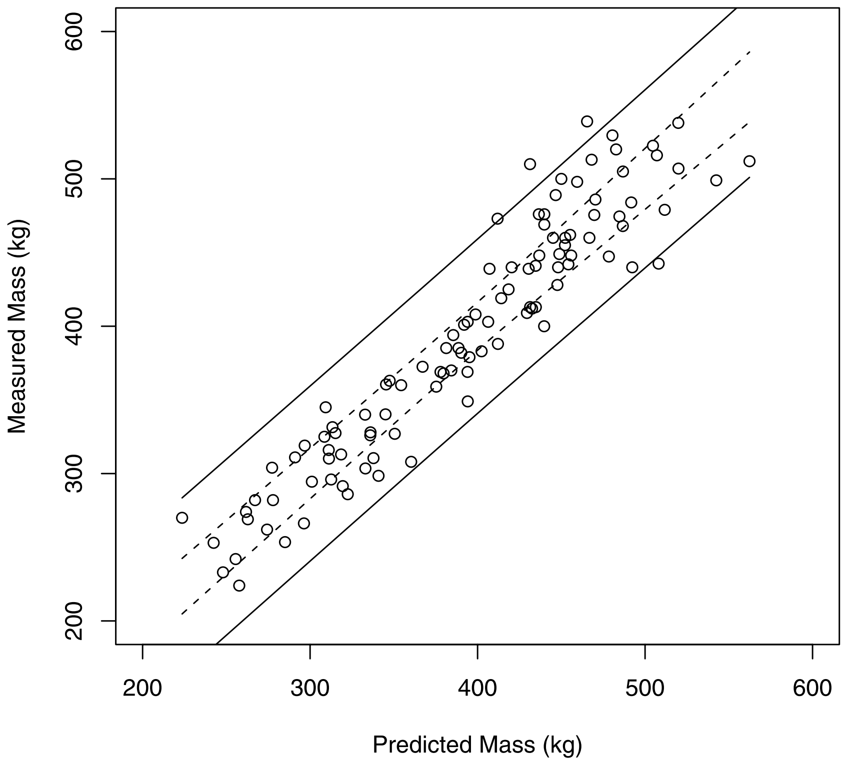

Figure 5. The relationship of the morphometric measurements and Fourier coefficients to Weddell seal body mass (model 26, Predicted mass = −176.4 − 0.007[OA] + 5.6[OW] + 0.03[SA] − 1.8[SH] − 0.001[B1] − 10.6[A2] − 4.0[C2] − 4.3[D2] − 23.1[B3] − 1.6[D1side] + 2.7[C2side]). The 95% confidence interval is represented by the dashed line and the 95% prediction interval is represented by the outer solid lines. The predictive ability of mass-estimation models developed based on morphometric measurements was improved by 12.2% with the inclusion of Fourier coefficients as model covariates.

mass-estimation models employing morphometric measurements as covariates is that the Fourier coefficients not only contain contour information similar to the morphometric measurements, but they provide more detailed form information that is not captured by conventional morphometric measurements. Form analyses may capture important irregularities about the body outline that help characterize animals with larger mass, and we would expect these techniques may be particularly useful in mass-estimation modeling of larger phocid species whose body form may be irregular when hauled out on the sea ice.

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