Electronic Supplementary Materials (ESMs)

The foraging benefits of being fat in a highly migratory marine mammal

Adachi et al.

Table S1. The results of generalized linear mixed models (GLMM) with (a) bottom duration and (b) dive efficiency (i.e., bottom duration per dive cycle, which is composed of transit time, bottom time and post-surface time) as the response variables, and round-trip strokes-per-metre (number of strokes per metre swam, represented in strokes m$^{-1}$) and dive depth as the explanatory variables, including individual as a random effect. Daily values are used for statistical analysis. Akaike’s information criterion corrected for small samples (AIC$_c$), AIC$_{weight}$, intercept and slope coefficient are shown for each model. The means as well as 95% confidence intervals of slope coefficient are also shown. The models with the lowest AIC$_c$ are shown in bold type.

(a)

<table>
<thead>
<tr>
<th>Candidate models</th>
<th>AIC$_c$</th>
<th>AIC$_{weight}$</th>
<th>Intercept</th>
<th>Slope coefficient</th>
<th>Dive depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom duration ~ Round-trip strokes-per-metre</td>
<td>6243.7</td>
<td>0.326</td>
<td>30.010</td>
<td>-49.130 -51.202 -46.643</td>
<td>-0.0006 -0.0019 0.0012</td>
</tr>
<tr>
<td><strong>Bottom duration ~ Round-trip strokes-per-metre</strong></td>
<td><strong>6242.2</strong></td>
<td><strong>0.674</strong></td>
<td><strong>29.610</strong></td>
<td><strong>-48.860 -50.911 -46.773</strong></td>
<td><strong>0.0094 0.0074 0.0117</strong></td>
</tr>
<tr>
<td>Bottom duration ~ Dive depth</td>
<td>7454.5</td>
<td>0</td>
<td>6.974</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom duration ~ 1</td>
<td>7526.3</td>
<td>0</td>
<td>12.040</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>Candidate models</th>
<th>AIC$_c$</th>
<th>AIC$_{weight}$</th>
<th>Intercept</th>
<th>Slope coefficient</th>
<th>Dive depth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dive efficiency ~ Round-trip strokes-per-metre</strong> + Dive depth</td>
<td><strong>-5010.4</strong></td>
<td><strong>1</strong></td>
<td><strong>0.917</strong></td>
<td><strong>-0.787 -0.830 -0.772</strong></td>
<td><strong>-0.0003 -0.0003 -0.0003</strong></td>
</tr>
<tr>
<td>Dive efficiency ~ Round-trip strokes-per-metre</td>
<td>-4745.6</td>
<td>0</td>
<td>0.720</td>
<td>-0.677 -0.721 -0.635</td>
<td>-0.0001 -0.0001 -0.0001</td>
</tr>
<tr>
<td>Dive efficiency ~ Dive depth</td>
<td>-4089.4</td>
<td>0</td>
<td>0.536</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dive efficiency ~ 1</td>
<td>-4058.3</td>
<td>0</td>
<td>0.477</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure S1. The detail of the on-board data processing algorithm programmed in Stroke Loggers to detect strokes: an example during ascent phase. Lateral accelerations often contained low frequency variations (i.e., static accelerations) that presumably relate to various turning and rolling movements (i.e., changes in posture) by seals (Sato et al. 2003). These static accelerations were separated from raw lateral accelerations (measured at 32 Hz: black line in the second row panel) to obtain dynamic accelerations associated with propulsive activities (i.e., flipper strokes) of seals by following three steps below: (1) a moving average using 60 points from the raw lateral accelerations data was calculated to obtain static accelerations (associated with posture), (2) these static accelerations were subtracted from the raw lateral acceleration data to obtain dynamic accelerations (associated with propulsive activities) (Wilson et al. 2006), and (3) these dynamic accelerations were then filtered with a moving average window using three data points to remove noise (e.g., Watanabe et al. 2006). These three steps gave us dynamic accelerations (blue line in the third row panel) that closely matched those obtained by the high-pass filtering method (gray bold line in the third row panel), which has been applied to detect strokes in previous studies (Sato et al. 2003; Watanabe et al. 2006). Then, the dynamic accelerations obtained from the algorithm (blue line in the third row panel) were used to detect each stroke (i.e., a cycle of swaying hind flippers: binary data in the bottom panel), identified as an acceleration amplitude exceeding the threshold of 0.08 g (red dotted lines in the third row panel) within 2.5-second time windows. Finally, the resulting number of strokes were counted and recorded every five seconds in the Stroke Loggers.
Stroke Loggers were designed to record raw lateral accelerations (32 Hz) for 12 hours from the point where the seals firstly exceeded 900 m depth in their migrations. These raw lateral accelerations obtained from all 14 individuals (i.e., 168 hours including 424 dives in total, with individual mean ± s.d. of 30.3 ± 4.2 dives) were used to show the validity of the algorithm to calculate number of strokes programmed in Stroke Loggers (see Figure S1). Vertical axis indicates number of strokes obtained from Stroke Loggers with the on-board data processing algorithm (see Figure S1). Horizontal axis indicates number of strokes obtained by high-pass filtering method (Sato et al. 2003; Watanabe et al. 2006) with the amplitude threshold of 0.08 g (the same value as Stroke Loggers: see Figure S1) to detect each stroke for all 14 individuals. Open blue and red circles represent number of strokes during descent and ascent phase of each dive, respectively. Dotted black line represents y = x. Blue and red lines represent regression lines obtained by the least-squares method for descent (y = 1.043*x - 0.026, slope coefficient = 0.971) and ascent (y = 1.004*x + 2.094, slope coefficient = 0.999) phase. Regression lines were fitted to all 14 individual data points pooled. Also, number of strokes was calculated when seals were over 100 m depth. Note that each stroke was detected as a cycle of swaying hind flippers.
Figure S3. Time series data for strokes-per-metre (number of strokes per metre swam, represented in strokes m⁻¹; top panels), the proportion of time spent in prolonged gliding (second row panels), swim speed (third row panels), drift rate (fourth row panels) and bottom duration (bottom panels) for all other 12 seals during short and long foraging migration. In the top panels, open blue and red circles represent daily-averaged values of descent and ascent strokes-per-metre, respectively, with standard errors. Filled black circles represent round-trip strokes-per-metre, which is calculated as the sum of descent and ascent strokes-per-metre. In the second row panels, open blue and red triangles represent daily-averaged values of the proportion of time spent in prolonged gliding during descent and ascent phases, respectively, with standard errors. In the third row panels, open blue and red squares represent daily-averaged values of descent and ascent swim speed, respectively, with standard errors. In the fourth row panels, grey cross marks represent drift rates calculated from each drift dive. Thick black lines represent interpolated values of drift rate. Grey dotted lines indicate neutral buoyancy (i.e., drift rate = 0). In the bottom panels, open black circles represent daily-averaged values of bottom duration with standard errors.
Figure S3. Continued.
Figure S3. Continued.
Figure S3. Continued.
Figure S4. The relationship between strokes-per-metre (number of strokes per metre swam, represented in strokes m⁻¹) and swim speed during dives for all 14 individuals. Circles and squares represent daily values for seals during the short and long foraging migration, respectively. The color indicates values of drift rate. Left and right panels show descent and ascent phase, respectively.

Figure S5. The relationship between dive pitch angle and drift rate for all 14 individuals. Left and right panels show daily values of descent (blue colors) and ascent (red colors) pitch angle, respectively. Filled dark and light blue (or red) circles represent daily values for seals during the short and long foraging migration, respectively.
Figure S6. The relationship between transit duration and drift rate during dives for all 14 individuals. Circles and squares represent daily values for seals during the short and long foraging migration, respectively. The color indicates values of dive depth. Left and right panels show descent and ascent phase, respectively.

Figure S7. The relationship between bottom duration and drift rate during dives for all 14 individuals. Circles and squares represent daily values for seals during the short and long foraging migration, respectively. The color indicates values of dive depth. Left and right panels show descent and ascent phase, respectively.
Figure S8. The relationship between dive efficiency (bottom duration per dive cycle, which is composed of transit time, bottom time and post-surface time) and round-trip strokes-per-metre (number of strokes per metre swam, represented in strokes m$^{-1}$) for all 14 individuals. Filled black and grey circles represent daily values for seals during short and long foraging migration, respectively.
Figure S9. Hypothetical calculations of round-trip gross energetic costs, plotted against drift rates for all 14 individuals. Round-trip gross energetic costs were calculated by assuming that seals dive to 500 m with the set of swim speeds (m s\(^{-1}\)) and pitch angles (degree) shown in Figure 2 and Figure S5, respectively. The following equation in Williams et al. (2004) was used:

\[
\text{Round-trip gross energetic cost (ml O}_2\text{ kg}^{-1}) = \text{BMR}*t + 0.044*S_{\text{sw}},
\]

where BMR is basal metabolic rate (ml O\(_2\) kg\(^{-1}\) min\(^{-1}\); i.e., maintenance cost), \(t\) is time required for a round-trip to 500 m depth, 0.044 is the net cost per stroke of Weddell seals reported by Williams et al. (2004) and \(S_{\text{sw}}\) is the total number of strokes required for a round-trip to 500 m depth, calculated based on the empirical values of strokes-per-metre obtained in this study. Here, we use four sets of BMR values, which are 2.5 ml O\(_2\) kg\(^{-1}\) min\(^{-1}\) (Kleiber 1975) multiplied by 2, 1, 0.8 or 0.5 (represented in the panel (a), (b), (c) and (d), respectively), because there are still discussions about the value of BMR, which varies 0.8 to 2.2 times that of Kleiber's estimation (Boyd 2002). The net cost per stroke is kept constant.

These results show that uncertainties in BMR values may alter the effects of buoyancy changes on round-trip gross energetic costs significantly, representing the limitation of our study; we did not measure and track the BMR. This limitation is significant, because the BMRs of seals are known to change seasonally (seasonal hypometabolism: Hedd et al. 1997; Sparling et al. 2006), though we needed to assume constant BMR throughout migrations in these calculations. These results highlight the need for the accurate measurement of maintenance costs in the field to understand fully how seals allocate available oxygen to locomotion and foraging activities.
References cited.


