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Photogrammetric Estimates of Size and Mass in Hawaiian Monk Seals (*Monachus schauinslandi*)

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Abstract

A non-invasive photographic technique was developed to estimate the body mass of Hawaiian monk seals (*Monachus schauinslandi*). Newly weaned monk seal pups (*n* = 31) were photographed and measured at Kure Atoll in the northwestern Hawaiian Islands. Length, side area, anterior/posterior area, and perimeter were measured from photographs to establish predictive relationships with body mass using regression analyses. Photographs were ranked subjectively in terms of quality, based on the degree to which the seal's body position deviated from the ideal position used to obtain standardized photographs. Results indicated that deviations in body positioning (e.g., a seal rolled on its side) did not significantly alter photogrammetric (surface area or perimeter) values compared to those obtained in a standard position.

Although the most reliable models (based on information criterion analysis and 95% CIs) were based on directly measured morphological variables, models using only photogrammetric variables also yielded practical and reliable models with 95% CI, ranging from ± 4.95 to 9.12 kg and R^2 values from 0.93 to 0.77. This finding indicated that the use of photogrammetry alone to assess body condition is suitable to estimate body mass in 10- to 120-kg weaned Hawaiian monk seal pups.

Key Words: Hawaiian monk seals, *Monachus schauinslandi*, photogrammetry, morphometric, mass, surface area, northwest Hawaiian Islands

Introduction

Body mass has long been used as a measure of size and condition in mammals (Ozaga & Verme, 1970; Tumbleson et al., 1970; Dauphine, 1971; Peters, 1983; Gershwin et al., 1985; McLaren & Smith, 1985; Eason et al., 1996). Monitoring the body condition of wild animals can provide valuable information concerning the "well-being" of their population, reproductive success, and potential survival. Mass often is used as an indicator of the nutritional state of animals and provides insight into factors influencing animal-habitat interactions, such as prey availability and age-class foraging ability (Caughley, 1977; Kilpatrick, 1980; Hanks, 1981; Lockmiller et al., 1989; Read, 1990; Altmann et al., 1993; Virgl & Messier, 1993). Although weighing is the most reliable estimate of body mass, it is often an impractical procedure for species that are either too large to weigh using traditional means or are sensitive to disturbance, such as the endangered Hawaiian monk seal (*Monachus schauinslandi*) (Kenyon, 1980).

Photogrammetry, which involves making measurements on photographs (Baker, 1960), is a tool that has been used successfully to study the size and condition of a number of aquatic and terrestrial mammalian species (Lockyer & Water, 1986; Ratnaswamy & Winn, 1993; Minagawa, 1994; Shaner et al., 1998). Photogrammetry was an accurate means to predict phocid body mass in species such as northern elephant seals (*Mirounga angustirostris*) (Haley et al., 1991) and southern elephant seals (*M. leonina*) (Bell et al., 1997). This technique has proven especially valuable in phocids because of their large size and the associated difficulties in obtaining direct physical measures. This study tested a photogrammetric technique for estimating mass in recently weaned Hawaiian monk seals. The purpose of our study was to develop a photogrammetric technique in which photographs of seals could be collected in a non-invasive manner (i.e., no direct handling), under diverse field conditions, and in varying body positions. This study contrasts with previous phocid research in that our goal was to develop a technique which reflected real field conditions and/or used no tranquilizers or sedatives. The development of a photogrammetric technique specific to monk seals is especially timely because an accurate and non-invasive assessment of body mass and size would help increase understanding of juvenile and subadult growth. There are particular conservation concerns with this age class because of low juvenile survival, which is thought to be at least partially linked to poor body condition due to food limitation and starvation (Ragen & Lavigne, 1999; Marine Mammal Commission, 2000).

Materials and Methods

Hawaiian monk seals were studied during the spring and summer of 1997 and 1998 at Kure Atoll (lat. 28° 25' N, long. 178° 10' W) in the northwestern Hawaiian Islands. Ten pups (4 females, 6 males) born in 1997 and 22 pups (6 females, 16 males) born in 1998 were repeatedly photographed over the field season. In total, 32 pups were photographed and, on average, each seal pup was photographed ~5 times (range 1 to 8). Although the number of times any individual seal was photographed varied, the average time between the first and last photograph within the field season was ~12 days (range 0 to 34 days) and depended on individual seal haul-out patterns and associated photographic opportunities. Physical measurements were taken once from individual seal pups during the tagging process, which occurred shortly after weaning and included axillary girth (cm), total body length (cm), and mass (kg).

Photogrammetric Methods

Photogrammetry was used to estimate the size of Hawaiian monk seal weanlings using surface area (not including flippers), perimeter (i.e., outline of the body), and total body length. A predictive relationship with mass was based on regression models containing (1) photogrammetric measurements alone, (2) morphometric measurements alone, and/or (3) a combination of both measurements. All data were analyzed using the statistical package *SPSS for Windows*, *Version 10.0.5* (SPSS Inc., Chicago, Illinois, 1999).

To sample as many weaned pups as possible, weanlings were photographed opportunistically over the entire 2-mo field season (June & July), regardless of weaning or tagging date. Most seals were photographed from two views: laterally and either anteriorly or posteriorly (as in Haley et al., 1991; Bell et al., 1997) at a standard distance of 10 m and from a camera height of 0.5 m. All photographs were taken using a Nikon N70 camera mounted on a tripod, with a 70- to 210-mm lens and Kodachrome color slide film AFA 64. The 10-m distance from camera to seal was determined using a laser rangefinder (Bushnell Lytespeed 400 Rangefinder, Kansas City, KS; accuracy ± 1 m).

When possible, seals were photographed on more than one occasion. A repeated-measures general linear model was used to identify differences in photogrammetric measures of individuals over the course of the field season to assess possible weight gain or loss after weaning. Ideally, seals were photographed when they were asleep on hard, packed sand and lying straight on their ventral surfaces at the point of maximum inhalation. Photographs of seals also were taken in nonstandard positions such as when the seal was found lying on its side, when its body position was curved, and during both inhalation and exhalation. During 1997, photographs were taken with a calibrated measuring rod held directly over the seal by a second person (Figure 1). In 1998, a tripod with an attached measuring rod was placed next to the sleeping seal before photographs were taken (Figure 2). The measuring rod was positioned parallel to and over the midline of the seal (lateral photographic view) or perpendicular to the longitudinal axis over the posterior edge of the foreflippers (anterior photographic view).

Monk seal pups were measured and weighed as soon as possible after weaning. Body mass was measured to ± 0.5 lb (later converted to kg for data analysis), with the seal restrained in a stretcher-net and suspended from a hanging spring scale; stretcher-net mass was subtracted from total mass to determine total body mass (accurate to ± 2 lbs). Axillary girth (AG) and dorsal standard length (DL) (tip of nose to tip of tail) (American Society of Mammalogists, 1967) were measured by using a flexible metric measuring tape (cm).

Photographs were analyzed without knowing the seal's identity. Slides were scanned (Microtex Slide Maker, Scanmaker 3.5t, Taiwan), and photogrammetric measurements were calculated by the *TNTmips 5.9* computer program (MicroImages, Lincoln, NE). The perimeter of the seal was outlined on the digital image and surface area, and perimeter measurements were automatically calculated by the program by using the measuring rod in each picture as a size reference.

Quality of images was subjectively ranked from 1 to 4 in which quality 1 represented a photograph in which the seal was lying in the ideal, standard position. An image ranked as quality 2 included seals lying curved or lying slightly to one side. An image was ranked quality 3 if the seal was on its side and was obviously curved. Images ranked

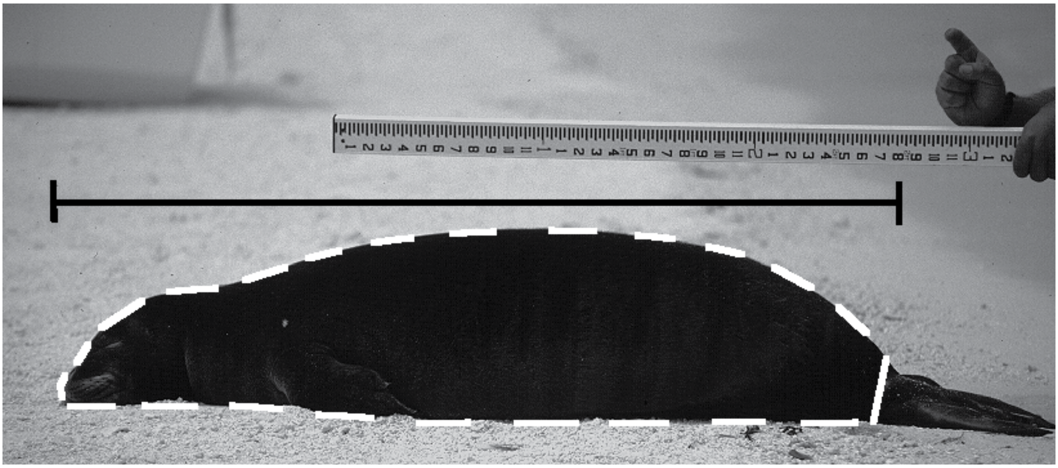

Figure 1. Representative lateral photograph of a weanling Hawaiian monk seal; dashed lines show the perimeter of the seal traced during the digitizing process. Lateral surface area is calculated for the area inside the dashed line.

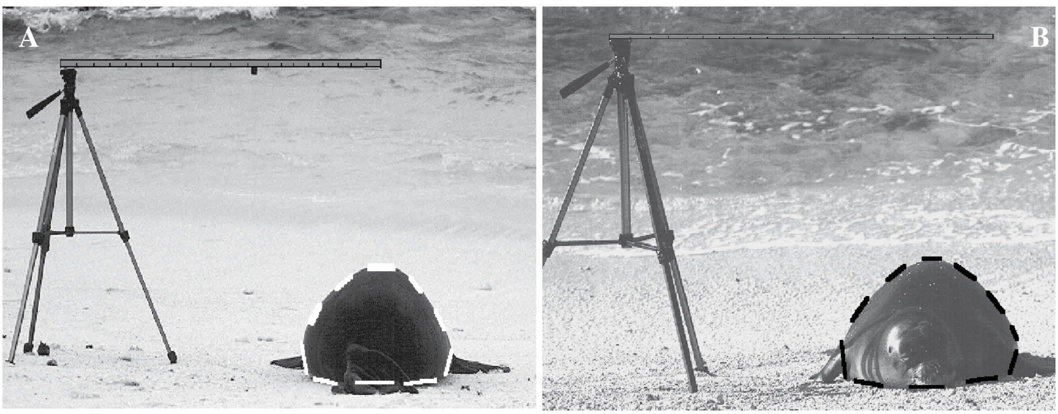

Figure 2. Representative photographs of (A) posterior view and (B) anterior view of weanling Hawaiian monk seal using the tripod-measuring rod method; dashed lines show the perimeter and maximum girth. The area inside the lines is used to obtain surface area.

quality 4 included seals lying entirely on their sides or backs. A repeated-measures analysis of variance (ANOVA) was used to assess differences in variables in photographs of the same individuals with different quality rankings and for different camera views (i.e., lateral, anterior, posterior). To assess if repeated photogrammetric measurements of the same seal taken over the course of the field season varied, a repeated-measures general linear model was used to identify possible mass gain or loss after weaning.

Three replicate measurements were obtained for the photographic variables defined in Table 1. The mean of these measurements was used for regression equations. Lateral surface area (LA) and perimeter (LP) measurements were taken from both the right and left lateral views. Girth area (GA) and perimeter (GP) measurements were taken from both the anterior and posterior. Because the position of the tail was obscured by the caudal flippers in photographs, the straight line length measurement (L) was measured from the tip of the nose to the base of the hind flippers. Digitally outlining the specific contours on the head was a somewhat more difficult part of the tracing process. We therefore tested if its exclusion significantly altered the predictive value of LA and LP measures. All lateral photographs of quality 1 and 2 were used to calculate the LA without the head (NH). The natural indentation behind the skull was chosen as a cut-off to collect lateral measurements that excluded the head. LP measurements were tabulated for samples which did not include the head (NP) in the overall measurement. Paired sample *t*-tests were used to test for differences between directly measured morphometric measurements of DL and AG with their photogrammetric analogs, LP, and GP.

A volume index was created because this variable has been shown to be a valuable predictor of body mass in other phocid species. The volume index was estimated from the equation AG^2 x DL (using morphometric values taken directly during the tagging process). The estimate is based on the theoretical geometric form of a phocid seal, which is similar to two abutting cones with a common base (Hofman, 1975). An indirectly measured volume index, based on photogrammetric analogs (i.e., GP^2 x L) and therefore based on photogrammetry and not direct physical measures, also was estimated.

Estimation of Body Mass

A multiple linear regression on body mass was conducted on all combinations of photogrammetric and morphometric variables (together and separately). Based on the results of Q-Q plots, data was assessed to be normal. Multicollinearity was assessed using the variance inflation factor (VIF) and by examining variable relationships from Pearson's bivariate correlation matrix. Multiple regression models were run with a forced entry of all variables. Models were then created based on all possible subsets of the pool of potential independent variables and detailed examination of a few "good" subsets which had Pearson's correlation coefficients (r) of no less than 0.80. Final models were selected based on several factors, but primarily on Akaike's information criteria (AIC) (Akaike, 1973) and the strength of their adjusted R^2 values. Other factors such as the reliability of each model based on low 95% CI, the degree of multicollinearity (low VIF factors are considered < 10), and the practical use of individual variables in the field also were considered when choosing the best models.

Table 1. Photogrammetric and morphometric variables collected from weanling Hawaiian monk seal pups at Kure Atoll, Hawaii in 1997-1998

Variable (units)	Variable type	Abbreviation
Lateral surface area (cm^2)	P	LA
Girth area (cm^2)	P	GA
Girth perimeter (cm^2)	P	GP
Lateral perimeter (cm^2)	P	LP
Lateral area without including the head (cm^2)	P	NH
Lateral perimeter without including head (cm^2)	P	NP
Length (cm)	P	L
Volume (cm^3)	P/M	V
Dorsal standard length (cm)	M	DL
Axillary girth (cm)	M	AG
Body mass (kg)	M	WT

*Theoretical volume index: $(AG)^2$ x (DL) = Vm; $(GP)^2$ x (L) = Vp

Regression models were created using all data minus approximately 20 to 30% (depending on the sample size) of randomly selected data, which were set aside for model validation. This percentage of data was selected for model selection because tests indicated that this number represented the maximum number of data points that could be excluded from model selection without sacrificing model reliability. We then inserted these data points into our models (which were developed excluding these data points) to assess the validity of the model (Sokal & Rohlf, 1981). CIs were calculated for predicted mass, which incorporated the actual mass and unstandardized predicted mass:

$$\text{CI} = \frac{\text{Body mass} - \text{Unstandardized predicted mass}}{\text{Unstandardized predicted mass}} \times 100$$

Using length and girth, Craig & Ragen (1999) developed equations for predicting mass of weaned monk seal pups from Laysan Island and French Frigate Shoals (FFS). In Craig & Ragen's study, mass was estimated using the following equation: $AG^{1.7}$ x (0.00016 x DL) for Laysan Island and $AG^{2.0}$ x (0.000045 x DL) for FFS. To assess if estimated mass using models for seals from Kure Atoll differed from those created for seals on other atolls, we compared our models to those created by Craig & Ragen.

Results

Seals were not visibly disturbed during 93% of photographic attempts ($n = 255$) in 1997 and 1998. We define disturbed as a visible physical reaction to the photogrammetric technique and included vocalization, moving away from haul-out site, or fleeing the beach. Approximately 4% of the disturbances resulted in the seal vocalizing or moving slightly, but not fleeing the beach. During 3% of the disturbances, seals were distressed enough by the presence of the photographer to flee into the water. Using a tripod with an attached measuring rod appeared to decrease disturbance (8.4% disturbance rate for 1997 vs 5.9% disturbance rate in 1998) relative to the presence of a second investigator in the photographing process.

Photographic Variables

Photographs of four different qualities had similar variances. Repeated-measures models indicated no significant within-subject differences in estimated surface area (F = 1.583, df = 3, p = 0.387) or perimeter (F = 0.468, df = 3, p = 0.513) measurements between photographs of individuals subjectively ranked in quality 1-3.

Within-subject variation was detected using a repeated-measures ANOVA of lateral photographs of quality 4; poor quality LA (mean = 15.23 cm) and LP (mean = 221 cm) measures were significantly smaller than those for quality 1-3 (mean LA = 21.22 cm; mean LP = 257 cm). For this reason, quality 4 lateral photographs were excluded from further analysis, and the remaining quality 1-3 photographs of the lateral view, which did not significantly differ based on their quality ranking, were pooled for further analysis.

Repeated-measures ANOVA detected no significant within-subject variation between LA or LP measures of either anterior (AO) or posterior (PO) views (F = 0.211, df = 1, p = 0.787). Additionally, an ANOVA between the different photographic views found no significant differences in these measures between AO and PO views (F = 1.33, df = 26, p = 0.450). Therefore, AO and PO measures were pooled and called girth area or girth perimeter (GA/GP). No significant differences in surface area measures were found between seals photographed during a maximum inhalation vs a complete exhalation for either lateral or anterior/posterior views, respectively (F = 0.026, df = 15, p = 0.810; F = 1.40, df = 15, p = 0.891). Males and females did not significantly differ in lateral or anterior/posterior surface area or perimeter measures from either the 1997 or 1998 field seasons (F = 0.036, df = 1, p = 0.850). When the three variables above (view, quality, and sex) were taken into account collectively, a three-way ANOVA (2 x 3 x 2) found no significant differences between or among these variables.

Paired sample correlations of photogrammetric measures indicated high correlations among all measures of the same seal taken by the same photographer (r = 0.860, p = 0.062). A repeated-measures ANOVA indicated no significant differences between all photogrammetric measures with the exception of LP (F = -12.22, df = 4, p = 0.000). The paired difference means for LP were negative, indicating that the second estimate was consistently larger than the first estimate.

Paired sample t-tests indicated that the morphometric measurement of dorsal standard length (DL) was approximately 6.8 cm longer than its photogrammetric equivalent length (L) (t_{30} = 4.74, p = 0.019). Axillary girth (AG) was more strongly correlated to mass (r = 0.946, p = 0.000) than DL (r = 0.75, p = 0.000). AG did not significantly differ from its photogrammetric equivalent, girth perimeter (GP) (t_{30} = -0.808, p = 0.187). AG was correlated with GP (r = 0.427, p = 0.000) while DL was significantly but not as highly correlated (r = 0.403, p = 0.000) to AG.

The morphometric variable of volume (Vm) was highly correlated to mass (r = 0.968, df = 31, p = 0.050), while the indirectly measured photogrammetric index of volume (Vp) was not as highly correlated to mass (r = 0.433, p = 0.015). Correlations and paired sample t-tests performed on Vm and Vp indicated that these variables were marginally correlated (r = 0.341, p < 0.050) and did not significantly differ from each other (t_{30} = 21.325, p = 0.480).

Comparisons of full lateral surface area (LA) and full lateral perimeter (LP) were made with corresponding measures that excluded the head (NH & NP). Paired sample correlations and t-tests performed on LA and NH indicated that these variables significantly differed but were highly correlated (r = 0.915, p = 0.020). On average, LA was 2.98% larger than NH. The variable of NH was more strongly correlated to mass (r = 0.966, p = 0.001) than LA (r = 0.892, p = 0.000). Paired sample correlations and t-tests performed on LP and NP indicated that these variables significantly differed and were highly correlated (r = 0.600, p = 0.001). LP was approximately 35.74% larger than NP, and was also more highly correlated to mass (r = 0.779 vs 0.600, respectively).

A repeated-measures general linear model was used to identify differences in photogrammetric measures of individuals (pooled by view, i.e., lateral, anterior) over the course of the field season to assess for possible weight gain or loss after weaning. Multiple photographs of the same individual were examined, and no significant differences between photogrammetric measures over the field season were found when data compared within-subject variation over time (F = 2.23, df = 7, p = 0.323).

Mass Estimation Regression Models

The overall best model contained only the morphometric variable AG (Table 2, Model 1; Figure 3) and had the lowest AIC value of -123.58, a small 95% CI (lower bound [LB] = 0.805 kg; upper bound [UB] = 3.50 kg), and an adjusted R^2 = 0.933. The 95% CI for the subsample of data which was not included in the original model was the lowest of any morphometric or photogrammetric models (95% CI = ± 4.28 kg) and supports the delegation of this model as the most accurate. The best model, which included only photogrammetric variables, was Model 3 (Table 2, Figure 4), which included GP and LP (AIC = -96.49, adjusted R^2 = 0.931, LB 95% CI = 4.90 kg, UB 95% CI = 0.86 kg). The 95% CI based on subsample data was very similar (± 5.0 kg) to subsample CIs for the

AG model. The model with the highest R^2 was not considered the "best model" (using NH) because of its substantially larger AIC and 95% CI; subsample CIs were not calculated for this variable due to low sample size.

The best model, which included both photogrammetric and morphometric variables, was a log-log model which included AG, GP, and LP (AIC = -131.90, adjusted R^2 = 0.981, LB 95% CI = 4.10 kg, UB 95% CI = 1.02 kg). The subsample CI (± 4.92 kg) was similarly low compared to the best photogrammetric or morphometric only models.

The photogrammetric variables most highly correlated (Table 3) to body mass were NH and GP (r = 0.966 and 0.925, respectively); the morphometric variables most highly correlated to body mass were both AG and Vm (r = 0.946 and 0.968, respectively). LA alone was highly correlated with mass, but failed to be a meaningful predictor variable for mass estimations (adjusted R^2 = 0.536).

To assess if estimated mass using models for seals from Kure Atoll differed from those created for seals on other atolls, we compared our models to those created by Craig & Ragen (1999). On average, mass estimated using the FFS model was approximately 1.03 kg larger than mass predictions made with our photogrammetric model (using GP and LP). A paired *t*-test indicated that mass estimated using the most reliable photogrammetric model (Table 2, Model 3) did not significantly differ from mass estimated using Craig & Ragen's FFS mass estimation model (t_{30} =1.50, p = 0.131). Paired *t*-tests comparing our mass estimation model, using the morphometric variable AG, were significantly smaller (3.20 ± 0.29 kg) than those calculated from the FFS model (t_{30} = 0.730, p = 0.001). *T*-tests did indicate that the Laysan model significantly differed in the mass estimation to that of both the FFS (t_{30} = 0.334, p = 0.000) and our photogrammetric model (t_{30} = 0.792, p = 0.038).

Discussion

Photographic Technique

One important finding from this study is that a simple photogrammetric technique can be used successfully on this species to produce accurate estimates of mass with a minimal amount of disturbance. In

Table 2. Models created for Hawaiian monk seal weanlings (1997-1998) from Kure Atoll for mass estimation. Aikaike's corrected information criteria (AICc), delta AICc, the adjusted R^2, and 95% confidence intervals (95% CI) for the mean unstandardized predicted values were calculated. 95% CI were also calculated for a subsample of data (n = 6), which were not included in the regression analyses and were later used to test the validity of each model. Model validation was performed only for n > 20. All models had low variance inflation factors (VIF < 10), indicating low multicollinearity between terms. All regression equations were significant at 0.05.

	Model number	AIC_c	ΔAIC_c	R^2	n	95% CI Lower	95% CI Upper	Subsample 95% CI
	Morphometric variables only							
1	LOG (M) = 0.669 + 0.010 (AG)	-123.58	8.32	0.933	31	0.80	3.50	4.28
2	M = -3.22 + 4.50E^{-05} (V*)	181.12	312.39	0.935	31	3.00	6.46	5.86
	Photogrammetric variables only							
3	LOG (M) = 0.667 + 0.0065 (GP) + 0.0015 (LP)	-96.49	35.41	0.926	26	0.86	4.90	5.00
4	M = -39.883 + 500.3 (NH)	101.25	233.15	0.928	16	-55.48	-24.18	--
5	M = -32.960 - 4.008E^{-02} (L) + 0.237 (GP) - 0.228 (LP) + 4.369 (NH) + 0.112 (NP) - 2.054 (GA) + 1.494 (LA)	105.99	237.80	0.911	16	0.57	1.30	--
6	M = -58.136 + 1.713 (LA) + 0.718 (GA)	170.92	275.73	0.880	26	- 4.90	2.97	6.23
7	M = -58.136 + 7.180 (LP) + 1.731 (LA)	213.37	345.28	0.770	26	-87.37	11.45	6.71
8	M = -85.362 + 0.899 (GP) + 0.184 (LP)	175.04	306.94	0.860	16	-47.34	12.23	--
	Both photogrammetric and morphometric variables							
9	LOG (M) = -0.102 + 0.0074 (AG) + 0.437 LOG (GP) + 8.53E^{-04} (LP)	-131.90	0.00	0.981	26	-1.12	2.21	4.92
10	M = -4.037 - L$^{(0.06347)}$ + GP$^{(0.446)}$ + LP$^{(.0206)}$ - GA$^{(0.0817)}$ + LA$^{(0.0630)}$ + AG$^{(1.882)}$ + DL$^{(0.433)}$	173.84	305.74	0.976	26	-10.90	-7.54	-9.12
11	LOG (M) = 0.705 + 0.0071 (AG) + 0.0029 (GP)	-127.87	4.03	0.971	31	0.62	0.78	2.80
12	LOG (M) = -3.552 + 2.25 LOG (AG) + 0.313 LOG (LP) 0.947	-124.75	7.15	0.847	26	-4.24	-2.86	1.69
13	M = -77.71 +1.037 (AG) + 1.376 (LA)	182.39	314.29	0.923	31	-29.33	-1.89	6.03

Table 3. Pearson's correlation coefficients and the significance of mass against the photogrammetric variables for weanling Hawaiian monk seals at Kure Atoll, Hawaii (1997-1998); correlations in bold are significant at the 0.05 level (two-tailed).

		Mass	Length	GP	LP	GA	LA	NH	NP
Mass	Pearson's Correlation	1.000	0.332	**0.925**	**0.770**	**0.909**	**0.892**	**0.966**	**0.600**
	n	31	31	27	30	29	30	16	16
Length	Pearson's Correlation		1.000	0.301	**0.956**	0.338	**0.846**	**0.913**	**0.607**
	n		31	27	30	29	30	16	16
GP	Pearson's Correlation			1.000	**0.811**	**0.930**	**0.852**	**0.919**	**0.596**
	n			27	26	27	26	16	16
LP	Pearson's Correlation				1.000	**0.661**	**0.857**	**0.944**	**0.576**
	n				30	28	30	16	16
GA	Pearson's Correlation					1.000	**0.849**	**0.907**	**0.619**
	n					29	28	16	16
LA	Pearson's Correlation						1.000	**0.915**	**0.511**
	n						30	16	16
NH	Pearson's Correlation							1.000	**0.544**
	n							16	16
NP	Pearson's Correlation								1.000
	n								16

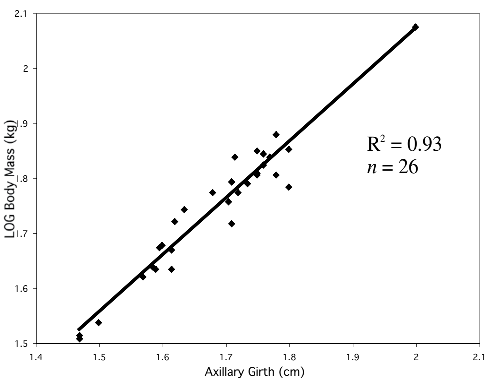

Figure 3. The relationship between body mass (M) and axillary girth (AG) for Hawaiian monk seal weanlings (1997-1998): LOG (M) = 0.669 + 0.010 (AG)

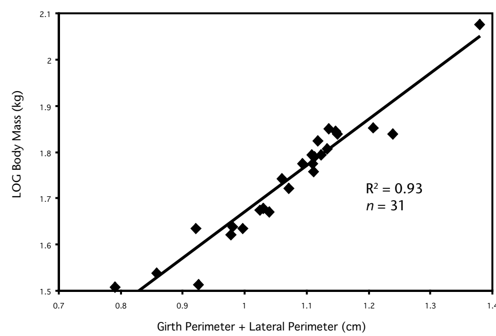

Figure 4. The relationship between body mass (M) and girth perimeter (GP) and lateral perimeter (LP) for Hawaiian monk seal weanlings (1997-1998): LOG (M) = 0.667 + 0.0065 (GP) + 0.0015 (LP)

general, as long as the seal was not severely curved or lying on its side, small deviations from the ideal position did not significantly degrade estimates of photogrammetric measures and, thus, demonstrate that the implementation of this field technique on a species sensitive to disturbance is feasible. Laterally viewed photographs ranked quality 4 had significantly lower surface area measures than those ranked 1 to 3, so only the quality 1 to 3 photographs should be used for photogrammetric analyses. The finding that anterior and posterior photographs did not differ significantly in photogrammetric measures is useful because researchers can potentially reduce disturbance by photographing the seal from the posterior, making it less likely for the seal to see the photographer if it awakens. Additionally, the use of a tripod appeared to reduce disturbance relative to the presence of a second investigator holding a measuring rod over the seal during the photographing process. This was due in part because even if pups awakened during the process, they usually were not alarmed by the tripod compared to the presence of a second observer; thus, we recommend this technique when disturbance is an issue.

Repeated-measures general linear models of photogrammetric measures were highly correlated between measures of the same seal and taken by the same photographer. These findings indicated that results would not reflect individual variation in the photographic technique; however, because repeated photogrammetric LP measures of the same seal taken by the same researcher tended to show that the second estimate was consistently larger than the first measurement, we suggest that particular attention be made to the tracing process.

Photogrammetric Measures Over Time

When analyzing changes in photogrammetric measures of weanling monk seals over the 6-wk field season, we expected that any differences in size would indicate that the weanling's surface area had decreased due to mass loss associated with post-weaning fasting generally found in this species; however, photogrammetric measures did not change significantly over the course of the field season. It is clear from previous studies (Craig & Ragen, 1999; NMFS, unpubl. data) that a substantial amount of mass is lost during the first year of life as weanlings learn to forage on their own. Due to the relatively short time frame in which photographs were collected for this study (under 3-mo post-weaning), it is possible that the field season was not long enough to reflect the actual mass loss changes which we expect to exist in this age class during their first year of life.

Comparisons of Photogrammetric and Morphometric Variables

This study found the photogrammetric variable length (L) was underestimated by approximately 14% compared to its morphometric equivalent, dorsal standard length (DL). In comparison, studies on southern and northern elephant seals found DL was an overestimate of L by 3% and 10%, respectively (Bell et al., 1997; Haley et al., 1991). A possible contributing factor may be the difference related to the researchers' choice in selecting the base of the hind flippers as a point of measurement, while L measured in the field uses the tip of the tail as the comparable point of measurement.

Regression Models

Mass was estimated with a high degree of certainty using photogrammetric variables, morphometric variables, and a combination of the two. The model selected as best, based on the selection criteria, was a model containing both photogrammetric and morphometric variables. Models which contained only morphometric variables were slightly better predictors of mass than those containing only photogrammetric variables; the most reliable morphometric-only model had a slightly lower 95% CI than a nearly identical photogrammetric model (in terms of explanatory power or R^2). CIs based on subsamples of the data validated the accuracy of each best photogrammetric, morphometric, and combined model and indicated similar degrees of certainty in predicting mass.

This study indicated that if photogrammetric models are the only choice for predicting mass, they appear to be very reliable, although slightly less precise. Much of the variation in these models may have been related to the digitizing and tracing process. The accuracy of tracing an image depended on a number of factors, including the skill of the researcher and the quality of the photograph.

The most precise model created using only photogrammetric data was one which included LP and GP. This differs from studies conducted on northern elephant seals (Haley et al., 1991) and southern elephant seals (Bell et al., 1997) in which the best models contained either GA and LA (Bell et al., 1997) or LA alone (Haley et al., 1991). Although a monk seal model using LA and GA was strong, it had significantly wider 95% CIs. This indicates that if highly precise body mass estimates are needed for a phocid species, it is better to use a species-specific model for mass estimations; however, it should be noted that even with the wider CIs found in the monk seal model using LA and GA, it still provided a high level of reliability as indicated by the high R^2 value of 0.88.

The best morphological model was one created using the variable AG. Previous studies on southern elephant seals (Bell et al., 1997) have shown that this variable was one of the most reliable morphological predictors of mass, second only to a model which included both DL and AG. Our second best model was one containing the variable volume. The advantage of using a volume index, as opposed to using only AG or DL separately, is that models which included volume take body shape into account (Hofman, 1975). A very long seal may be thin, while a seal with a large girth may be very short, and, without using both variables, one aspect of the morphology is neglected; however, the model containing AG alone was a better fit to the data than a volume index because of the low correlative power between DL and mass.

We suggest that if no morphometric data are available, models for predicting mass could include just the single variable NH because such a regression model is easily attained from a single photograph from the lateral view. A regression model including only NH provides a reliable and accurate estimate of mass; however, a model which includes both anterior and lateral views (Table 2, Model 4; $LOG(M) = 0.667 + 0.0065\ GP + 0.0015\ LP$) improves the reliability of the model, as judged from the decrease in both the AIC and 95% CI.

This technique cannot be used as a complete substitute for direct weighing since initial weights must be collected to develop the models. Although this paper presents data for only weanling seals, unpubl. data (McFadden, 1999) of the photogrammetric and morphometric relationship of captive, subadult Hawaiian monk seals indicated that the utility of this technique will hold for other age classes on Kure Atoll. Differences in morphometric measurement relationships appear to exist for other subpopulations of Hawaiian monk seals (Craig & Ragen, 1999; McFadden, 1999), however, especially those in which the general population tends to be either significantly more emaciated or fatter than the seals at Kure Atoll. A photogrammetric tool may still be useful in light of the difficulties in weighing large seals—in particular, those that are sensitive to human disturbance. This technique has the potential for better estimating mass and condition in the endangered Hawaiian monk seal since few other alternatives are currently available on a large scale for seals older than weanlings.

Photogrammetry is a non-invasive tool which can provide more accurate data on conditions for this species if weighing or direct morphological measurement are difficult to obtain. Future studies on photogrammetry should sample a larger group of seals (ranging in age classes) if this technique is to be applied on a larger scale. Non-weanling juvenile seals, which are particularly at risk for poor body condition (Craig & Ragen, 1999), are an important age class which this study did not sample.

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