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JOURNAL OF AVIAN BIOLOGY 32: 198–203. Copenhagen 2001

Avian forensics: predicting body fat and body mass from wing remains

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We describe the development of a method to predict percent body fat of killed birds from the percent fat in the most distal wing tissue, which is often left uneaten by aerial predators. When combined with a measure of body structural size, such as tarsus, culmen or keel length, percent wing fat can be used to predict fresh body mass at the time of death. These techniques may prove useful in field studies of mass-dependent predation risk.

Acts of predation are rarely witnessed, and field researchers often must glean information about predators and prey from evidence found at a kill. The identity of a predator can be discerned from tracks, scat or the treatment of prey (e.g. chewed versus plucked feathers). The remains of a bird left uneaten by a predator (or undigested in the case of pellets or scat) can reveal the characteristics that made an individual vulnerable to attack. Species, and sometimes age and sex, can be determined from plumage or other morphological characteristics (Page and Whitacre 1975, Kus et al. 1984, Götmark and Post 1996). Information about body condition or health at the time of death is highly valuable, but usually difficult to obtain. In mammals, bone marrow fat from carcasses has been used to study the relationship between nutritional condition and predation risk (Huggard 1993, Sinclair and Arcese 1995 and references therein). Marrow fat in the non-pneumatized bones of birds is also a useful indicator of condition (Hutchinson and Owen 1984, Willebrand and Marcström 1989, Ringelman et al. 1992, Jeske et al. 1994, Thouzeau et al. 1997). Unfortunately, marrow fat is of limited use for investigation of the relationship between fat storage and predation risk above the threshold of malnutrition because this fat depot is generally mobilized only after most other body fat has been depleted (Hutchinson and Owen 1984, Mech and DelGiudice 1985, Torbit et al. 1988, Ringelman et al. 1992, Thouzeau et al. 1997, but see Willebrand and Marcström 1989).

The amount of body fat a bird carries is thought to be determined by fitness tradeoffs between the benefits of energy storage (e.g. for resisting starvation or fuelling migration) and a variety of costs, including predation risk (see Witter and Cuthill 1993 for a review). High body mass resulting from fat storage may increase an individual's risk of predation by increasing wing loading (mass/wing area), and thus impairing its escape performance (Blem 1975, Lima 1986). Although decreased flight performance with increasing body mass has been demonstrated in a number of studies (Kullberg et al. 1996, Lee et al. 1996, Lind et al. 1999, J. G. Burns and R. C. Ydenberg unpubl. data), a clear linkage to increased mortality in the field has not been made. Whitfield et al. (1999) found no relationship between Redshank *Tringa totanus* body condition and the probability of predation by Sparrowhawks *Accipiter nisus*; however, in only a minority of cases was body mass at the time of death measured directly.

The ability to determine body fat and body mass of a bird at the moment of capture, from body parts consistently left by predators, would facilitate the study of mass-dependent predation risk. In Ruffed Grouse *Bonasa umbellus*, the percent of fat in the plucked wing distal to the humerus can be used as an index of total body fat (Servello and Kirkpatrick 1987). Aerial predators typically do not consume the metacarpals and phalanges (Kus et al. 1984, Ringelman et al. 1992, Sodhi and Oliphant 1993, Jeske et al. 1994, Götmark and Post 1996), and mean wing recovery rates for wintering and migrating birds can range between 0.5 and 10 per day (Page and Whitacre 1975, Kus et al. 1984, Jeske et al. 1994, Whitfield et al. 1999, J. G. Burns and S. L. Wardrop unpubl. data). In this study, we describe a technique to predict percent body fat and total body mass of Western Sandpipers *Calidris mauri* from the fat content of the most distal wing tissue, and suggest its application in field research.

Materials and methods

Migrant Western Sandpipers were sampled at Boundary Bay, British Columbia, Canada (49°10′N, 123°05′W; Butler and Campbell 1987). Spring migrants of each sex were collected between 25 April and 10 May 1996. Fall migrants were collected in July (adults) and August (juveniles) of 1995 and 1996. Wintering (non-migratory) and pre-migratory birds were sampled in the Gulf of Panama (8°N, 79°W) from December 1995 to January 1996, and in March 1996, respectively. In the winter, body masses and body fat levels are low in both adult and first-year sandpipers. Beginning in February, pre-migratory adults in Panama accumulate fat, but do not alter lean body mass (controlling for body structural size), while yearlings which generally do not migrate remain light and lean (P. D. O'Hara unpubl. data, Guglielmo 1999). Due to permit limitations we studied only females in Panama.

We captured sandpipers with mist nets (Avinet, Dryden, NY, USA) under permits from the Canadian Wildlife Service, INRENARE (Panama) and the Simon Fraser University Animal Care Committee. Birds were sacrificed under anaesthesia (Guglielmo et al. 1998). Body mass was measured with a field balance (± 0.01 g) and sex was determined by gonadal inspection. Total tarsus, culmen and keel length were measured with digital calipers (± 0.01 mm). Birds from Panama were transported frozen to Canada for analysis.

All organs and flight muscles (pectoralis and supracoracoideus) were removed, lyophilized and weighed. Mesenteric fat was returned to the carcass for fat extraction. The distal wings (metacarpals and phalanges) were removed by cutting the carpal joints with scissors (Fig. 1a), and oven dried (with feathers) at 60°C to constant mass. The culmen and lower legs (excluding major muscles) were removed and oven dried. The remaining carcass was plucked, frozen, cut into small pieces, and placed in a pre-weighed filter paper envelope (Whatman # 1) for lyophilization. The dry carcass was Soxhlet extracted for eight hours with petroleum ether, and oven dried at 60°C. Carcass fat was calculated as dry mass before extraction minus dry mass after extraction, plus liver, heart and flight muscle fat (measured separately), and was corrected for small adipose tissue samples taken for other analyses (Egeler and Williams 2000). Percent body fat was calculated as carcass fat divided by fresh mass at capture.

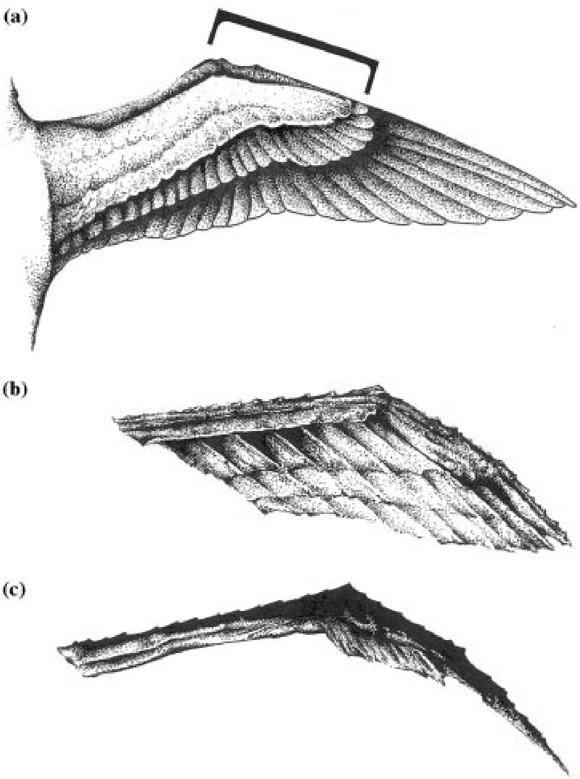

Fig. 1. (a) Ventral view of the wing of a Western Sandpiper indicating the portion of the wing used for analysis. (b) The appearance of the wing sample fat extracted in Method 1. (c) The appearance of wing samples used in Method 2.

Dried wings were stored in plastic bags for up to three years at room temperature, or frozen at −20°C for four years (fall 1995 birds) prior to analysis. Fat content of the right and left distal wings combined was measured by two methods. In Method 1, the wing coverts were carefully plucked, and the remiges cut with a scissors along a naturally occurring line of pigmentation near the bases of the feather shafts (Fig. 1b). In Method 2, feather shafts were completely cut from the tissue with a scalpel (Fig. 1c). Samples were re-dried over night at 60°C, weighed (± 0.0001 g), fat extracted for six hours, and dried at 60°C. Percent wing fat was calculated as extracted fat divided by distal wing dry mass.

Statistical tests of proportions were performed on arcsine transformed data; however, results are presented for untransformed data because the results of statistical tests and probabilities were nearly identical. Pearson correlation analysis was used to test for relationships among percent wing fat (%WF), percent body fat (%BF), and body mass. Analysis of covariance (ANCOVA) was used to test for differences in the relationship of %WF to %BF between ages, and among migratory stages. Least squares regression was used to develop predictive equations for %BF from %WF measurements. Multiple regression was used to develop predictive equations for body mass from %WF and either keel, tarsus or culmen length.

Results and discussion

Our initial analysis using Method 1 indicated that %WF was positively correlated with %BF in fall adult migrants, but not in any other migratory stage (Table 1), or in the entire sample combined (N = 80; R = 0.16,

Table 1. Correlation statistics for the relationship between percent fat in the metacarpus and phalanges of Western Sandpipers measured by two methods (see text for description) and percent body fat. Also shown is the range of body fat percentages for each migratory stage and age.

		Method 1			Method 2			Range
Stage	Age	N	R	P	N	R	P	% body fat
Fall 1995[1]	A	–	–	–	12	0.87	0.001	2.6–26.6
Winter	A	13	−0.06	0.850	–	–	–	2.5–7.6
Winter	J	4	0.40	0.600	8	0.28	0.510	2.4–12.2
Pre-migrant	A	6	0.16	0.760	8	0.74	0.036	4.9–19.7
Pre-migrant	J	10	0.31	0.380	5	0.04	0.950	2.1–6.5
Spring 1996	A	11	−0.28	0.400	20	0.54	0.014	1.5–24.0
Fall 1996	A	18	0.71	0.001	14	0.57	0.034	1.1–19.5
Fall 1996	J	18	0.30	0.230	10	0.61	0.063	1.6–28.2

[1] Sample contains one juvenile.

P = 0.76). We observed that birds which had grown the remiges nearer to the time of collection tended to have greater amounts of ether-extractable material in the distal wing than those with older feathers (e.g. winter adults had 20.4 ± 0.66%WF, while fall adults had 13.6 ± 0.75%WF, P = 0.0001). We also noted that feather shafts varied in color from bright yellow in the youngest feathers (fall juveniles) to a dull yellow or brown in older feathers (fall adults)

Analysis by Method 2 was a substantial improvement over Method 1, indicating that ether-extractable material in the feather shafts can obscure the relationship between %WF and %BF. Using Method 2, %WF was positively correlated with %BF combining samples from all stages (N = 77; R = 0.31, P = 0.006). When the data were divided by stage and age, %WF was significantly positively correlated with %BF in four of seven cases, and nearly so (P = 0.063) in a fifth (Table 1). Low sample size and insufficient variation in %BF may have contributed to the lack of significance in the remaining two cases. Ages were combined for subsequent analysis because we could detect no differences in the relationship between %WF and %BF between adults and juveniles during pre-migration (ANCOVA, slope P = 0.23, intercept P = 0.08) or fall 1996 (slope P = 0.91, intercept P = 0.18).

Although the relationship between %WF and %BF was consistently positive, our results suggest that it may be necessary to derive a predictive equation for the particular population of interest. ANCOVA indicated that samples of spring and fall migrants collected in 1996 could be combined (slope P = 0.85, intercept P = 0.51), however, the slope of the relationship between %WF and %BF differed significantly between 1995 fall and 1996 migrants (P = 0.03). The difference in slope may have been due to the fact that fall 1995 wings had been stored frozen prior to analysis while the 1996 samples were stored at room temperature, or because different personnel had conducted the carcass dissections. The slope of the relationship of %WF to %BF did not differ between pre-migrants and fall 1995 migrants (P = 0.57) or between pre-migrants and 1996 migrants (P = 0.27), however, the Y-intercept differed in both cases (P < 0.0003). One might expect a different relationship for pre-migrants because, controlling for body structural size, they have significantly lower lean body masses than migrants (Guglielmo 1999). Thus, the same absolute change in fat represents a greater proportional change in pre-migrants. We derived separate predictive equations for each group identified by ANCOVA (Fig. 2).

In some situations, such as when studying the relationship between wing loading and vulnerability, a prediction of body mass is more useful than one of %BF. While body fatness contributes significantly to variation in body mass (sandpiper body mass was positively correlated with %BF; R = 0.82, P = 0.0001), variation in lean body mass is also important. The masses of lean body components are known to be dynamic during migration, and may contribute to changes in total body mass (Lindström and Piersma 1993, Jehl 1997, Guglielmo 1999, Piersma et al. 1999). Nonetheless, some variation in lean mass should be related to body structural size (Lindström and Piersma 1993), particularly in a sexually dimorphic species like the Western Sandpiper (Wilson 1994). For each group previously identified by ANCOVA (above), we developed multiple regression equations to estimate sandpiper body mass from %WF and each of three morphometric indicators of body structural size likely to be recovered in carcasses (culmen, tarsus and keel). Adding a measure of structural size improved the model fit in every case, and

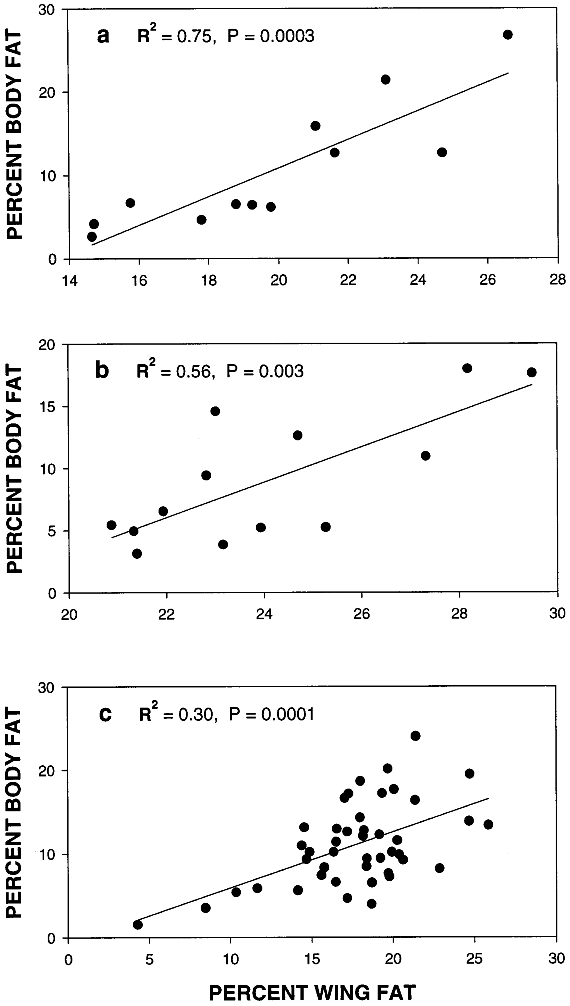

Fig. 2. The relationship between percent body fat of Western Sandpipers and percent fat of the distal wing prepared by Method 2. (a) fall migrants 1995, %BF = 1.71 ± 0.31 (%WF) − 23.3 ± 6.24; (b) pre-migrants, %BF = 1.42 ± 0.38 (%WF) − 25.2 ± 9.16; and (c) fall and spring migrants 1996, %BF = 0.67 ± 0.16 (%WF) − 0.74 ± 2.87. Note different scales.

Table 2. Univariate and multiple regression models to predict fresh body mass (BM) of Western Sandpipers from the percent fat in the distal wing tissue (%WF; B_1) alone, or along with culmen, tarsus or keel length (B_2) and the regression intercept (C). Data are from Method 2. Standard errors shown in parentheses.

Sample/Model	B_1	B_2	C	R^2	P
Fall 1995 (N = 12)					
BM = %WF	0.76 (0.31)	–	9.73 (4.88)	0.49	0.011
BM = %WF + Culmen	0.82 (0.25)	0.43 (0.43)	−1.66 (12.59)	0.55	0.029
BM = %WF + Tarsus	0.92 (0.28)	1.08 (0.94)	−20.55 (27.00)	0.56	0.025
BM = %WF + Keel	0.71 (0.23)	1.69 (1.18)	−30.09 (28.13)	0.59	0.018
Pre-migrant (N = 13)					
BM = %WF	0.93 (0.24)	–	2.84 (5.74)	0.58	0.002
BM = %WF + Culmen	0.89 (0.23)	1.04 (0.72)	−24.44(19.62)	0.66	0.005
BM = %WF + Tarsus	0.86 (0.19)	2.51 (0.88)	−61.71 (23.09)	0.77	0.001
BM = %WF + Keel	0.82 (0.22)	1.22 (0.66)	−24.19 (15.58)	0.69	0.003
Spring, Fall 1996 (N = 44)					
BM = %WF	0.36 (0.10)	–	20.71 (1.90)	0.22	0.001
BM = %WF + Culmen	0.28 (0.09)	0.67 (0.14)	5.75 (3.45)	0.50	0.001
BM = %WF + Tarsus	0.28 (0.08)	1.37 (0.23)	−12.93 (5.90)	0.58	0.001
BM = %WF + Keel	0.39 (0.09)	1.74 (0.38)	−21.40 (9.28)	0.49	0.001

the models explained between 49% and 77% of the variation in fresh body mass of sandpipers (Table 2).

Percent wing fat (measured by Method 2) can be used to obtain a prediction of percent body fat, and, if combined with a measure of structural size, a prediction of body mass of sandpipers from incomplete carcasses. Our technique may be widely applicable in birds, provided it is validated for the species or population of interest. The method is likely to be of most use in situations where body mass varies over a wide range due to fat storage. Rapid recovery of samples should minimize the effects of environmental conditions (temperature or sun) on the quality of carcasses, but freshness at collection did not affect marrow fat in Mallard *Anas platyrhynchos* wings (Ringelman et al. 1992). Percent fat of dry wings may have been affected by long-term storage conditions; however, wings stored in the same manner were still suitable even several years after the carcasses had been processed.

Extra body fat may impair flight performance by increasing wing loading, making a bird more vulnerable to capture by aerial predators (Blem 1975, Lima 1986). The methods we have described offer a possible means to test for the effects of fatness on predation risk by allowing comparison of killed birds to survivors in the field.

Acknowledgements – The authors are grateful to T. D. Williams for the use of equipment, and S. L. Wardrop for assistance in the laboratory. Thanks to R. W. Butler, M. C. Drever, D. B. Lank, T. Piersma, J. Williams and R. C. Ydenberg for their thoughtful comments, and to the Smithsonian Tropical Research Institute and P. D. O'Hara for assistance in Panama.

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