A new device for monitoring the activity of freely swimming flatfish, Japanese flounder

Paralichthys olivaceus

Ryo KAWABE, Katsuki NASIMOTO, Tomonori HIRAIASHI, Yasuhiro NAITO AND Katsufumi SATO

ABSTRACT: The tail beat and activity behavior of four captive Japanese flounder Paralichthys olivaceus, were monitored with acceleration data-loggers while the fish swam in an aquarium. Depth, swimming speeds and two-axis acceleration data were collected continuously for approximately 20 h per fish. Simultaneously, the swimming behaviors of the fish were filmed at different angles. Using the specific characteristic of the acceleration profiles, in tandem with other types of data (e.g. speed and depth), four behavioral patterns could be distinguished: (i) ‘active’ swimming; (ii) burying patterns; (iii) ‘inactive’ gliding; and (iv) lying on the bottom. Tail beat frequency ranged from 1.65 ± 0.47 to 2.04 ± 0.25 Hz (mean ± SD; n = 4). Using the relationship between tail beat frequency and swimming speed, the ‘preferred’ swimming speed of the fish was estimated to be between 0.6 and 1.2 body lengths (BL)/s. Additionally, fish rarely swam faster than 1.2 BL/s. This study shows that the acceleration data-loggers represent a useful and reliable system for accurately recording the tail beat of free-ranging fish and estimating flatfish behavior.

KEY WORDS: acceleration data-logger, behavior, Japanese flounder, Paralichthys olivaceus, swimming speed, tail beat frequency.

INTRODUCTION

In order to understand fish ecology better, the underwater behavior of free-ranging individuals must be reliably monitored. However, since direct assessments of swimming speed and the proportion of time spent swimming by free-ranging fish are difficult to obtain, there is a growing need for a reliable methodology that would provide accurate information on the behavior and energetics of free-ranging fish. Although direct underwater observations by scuba divers or video cameras delivered some first insights into the behavior of free-ranging fish, such approaches remain limited, especially in the case of highly mobile species or nocturnal foragers. However, behavioral studies using water speed sensing transmitters have allowed researchers to investigate the actual underwater behavior of free-ranging fish. Unfortunately, speed sensors are known to sometimes overestimate swimming speed and energy expenditure if the fish is gliding and may be influenced by water-current speed and direction. Facilitated by recent advances in data-logger technology, data-loggers that record body movements through two accelerometer signals were developed and deployed on a variety of free-ranging aquatic animals. This enabled researchers to monitor various activities, such as, the porpoising behavior and postures of penguins or the fin-beating activity of free-ranging migrating chum salmon, in tandem with records of swimming speed, diving angle and diving depth.

Yet, few behavioral data are available for demersal fish, such as, flatfish. Flatfish do not have an air bladder and are therefore negatively buoyant in their medium. This forces them to lie on one side on the seabed, which may be advantageous for camouflage and cryptic behavior. Olla et al. classified the following categories of behavior in captive summer flounder Paralichthys dentatus: resting (lying on the bottom), burying, swimming, gliding and feeding. These activities, while mainly exhibited during daytime, were observed throughout the 24 h day-cycle. To measure the energetic costs of an active behavior, it is important to systematically integrate all of the activities of free-ranging flatfish and establish behavioral time bud-
gets. However, time allocation and/or precise energy budgets cannot be estimated using only visual observation of captive fish. A method to measure the energy budgets of free-ranging flatfish is therefore a prime necessity.

In this regard, acceleration data-loggers were attached to freely swimming Japanese flounder *Paralichthys olivaceus* (a key species in stock enhancement and sea ranching activities in Japan) in a seawater aquarium to measure their tail beat activity and swimming speed. The behavior of instrumented fish was also filmed by video cameras of multiple angles.

**MATERIALS AND METHODS**

Four Japanese flounders *Paralichthys olivaceus* were captured by commercial fishermen off the coast of Kashima, Ibaraki prefecture, Japan and transported to the Fish Behavior Laboratory of the National Research Institute of Fisheries Engineering (NRIFE; Table 1). The fish were kept in a circular tank of 2.5 m in diameter and 0.9 m deep (5000 L) with a constant flow-through of seawater. The water temperature in the tank was maintained at ambient ocean temperatures (−14°C) and natural light cycles were also simulated.

The behavior of the flatfish was monitored with a 12 bit resolution, 16 Mbyte memory, four channel ('acceleration') data-logger with two acceleration sensors (UWE-200 PD2G, Little Leonardo, Tokyo, Japan). These cylindrical-shaped, 20 mm diameter 120 mm long loggers weigh 64 g in air and 22 g in seawater. The devices include a depth recorder, speed meter and two piezo-resistive accelerometers (Model 3031, IC Sensors, Milpitas, CA, USA). These accelerometers record the ‘surging acceleration’ in the direction of the main axis of the flatfish (forward and backward) and the ‘heaving acceleration’ along the axis crossing the fish’s body from the eye side (upward facing) to the blind side (downward facing; Fig. 1). The measuring ranges of both accelerometers were between −39.2 and 39.2 m/s² (−4 and 4 G [G = 9.8 m/s²], parallel and orthogonal to the main axis of the data-logger, respectively). The amplitude of acceleration was sampled at 16 Hz and filtered using an analog sensor signal in the band pass between 0.5 and 8.0 Hz. Depth and swimming speed were sampled every second, with the resolution of 5 cm and 5 cm/s, respectively. Swimming speed was measured by counting the number of revolutions per second (r.p.s.) of an anteriorly mounted propeller. The stall speed of the speed sensor was determined experimentally to be 25 cm/s. Speeds below these values were considered indistinguishable from zero. A regression line was used to relate r.p.s. to swimming speed. To calibrate the speed sensor, we examined the relationship between r.p.s. and flow velocity (cm/s) at the Fish Behavior Laboratory in NRIFE. The relationship was linear from 25.0 to 120.0 cm/s and the coefficient of determination was greater than 0.98.

Fish were transferred from the holding tank into individual tanks, where they were anesthetized by being briefly submerged into well-oxygenated seawater containing 0.125 g/L of MS-222 (Ethyl m-Amino benzoate methanesulfonate; Nacalai Tesque, Kyoto, Japan). The acceleration data-logger was attached to each fish with two nylon straps, inserted through the dorsal musculature and aligned along the body axis. The fish were then allowed to recover for at least 12 h before being released into an experimental rectangular seawater aquarium (13.0 m × 7.5 m, 2.5–2.3 m deep). The water temperature in the aquarium was maintained between 15.5 and 18.5°C.

The activities of the instrumented flounder were divided into four major categories based on differences within the acceleration profiles: lying on the

![Fig. 1 Schematic diagram showing the direction of surging and heaving accelerations recorded by an acceleration data-logger on the surface of the body of Japanese flounder.](image)

<table>
<thead>
<tr>
<th>Fish no.</th>
<th>Total length (cm)</th>
<th>Body length (cm)</th>
<th>Body weight (g)</th>
<th>Date of experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish 1</td>
<td>65.5</td>
<td>52.0</td>
<td>2728.0</td>
<td>5–6 March</td>
</tr>
<tr>
<td>Fish 2</td>
<td>66.5</td>
<td>52.5</td>
<td>3039.0</td>
<td>5–6 March</td>
</tr>
<tr>
<td>Fish 3</td>
<td>66.5</td>
<td>52.5</td>
<td>3042.0</td>
<td>9–10 March</td>
</tr>
<tr>
<td>Fish 4</td>
<td>68.0</td>
<td>54.0</td>
<td>3060.5</td>
<td>10–11 March</td>
</tr>
</tbody>
</table>
bottom; swimming; gliding; and burying. The fish were also observed from three different angles using video cameras. One video camera was hand-held and two others were placed on the bottom of the aquarium. Once the experiments ended, the fish were removed from the experimental aquarium and the acceleration data-loggers were retrieved.

After retrieval of the acceleration data-logger, data were downloaded into a laptop computer and analyzed with IGOR Pro 3.1.4 software (WaveMetrics, Lake Oswego, OR, USA). Data were analyzed to statistical significance using STATVIEW 4.5 software (SAS Institute, Cary, NC, USA). Results are presented as mean ± SD. Body length per second (BL/s) is a common unit of measure for swimming speed in fish. Swimming movements off the bottom to depths of at least twice the depth resolution (±0.05 m) of the acceleration data-loggers were considered to be vertical and horizontal movements and were analyzed for swimming duration (s) and swimming speed (cm/s and BL/s). The acceleration profiles were compared frame by frame with a visual analysis of the videotapes (30 frames/s), and synchronized using a dubbed time interval of 0.033 s. Dynamic behaviors (i.e. swimming and burying), were categorized by examining the acceleration profiles. The periodic properties of the acceleration signals obtained from the dynamic behavior of the flatfish allowed us to apply an auto-correlation and the Fast Fourier Transform (FFT) analysis to determine the frequency of swimming and burying.

RESULTS

Figure 2 provides an example of the raw data from Fish 4. Approximately 20 h of continuous behavior were recorded by the video cameras and the acceleration data-logger on each of the four individuals.

A visual analysis of videotapes revealed that all four fish spent most of the time lying on one side of their body on the bottom of the aquarium. It was also observed that they occasionally swam for a few minutes, either horizontally or vertically (Fig. 3a). While swimming, the fish's entire body oscillated with an undulatory wave of vertical bending, progressing from the tip of the head to the end of caudal fin. While steadily swimming, the profiles of heaving acceleration, as recorded by the acceleration data-logger, showed a cyclic and sinusoidal waveform (Fig. 3b). When compared with the data from the video camera, the frequency of heaving acceleration was synchronized with the sequences of swimming activity (Fig. 3). In addition, the fish's tail beat frequency could be visually identified within the cycle of heaving acceleration during steady swimming phases.

Four distinct behaviors of the Japanese flounder were categorized using the data recorded by the acceleration data-loggers.

![Fig. 2](Representative examples of depth, speed and acceleration profiles for instrumented Japanese flounder.)
Fig. 3  (a) Schematic diagrams, horizontal-view, of one cycle of undulatory swimming in Japanese flounder. The wave frequency during steady swimming was 1.56 Hz. (b) Representative example of a heaving acceleration profile for Japanese flounder while steady swimming, as recorded by an acceleration data-logger. The cycle frequency of heaving acceleration is synchronized with the photo sequences of swimming activity (Fig. 3a).

Fig. 4  Depth, speed and heaving acceleration profiles for Japanese flounder (recorded from Fish 4), showing (a) lying on the bottom (b) swimming (c) gliding and (d) burying.
New device for monitoring activity of flatfish

**Fisheries Science**

7

Lying on the bottom

When lying on the bottom, each fish kept a rigid posture and its head, caudal fin and body laid flat on the bottom (Fig. 4a). Depth values remained constant around 2.3–2.5 m, and the swimming speed sensor recorded the ‘stall speed’ (<25 cm/s). Additionally, the acceleration remained constant at 0 m/s². Thus, low and stable acceleration profiles indicate when the fish was lying on the bottom of the aquarium.

Swimming

Fish were able to start swimming from any lying position (Fig. 4b). After taking-off from the bottom of the aquarium, they moved their head upwards and downwards, while the body musculature expanded and contracted. Depth values ranged from 1.1 to 2.5 m and swimming speed was 25–153 cm/s. The heaving acceleration profile showed a series of rhythmical waveforms with an amplitude ranging from 0.29 to 16.83 m/s² (mean ± SD, 1.10 ± 0.76 m/s²). An example of a typical heaving acceleration spectrum, whose frequency ranged from 0 to 6 Hz, is shown in Fig. 5a. Heaving acceleration profiles of steady swimming had one or two marked peaks in the spectrum.

Gliding

Before gliding, the fish would swim upward in the water column, and then, by positioning the head downward and flattening the body, glide downward to the bottom of the aquarium. When gliding, the heaving acceleration value was approximately 0 m/s² or occasionally ±1 m/s² and unchanging (Fig. 4c). Depth values decreased gradually as the fish descended towards the bottom of the aquarium.

Burying

Soon after landing on the bottom of the aquarium, the fish would bury themselves by alternately beating their head and tail against the bottom (Fig. 4d). When the fish were engaged in burying activity, the depth value was that of the bottom of the aquarium, swimming speed was <25 cm/s. An example of a typical spectrum of heaving acceleration while burying, is shown in Fig. 5b (note: the frequency ranged from 0 to 6 Hz). The heaving acceleration profiles while the fish was burying had multiple peaks.

Data for each of the behavioral categories

Data for each of the behavioral categories, based on depth, swimming speed and heaving acceleration data recorded by the acceleration dataloggers, are shown in Table 2. The duration of recorded behaviors for each fish ranged from 16.8 to 19.5 h (n = 4). They spent most of their time on the bottom of the aquarium (Fish 1, 89.5%; Fish 2, 94.1%; Fish 3, 92.2%; Fish 4, 94.5%). The swimming periods lasted from 55.9 to 122.6 min (mean ± SD, 83.1 ± 29.8 min; n = 4), representing 5.5–10.5% of the duration of the experiments. The gliding periods lasted from 5.9 to 16.2 min (mean ± SD, 9.9 ± 4.8 min; n = 4), representing 0.5–1.4% of the...
duration of the experiments. The burying periods lasted from 0.9 to 14.8 min (mean ± SD, 6.0 ± 6.5 min; n = 4), representing 0.08–1.50% of the duration of the experiments (Table 2).

Of the total 451 swimming periods recorded, the four fish swam at speeds ranging from 0.4 to 2.8 BL/s, with a mean swimming speed ranging from 0.8 to 0.9 BL/s. While steadily swimming, undulatory cycles in the recorded heaving acceleration (indicating tail beat frequency) occurred between 1.00 and 2.67 Hz. Tail beat frequency increased linearly with increasing swimming speed (Fig. 6; n = 1508; \( r^2 = 0.70 \); \( P < 0.0001 \)) according to the equation:

\[
F = 1.08V + 0.87,
\]

where \( V \) represents the swimming speed (BL/s) and \( F \) is the tail beat frequency (Hz). Previous studies have demonstrated that tail beat frequency is related to swimming speed.\(^{13-15}\) During most of the time spent swimming (88.1%), the frequency range of tail beating was between 1.45 and 2.29 Hz, with

---

**Table 2** Summary statistics of swimming, gliding and burying behaviors for the four Japanese flounder instrumented for this study

<table>
<thead>
<tr>
<th>Fish no.</th>
<th>Fish 1</th>
<th>Fish 2</th>
<th>Fish 3</th>
<th>Fish 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record duration (h)</td>
<td>19.5</td>
<td>18.2</td>
<td>19.2</td>
<td>16.8</td>
</tr>
<tr>
<td>Total number of taking off the bottom</td>
<td>132</td>
<td>129</td>
<td>104</td>
<td>39</td>
</tr>
<tr>
<td>Total swimming duration (min)</td>
<td>122.6</td>
<td>64.8</td>
<td>89.2</td>
<td>55.9</td>
</tr>
<tr>
<td>Mean duration of one swimming event (s ± SD)</td>
<td>53.0 ± 52.8</td>
<td>25.1 ± 12.3</td>
<td>42.1 ± 24.1</td>
<td>76.3 ± 54.4</td>
</tr>
<tr>
<td>Maximum duration of one swimming event (s)</td>
<td>325</td>
<td>69</td>
<td>148</td>
<td>321</td>
</tr>
<tr>
<td>Total gliding duration (min)</td>
<td>5.9</td>
<td>11.0</td>
<td>16.2</td>
<td>6.3</td>
</tr>
<tr>
<td>Mean duration of one gliding (s ± SD)</td>
<td>2.7 ± 2.9</td>
<td>5.1 ± 3.3</td>
<td>9.3 ± 5.5</td>
<td>9.6 ± 10.3</td>
</tr>
<tr>
<td>Maximum duration of one gliding event (s)</td>
<td>17.1</td>
<td>15.3</td>
<td>28.4</td>
<td>47.2</td>
</tr>
<tr>
<td>Total number of burying events</td>
<td>52</td>
<td>10</td>
<td>14</td>
<td>85</td>
</tr>
<tr>
<td>Total burying duration (min)</td>
<td>7.0</td>
<td>0.9</td>
<td>1.1</td>
<td>14.8</td>
</tr>
<tr>
<td>Mean duration of one burying event (s ± SD)</td>
<td>8.0 ± 5.0</td>
<td>5.2 ± 4.4</td>
<td>4.8 ± 2.9</td>
<td>10.4 ± 9.0</td>
</tr>
<tr>
<td>Tailbeat frequency (Hz) (Range)</td>
<td>1.84 ± 0.31</td>
<td>2.04 ± 0.25</td>
<td>1.65 ± 0.47</td>
<td>1.73 ± 0.68</td>
</tr>
<tr>
<td>(1.14–5.33)</td>
<td>(1.33–2.67)</td>
<td>(1.10–8.00)</td>
<td>(1.00–8.00)</td>
<td></td>
</tr>
<tr>
<td>Mean swimming speed (cm/s)</td>
<td>43 ± 9</td>
<td>58 ± 12</td>
<td>42 ± 12</td>
<td>46 ± 17</td>
</tr>
</tbody>
</table>

---

**Fig. 6** Tail beat frequency (Hz) as a function of body length swimming speed (BL/s). The solid line indicates the significant linear relationship (\( P < 0.0001 \); \( r^2 = 0.84 \); \( n = 1499 \)).

**Fig. 7** Distribution of time spent swimming using different tail beat frequencies (Hz) for the four Japanese flounder.
a mean frequency of \(1.65 \pm 0.47 - 2.04 \pm 0.25\) Hz depending on the individual (Fig. 7). The fish rarely (0.75%) exceeded frequencies of 2.29 Hz, the highest frequency being 8 Hz in Fish 3 and Fish 4.

**DISCUSSION**

As most aquatic locomotion is unsteady over short-time ranges, the swimming behavior of most marine animals includes acceleration and deceleration phases.\(^6\) To our knowledge, Ogilvy and Dubois carried out the preliminary study to investigate the acceleration of fish using accelerometers.\(^7\) They inserted an accelerometer into the body of a blue fish *Pomatomus saltatrix* and recorded the acceleration signals on both the lateral and forward directions of a swimming fish, and obtained a symmetrical acceleration profile.\(^7\) However, the accelerometers in their study were connected by cables to a writing recorder, which limited the range of application of their methods. The acceleration data-logger used in our study had no cables, and therefore the tail beat frequency of a freely swimming fish could be recorded continuously.

Flatfish have been thought of as laterally compressed, benthic fishes that spend their adult lives lying on one side of their bodies on the seabed.\(^8\) However, very little quantitative information is available about how much time a flatfish spends lying there. Similar to the results of Olla et al., we discriminated four behaviors of the flatfish using acceleration profiles simultaneously with speed and depth data.\(^9\) The acceleration data-loggers allowed us to distinguish between ‘active’ (swimming and burying) and ‘inactive’ phases (gliding and lying on the bottom of the aquarium).

Using data from the acceleration data-logger, the precise frequencies of the four behavior types were calculated (Table 2). The flounders were observed mostly lying on the bottom of the aquarium (89.5–94.5% of the total recording period; \(n = 4\)). The burying behavior displayed by most flatfish has been thought to be a way to both reduce the risk of predation and enhance the ability of the fish to catch prey.\(^9\) In our experiments, the burying behavior was observed to be only 0.1–1.5% of the total recording period; occurring immediately at the end of a swimming period. Our results also indicate that flatfish seem to rely on a swim-glide technique (Fig. 4). In the case of negatively buoyant fish this behavior has been suggested to be an efficient way to save energy for swimming long distances.\(^9\) The effects of captivity and instrumentation appeared to have little influences on the behavior of flatfish. Previous investigations of the swimming abilities of captive Japanese flounder showed that the maximum sustainable swimming speed was 1.0 BL/s and 1.2 BL/s at 18.5°C and 19.4°C, respectively.\(^21\) These values are similar to the maximum swimming speeds recorded in other flatfish species (e.g. 0.95 and 1.50 BL/s at 15°C).\(^22\) Additionally, the preferred tail beat frequency of captive Japanese flounder (1.45–2.29 Hz), corresponded to a ‘preferred’ swimming speed of 0.6–1.2 BL/s. However, when compared with the range of values obtained by Duthie, the Japanese flounder in our experiments rarely swam in excess of 1.2 BL/s.\(^22\) Thus, it might be inferred from these results that we could find no clear differences in swimming speed and tail beat frequency between instrumented and non-instrumented fish.

Most telemetry studies have estimated a fish’s rate of activity or ‘rate of movement’ (speed over ground) by measuring the distance traveled during fixed time intervals.\(^5,^{23-25}\) However, such methodology does not take into consideration fine-scale movements, and therefore, the actual rate of activity may be underestimated. Indeed, the locomotory rates measured from instantaneous swimming speeds, using speed meters, and from tail beat frequency using acceleration data-loggers (mean, 0.79–1.10 BL/s; \(n = 4\)), are 1.8–15.7 times faster than those estimated by methods using the ‘rate of movement’ (mean, 0.07–0.43 BL/s; \(n = 3\)).\(^{24}\) However, the instantaneous swimming speed, according to the acceleration data-logger, may be more similar to the ‘rate of movement’ if a fish only swims in straight lines. Similar observations were made by Gruber et al. using water speed sensors to determine the instantaneous swimming speeds of free-swimming lemon sharks.\(^{26}\) However, water speed sensors cannot indicate whether an animal is continually swimming or gliding in order to save energy.\(^{27}\) Thus, to estimate energy expenditure precisely, one needs to simultaneously monitor both the swimming speed and tail beat activity of free-swimming fish.

The acceleration data-logger appears to be a useful and reliable device for accurately recording the tail beat frequency of freely swimming flatfish and for estimating their activity. Future improvements in the miniaturization of the logger would allow experimentation on smaller fish.

**ACKNOWLEDGMENTS**

We would like to thank the following people for their cooperation: Toshihiro Watanabe and Shintaro Yamasaki of the Fishing Technology...
Division, National Research Institute of Fisheries Engineering; Seiji Otani, Takashi Kitagawa, Ken Yoda and several other students for their assistance with these experiments and Yan Ropert-Coudert and Michael F Cameron for constructive criticism of the manuscript. This study was supported by Grant-in-Aid for Scientific Research (C) from the ministry of Education, Science and Culture (No. C12660157).

REFERENCES


