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EMPIRICAL LENGTH AND WEIGHT CONVERSION EQUATIONS FOR BLUE MARLIN, WHITE MARLIN, AND SAILFISH FROM THE NORTH ATLANTIC OCEAN

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ABSTRACT

Because commercially caught billfishes are usually processed at sea, and because size measurements are usually taken after the fish have been dressed, there is a need for conversion among different measures of size (length or weight) for assessment and management purposes. Here, we present empirical equations for converting among measures of size for blue marlin, *Makaira nigricans*; white marlin, *Tetrapturus albidus*; and sailfish, *Istiophorus platypterus*, from the North Atlantic Ocean. A series of length–length equations allows conversion from any of six length measures to lower jaw–fork length; and a series of length–weight and weight–length equations allow conversion between lower jaw–fork length and round weight. To estimate the equations, we used large data sets that have recently become available. We incorporated bias corrections into the length–weight and weight–length equations and used robust regressions for the length conversions. Equations for each species are given by sex and also for combined sexes, so that conversions can be made whether the sex of the specimen is known or not.

About 90% of the world's landings of billfishes (Istiophoridae) are taken as incidental catch in offshore longline fisheries targeting tunas and swordfish (King, 1989). In the North Atlantic, billfishes caught in such fisheries are usually processed at sea, with heads, fins, and viscera removed and carcasses frozen for offloading months later (Prince and Brown, 1991). Billfish carcasses may have been dressed in one of 10 or more ways (Prince and Miyake, 1989; Fig. 1) before length measurements are taken. This leads to many common measures of whole and dressed length (Fig. 2) and the need for empirical equations for conversion among them. Because the fish are rarely weighed by fishermen or dealers, there is also a need for conversion equations between length and weight.

Empirical equations for converting among size measures of these three species in North Atlantic waters have been presented by several previous authors. de Sylva and Davis (1963) gave length–weight relationships for postspawning male and female white marlin collected off the mid-Atlantic coast of the United States. Jolley (1974) presented similar equations for Atlantic sailfish, based on observation of 412 specimens. Lenarz and Nakamura (1974) estimated a variety of conversion equations for the three species considered here. Rivas (1974) provided illustrations of length–weight curves for blue marlin, fitted by eye to data on 58 males and 104 females. Baglin (1979) presented weight-to-length estimation equations for white marlin, by sex, in the North Atlantic and the Gulf of Mexico. Prince and Lee (1989) gave empirical conversion equations for estimating lower jaw–fork length (LJFL) from four other length measures on Atlantic billfishes: eye orbit–fork length (EOFL), pectoral–second dorsal length (PDL), dorsal–fork length (DFL), and pectoral–fork length (PFL). Lee and Prince (1990) presented empirical equations for converting LJFL to total length (TL) and TL to LJFL, but several of their equations contained typographical errors. Lee and Prince (1990) also gave conversions between TL and round weight and between LJFL and round weight. Many of the preceding authors gave results for each sex separately, but did not develop equations for use on specimens of unknown sex. However, the sex of fish taken in these offshore fisheries is rarely known, unless sex data are

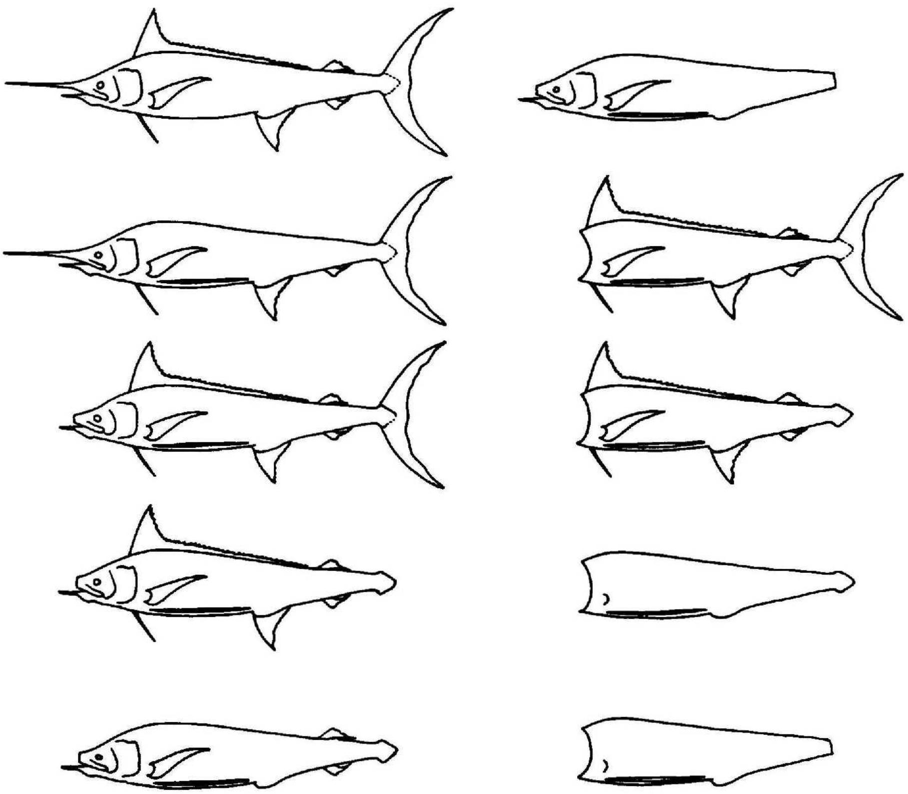

Figure 1. Ten methods used to dress billfishes (Istiophoridae) at sea. Length measurements are generally taken on dressed carcasses, making conversion to a standard length measurement necessary.

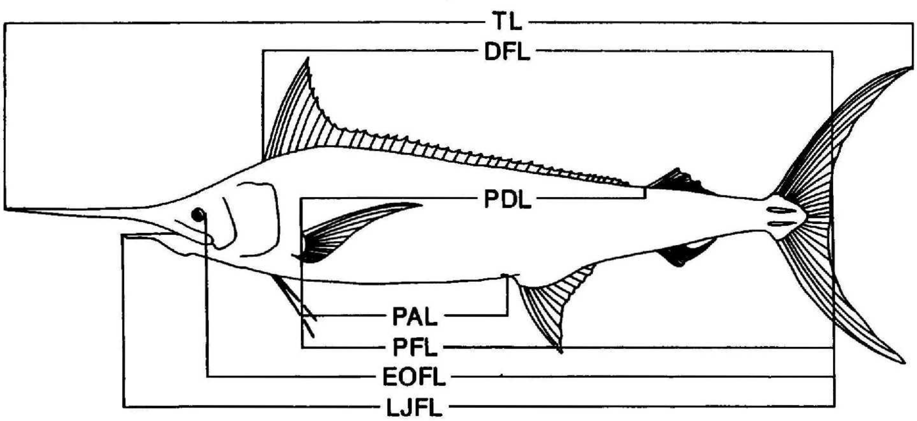

Figure 2. Length measures used for recording lengths of billfishes (Istiophoridae) landed in commercial and recreational harvests. TL, total length; DFL, Dorsal–fork length; PDL, Pectoral–second dorsal length; PAL, pectoral–anus length; PFL; pectoral–fork length; EOFL, eye orbit–fork length; LJFL, lower jaw–fork length.

collected by scientific observers (Prince and Brown, 1991). Thus, it is often necessary to estimate weight from the length of fish of unknown sex.

Prager et al. (1992) reanalyzed the data of Lee and Prince (1990) to arrive at slightly revised equations for the length–weight and weight–length conversions. The revisions comprised correction of the equations for bias and development of equations intended for use when the sex of a fish is not known.

The present paper has two objectives. The first is to present revised versions of many of the existing conversion equations; these new equations are based on large data sets that have recently become available. We also include a new equation for conversion of pectoral–anus length (PAL) to LJFL. The second objective is to present a comprehensive set of conversion equations in a single readily accessible reference. In addition, our use of robust regression, a statistical technique relatively new to fishery science, may be of methodological interest.

Data and Methods

Data were obtained from the files of the National Marine Fisheries Service (NMFS) Southeast Fisheries Science Center, Miami, Florida, and had two origins. Some of the data were originally recorded by NMFS personnel and describe fish caught from 1972 through 1992 in the U.S. Atlantic EEZ, the Gulf of Mexico and the Caribbean Sea. These data are mainly records of LJFL, TL, and round weight. About 80% of these data were taken at recreational billfish tournaments, and the remaining data are on non-tournament recreational billfish landings (Farber et al., 1992). The second original source of data was the Enhanced Research Program for Billfish of the International Commission for the Conservation of Atlantic Tunas (ICCAT). These data were taken from 1987 through 1992 by scientists of several nations, and include observations on fish caught in the waters off Barbados, the Canary Islands (Spain), Grenada, Senegal, Trinidad, and Venezuela. Data were collected both at sea and on shore; longline, artisanal, and recreational rod-and-reel fisheries are represented (Carter, 1992). Data from these two sources were used to develop equations to estimate LJFL from any of six other measures of length (Fig. 2) and to convert between LJFL and round weight. Before the data were used for estimation, they were visually screened for gross outliers, which were removed.

Conversions between Length and Weight.—Equations for conversion between length and weight used the allometric (power-equation) form. In fitting allometric equations to data, we used logarithmic transformations: Instead of fitting directly a length–weight relationship of the form

$$w = a \cdot l^b, \quad (1)$$

(where w is the weight of a fish, l is its length, and a and b are estimated constants), we took the natural logarithm of each side of the equation so that it became

$$\ln(w) = \ln(a) + b \cdot \ln(l). \quad (2)$$

Use of this transformation allows estimating the constants a and b by ordinary least squares. In addition, the transformation is theoretically consistent with the observation that the coefficient of variation of length at weight (or of weight at length) tends to be constant; i.e., that the error around equation (1) follows a lognormal distribution.

The logarithmic transformation, however, introduces a bias into the resulting equation when it is used for prediction. The correction for this bias was described in the ecological literature by Baskerville (1972) and Whittaker and Marks (1975); a minor correction was given by Sprugel (1983). The correction is not complex. If a prediction from equation (2) is denoted $\hat{Y}_{OLS}$ and the correction factor is denoted CF, then the corrected prediction is

$$\hat{Y}_{corr} = \hat{Y}_{OLS} \cdot CF. \quad (3)$$

The correction factor as given by Sprugel (1983) is

$$CF = [\exp \mathrm{SSE}/2(n - 2)], \quad (4)$$

where SSE is the sum of squared errors from the OLS regression [equation (2)] and n is the sample size.

We fit allometric equations for the most common measure of billfish length, lower jaw–fork length (LJFL), computed the correction factors, and incorporated them directly into the equations as presented here. Because sample sizes were large, the correction factors were within 1% of unity. All allometric conversion equations were estimated with the REG procedure of the Statistical Analysis System (SAS, 1988).

Table 1. Coefficients of bias-corrected equations for predicting round weight (kg) from lower jaw–fork length (cm) using the equation $\hat{w} = a{\cdot}l^b$ or predicting lower jaw–fork length from round weight using the equation $\hat{l} = c{\cdot}w^d$. Bias-correction factors have been incorporated into parameters a and c so that no further correction is necessary. For explanation, see text.

Sex	Sample size	Weight range, kg	Length range, cm	Coefficients a	b	c	d	Model R^2 (log data)
Blue Marlin								
♀	3,267	0.06–540.9	23.0–378.5	1.9034×10^{-6}	3.2842	61.731	0.28180	0.93
♂	1,978	0.06–178.0	23.0–277.0	2.4682×10^{-6}	3.2243	61.961	0.28137	0.91
♀♂	5,245	0.06–540.9	23.0–378.5	1.1955×10^{-6}	3.3663	62.010	0.28065	0.94
White marlin								
♀	3,149	2.7–67.1	91.4–205.0	3.9045×10^{-6}	3.0694	78.423	0.23191	0.71
♂	1,719	3.6–41.3	96.0–195.5	1.9556×10^{-5}	2.7487	76.847	0.23548	0.65
♀♂	4,868	2.7–67.1	91.4–205.0	5.2068×10^{-6}	3.0120	76.460	0.23888	0.72
Sailfish								
♀	1,280	0.04–52.7	27.1–204.5	1.1441×10^{-6}	3.2683	74.614	0.26460	0.86
♂	907	0.04–30.1	27.1–188.0	1.6922×10^{-6}	3.1879	70.907	0.28191	0.90
♀♂	2,187	0.04–52.7	27.1–204.5	1.2869×10^{-6}	3.2439	72.962	0.27201	0.88

Conversions among Measures of Length.—Conversions among length measures (Fig. 2) can generally be accomplished with simple linear regression models. To increase robustness to other possible outliers or data errors, the equations presented here were fit with a robust-regression method, least-absolute-values (LAV) regression. In the LAV technique, the quantity minimized is not the sum of the squares of the residuals, as in ordinary-least-squares (OLS) regression, but instead is the sum of the absolute values of the residuals (Krasker, 1988; Berk, 1990). When the data contain no outliers, estimates from LAV regression are nearly identical to those from OLS regression. However, the OLS parameter estimates can be influenced quite strongly by relatively few outliers, especially if they occur near the extremes of the data. In contrast, the parameter estimates from LAV regression are much less influenced by outliers; hence the term "robust regression." Equations derived from LAV are applied in the same way as those derived from OLS.

Estimation of LAV regressions can be accomplished with most commercially available nonlinear estimation software; we used the NONLIN procedure of Systat (Wilkinson, 1990). We were unable to obtain correct results from version 6.04 of the NLIN procedure of SAS for Personal Computers (SAS, 1988), and we have concluded that this program contains an error that makes its use with non-OLS loss functions unreliable.

Results

For predicting round weight from lower jaw–fork length, we use the notation

$$\hat{w} = al^b. \quad (5)$$

For predicting lower jaw–fork length from round weight, the corresponding notation is

$$\hat{l} = cw^d. \quad (6)$$

The bias-corrected coefficients a, b, c, and d of equations (5) and (6) are tabulated in Table 1, along with the R^2 values for the equations on the logarithmically transformed data.

Conversions among length measures are given in Tables 2 through 4. Because these models were fit by LAV regression, they are not optimal for R^2. Nonetheless, the R^2 was within 1% of OLS regressions in all cases. The R^2 values in these tables were computed as the square of the Pearson correlation coefficient r between the observed and predicted LJFL values. This is equivalent to the usual R^2 of OLS models.

Table 2. Blue marlin from the North Atlantic Ocean. Coefficients of robust-regression equations for predicting lower jaw–fork length λ_0 (cm) from another measure of length λ_1 (cm) using the equation $\hat{\lambda}_0 = \alpha + \beta\lambda_1$. "Approx. length range" refers to λ_1. A question mark in column 2 indicates that the sex of some specimens was not known.

Predictor variable λ_1	Sex(es)	Sample size (N)	Approx. length range (cm)	Model R^2	Intercept, α	Slope, β
PAL	♀	123	34–120	0.70	19.464	2.707
	♂	249	35–90	0.42	93.600	1.600
	♀♂?	453	30–120	0.57	61.656	2.156
PFL	♀	243	80–270	0.96	9.725	1.252
	♂	387	100–220	0.94	14.651	1.209
	♀♂?	732	65–280	0.97	7.696	1.261
PDL	♀	140	85–190	0.91	17.419	1.726
	♂	276	66–150	0.69	36.500	1.500
	♀♂?	482	60–190	0.92	9.836	1.772
TL	♀	69	250–490	0.95	−3.563	0.784
	♂	153	200–330	0.75	19.182	0.691
	♀♂?	258	30–500	0.96	2.000	0.763
EOFL	♀	113	130–300	0.97	10.000	1.091
	♂	104	135–210	0.92	9.095	1.095
	♀♂?	250	120–300	0.98	8.887	1.096
DFL	♀	115	125–280	0.96	10.254	1.198
	♂	125	115–200	0.92	4.302	1.231
	♀♂?	271	100–280	0.97	7.152	1.212

Table 3. White marlin from the north Atlantic. Coefficients of robust-regression equations for predicting lower jaw–fork length λ_0 (cm) from another measure of length λ_1 (cm) using the equation $\hat{\lambda}_0 = \alpha + \beta\lambda_1$. "Approx. length range" refers to λ_1. A question mark in column 2 indicates that the sex of some specimens was not known.

Predictor variable λ_1	Sex(es)	Sample size (N)	Approx. length range (cm)	Model R^2	Intercept, α	Slope, β
PAL	♀	105	40–66	0.40	96.462	1.231
	♂	123	40–85	0.46	103.501	1.100
	♀♂?	272	35–85	0.42	108.000	1.000
PFL	♀	188	92–145	0.83	9.400	1.280
	♂	172	80–180	0.88	26.000	1.133
	♀♂?	424	80–180	0.84	13.572	1.242
PDL	♀	127	72–115	0.74	48.834	1.278
	♂	121	68–110	0.87	53.316	1.211
	♀♂?	294	65–115	0.75	39.250	1.375
TL	♀	51	190–245	0.60	5.923	0.731
	♂	65	130–235	0.83	18.664	0.667
	♀♂?	127	130–280	0.74	−0.720	0.760
EOFL	♀	65	128–165	0.92	14.743	1.061
	♂	30	115–160	0.92	9.581	1.097
	♀♂?	102	115–165	0.93	15.444	1.056
DFL	♀	75	115–150	0.78	29.184	1.053
	♂	47	105–150	0.95	14.539	1.154
	♀♂?	129	105–150	0.89	13.834	1.167

Table 4. Sailfish from the north Atlantic. Coefficients of robust-regression equations for predicting lower jaw–fork length λ_0 (cm) from another measure of length λ_1 (cm) using the equation $\hat{\lambda}_0 = \alpha + \beta\lambda_1$. "Approx. length range" refers to the predictor variable in the equation. A question mark in column 2 indicates that the sex of some specimens was not known.

Predictor variable λ_1	Sex(es)	Sample size (N)	Approx. length range (cm)	Model R^2	Intercept, α	Slope, β
PAL	♀	652	30–90	0.33	126.615	0.692
	♂	455	35–80	0.31	121.717	0.736
	♀♂?	1,553	30–100	0.47	107.000	1.000
PFL	♀	728	75–175	0.77	21.404	1.146
	♂	484	90–150	0.77	14.400	1.200
	♀♂?	1,810	75–180	0.78	14.800	1.200
PDL	♀	113	55–120	0.71	31.640	1.414
	♂	42	75–110	0.86	12.800	1.598
	♀♂?	330	55–120	0.68	22.551	1.504
TL	♀	83	120–260	0.69	10.186	0.718
	♂	52	110–245	0.80	14.049	0.695
	♀♂?	142	40–270	0.81	10.186	0.718
EOFL	♀	58	85–175	0.93	10.330	1.075
	♂	27	105–155	0.89	20.300	1.000
	♀♂?	251	85–175	0.89	7.719	1.106
DFL	♀	59	75–165	0.77	11.369	1.150
	♂	21	110–145	0.95	−2.915	1.248
	♀♂?	252	75–165	0.75	13.143	1.143

Discussion

The bias correction used for the allometric equations is simple to compute and apply. In the present case, the models fit well (Fig. 3), giving correction factors within 1% of unity. Corrections encountered in other cases can be larger. For example, Saila et al. (1988: 149) found that a correction factor of about 1.1 was necessary in an age–fecundity relationship for yellowtail flounder. Because it seems logical to correct for a known bias, the correction should be incorporated routinely into equations for conversion between length and weight.

All three allometric models seem to overestimate the weight of very small fish (Fig. 3), although the degree of bias is hard to quantify because of the small number of very small fish in each sample. This suggests that the equations should probably not be used for very small fish. We did refit the equations without the very small fish, but the changes in the regression coefficients were extremely small; the sample sizes are quite large (Table 1). If more specimens of very small fish were available, it might be useful to fit separate length–weight models for that size category or a nonlinear model covering all sizes.

The length–length regressions were fit with a form of robust regression, a useful statistical technique with a large literature. The development of robust regression was motivated by the inefficiency of OLS when the errors in the data have heavier tails than a normal distribution (Krasker, 1988), which may be the case for many fisheries data, especially when quality control is not perfect. Of course, data sets should always be screened for obvious outliers, but in many practical cases questionable points will remain after this is done. Then the investigator is faced with a difficult choice—whether to discard a few potentially influential (in the statistical sense) observations because they *might* be wrong. The use of robust regression is not a replacement for quality control nor a panacea for all problems, yet

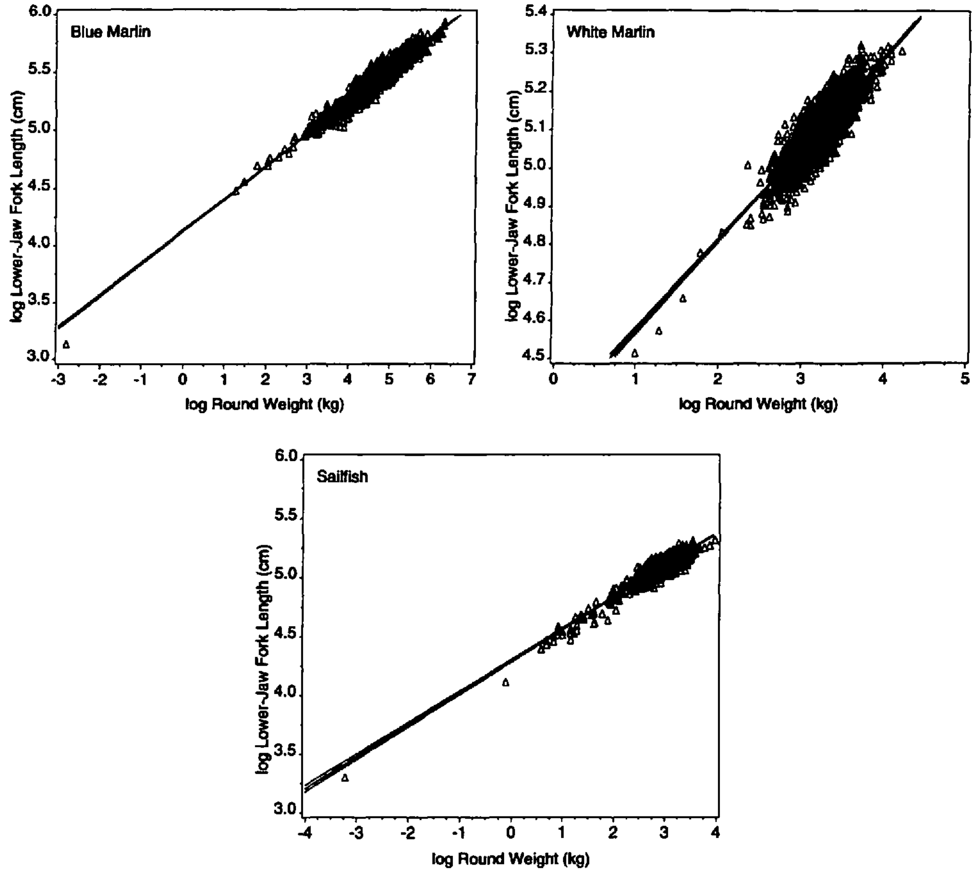

Figure 3. Length–weight relationships for billfishes (Istiophoridae). Data (natural logarithms), regression line, and 95% confidence limits for the mean are shown. Confidence limits are quite narrow, and may be difficult to see.

it provides a practical solution to the type of difficulties mentioned, as it allows questionable data to be retained while reducing their influence on the final estimates.

The resulting length–length equations (Tables 2–4) are predictive equations; i.e., when estimating them, the errors in the estimated quantity (LJFL) were minimized. Predictive equations, whether fit by OLS or LAV, should not be inverted and used to estimate other length measures from LJFL. Equations for estimating other measures from LJFL could be derived from the same data, but would not be equivalent to the inverses of the equations given.

Many of the length–length models fit quite well (Fig. 4a), as indicated by many high R^2 values in Tables 2 through 4. Where the R^2 is relatively low, it appears to indicate not a lack of linearity, but a relatively high variance about the predicted value, as in the PAL–LJFL relationship for male blue marlin (Fig. 4b). In such a situation, the linear model nonetheless provides a good estimate of the average LJFL corresponding to the observed PAL. The high variance suggests that information is lost by measuring only PAL (for example), rather than LJFL or some other measure closer to total length. This loss of information would be of serious

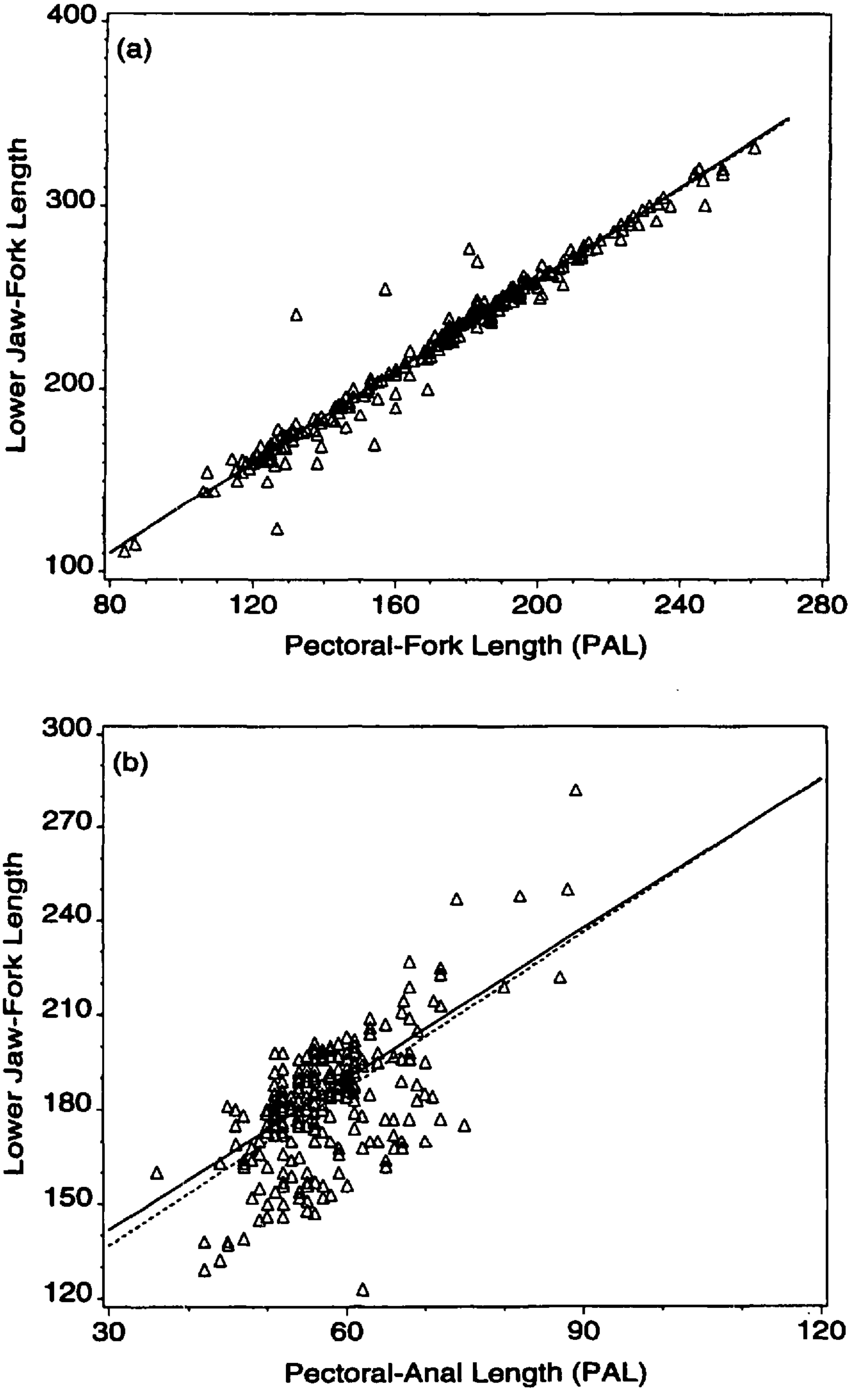

Figure 4. Examples of length–length models for billfishes. Both panels: Δ, observed data; ——, LAV regression line; – – –, OLS regression line. (a) PFL–LJFL model for female blue marlin. R^2 = 0.96, one of the highest observed. LAV and OLS lines are almost coincident. (b) PAL–LJFL model for male blue marlin. R^2 = 0.42, one of the lowest observed. LAV line is closer to the mode (e.g., between 50 cm and 70 cm PAL). Although there is considerable variability about the regression line, it does not appear that the relationship is nonlinear.

concern if growth curves based on LJFL or TL were to be used, along with converted values of PAL, to make estimates of the population's age structure. Such estimates would have very high variance; if the noise in the PAL–LJFL relationship reflects seasonal or other systematic effects, the estimates could be badly biased, as well.

The length data used in this study were taken by placing measuring tapes over the curve of the body (curved body measurements). In contrast, many of the length measurements available from the offshore longline fleets are straight measurements (i.e., taken by fixing a ruler to the deck and not including the body curvature). Because billfishes are elongated species, the differences between straight and curved body measurements are probably quite small in most cases. The difference would likely be largest for large blue marlin, which are more robust in shape than sailfish, white marlin, or smaller blue marlin. Because swordfish *Xiphias gladius* are at least as robust as blue marlin of equivalent length, a study of straight and curved measurements on swordfish made by Lee and Scott (1992) is pertinent. Lee and Scott found that parameter estimates of size-conversion equations for swordfish based on curved measurements did not differ significantly ($P < 0.05$) from equivalent equations based on straight measurements. Thus the same equations could be used for converting either straight or curved measurements to the corresponding LJFL. Although we believe the difference between straight and curved lengths is negligible for most individuals, it is preferable not to mix straight and curved length data until a study examining this proposition is conducted. Such a study could develop conversion equations, if needed, for conversion between straight and curved measurements.

In summary, lower jaw–fork length is regarded as the most reliable measure of length for the Istiophoridae (Rivas, 1956), but because of the nature of the fisheries, records of LJFL are often not available. The models given here should allow most size and size–frequency data to be converted into a standard unit of measurement (LJFL), and thus facilitate data collection and study.

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