Simultaneous measurement of swimming speed and tail beat activity of free-swimming rainbow trout
Oncorhynchus mykiss using an acceleration data-logger

Ryo KAWABE,1,∗ Takafumi KAWANO,2a Norihiko NAKANO,2 Nariharu YAMASHITA,2 Tomonori HIRAISHI2 AND Yasuhiro NAITO3

1Laboratory of Marine Ecosystem Change Analysis, Field Science Center for the Northern Biosphere, 2Laboratory of Fishing Production System, Graduate School of Fisheries Sciences, Hokkaido University, Hakodate, Hokkaido 041-8611 and 3National Institute of Polar Research, Itabashi, Tokyo 173-8515, Japan

ABSTRACT: A recently developed motion detector (acceleration data-logger), based on acceleration measurements, was used to monitor the swimming behavior of two free-swimming captive rainbow trout Oncorhynchus mykiss in an aquaculture net cage. Depth, swimming speeds and two-direction acceleration data were collected continuously for approximately 20 h per fish. To define relationships between swaying acceleration profiles and tail beat activity of rainbow trout, the tail beat activity of trout was monitored using a video camera in a small tank with the simultaneous use of the acceleration data-logger. During steady swimming, there were sharp, distinct peaks of swaying acceleration. When compared with the data from the video camera, the frequency of swaying acceleration was synchronized with the sequences of swimming activity. In addition, the tail beat frequency of the fish could be identified within the cycle of swaying acceleration during steady swimming phases. Mean tail beat frequency was 1.27 ± 0.40 and 1.40 ± 0.5 Hz (mean ± SD). Using the relationship between tail beat frequency and swimming speed, the ‘preferred’ swimming speed of trout was estimated to be between 0.48 and 0.58 body length (BL)/s, and trout rarely swam in excess of 2.0 BL/s. The present study shows that acceleration data-loggers used to record spontaneous measurements of swimming speed and tail beat activity represent a useful and reliable system for accurately estimating both the rate of activities and movements of free-ranging fish.

KEY WORDS: acceleration data-logger, rainbow trout, swimming speed, tail beat frequency.

INTRODUCTION

Estimating the complete energy budget of fish in the field has proven to be a formidable task. Of the various components of the energy budget of free-ranging fish,1 the activity rates or rate of movement have been especially difficult to measure. As the cost of activity (or movement) is thought to represent a large and variable portion of the fish energy budget, precise measurement of the activity rates (swimming speed and/or tail beat activity) of fish in the field, although difficult to obtain, are important for more accurate estimations of energy budgets.

Several methods have been used to estimate activity (e.g. swimming speed) of free-ranging fish. Physiological telemetry has been the primary tool used to measure activity or energy expenditure of fish in the field. Electrocardiogram (ECG) transmitters in combination with telemetry have been used to acoustically measure heart rate2,3 and are useful in estimating in situ metabolic rates. However, ECG measurements always require precise surgical implantation of electrodes and are restricted to fish that have relatively low activity levels because active fish, such as salmonids, can alter stroke volume as well as heart rate during exercise.4 Electromyogram (EMG) transmitters have many of the same drawbacks because electrodes have to be precisely implanted into the swimming muscle and require long surgical attachment times.5,6 Water speed-sensing transmitters and timedepth-speed recorders have been used to determine swimming speeds of large, free-swimming
fish and marine mammals with great success. However, the speed sensor (e.g., a propeller rotation counter) may overestimate swimming speed and energy expenditure if the fish is gliding and may be affected by water-current speed and direction. For these reasons, easily attachable tail beat detectors may offer a better solution for instantaneous swimming speed determination of active fish, although the tail beat detectors may underestimate energy consumption, but can still detect if the fish is swimming or gliding. Thus, to more accurately estimate energy expenditure in the field, we need to measure swimming speed and tail beat activity of free-ranging fish, simultaneously.

Here, we describe the design of an acceleration data-logger that is easy to attach and use, and the use of this logger to be able to simultaneously record depth, swimming speed and tail beat activity of rainbow trout in aquaculture net cages. We present here the first direct measurements of continuous swimming speed and tail beat activity of free-swimming rainbow trout in enclosures, and show that they spend most of their time swimming slowly.

MATERIALS AND METHODS

Two rainbow trout *Oncorhynchus mykiss* cultivated by commercial fishermen of Ohata, Aomori prefecture, Japan, were used in this experiment (Table 1).

The behavior of the trout in an aquaculture net cage was monitored with a 12-bit resolution, 16 MB memory, four-channel (acceleration) data-logger with two acceleration sensors (UWE-200 PD2G; Little Leonardo Co. Ltd, Tokyo, Japan). This cylindrical-shaped, 20-mm-diameter, 120-mm-long logger weighs 64.0 g in air and 22.0 g in seawater. The device includes a depth recorder, speed meter and two piezo-resistive accelerometers (Model 3031; IC Sensors, Milpitas, CA, USA). These accelerometers record surging acceleration in the direction of the main axis of the trout (forward and backward) and swaying acceleration along the axis crossing the trout body from the left side to the right side (Fig. 1). The measurement range of both accelerometers was between −39.2 and 39.2 m/s² (−4 and 4 g, parallel and orthogonal to the main axis of the data-logger, respectively). The amplitude of acceleration was sampled at 16 Hz, while depth and swimming speed were sampled every second. Absolute accuracy was 5 cm and 5 cm/s for depth and swimming speed, respectively. To define relationships between swaying acceleration profiles and tail beat activity, and to evaluate the effect of our data-logger on the swimming performance and behavior of rainbow trout, the tail beat activity of trout was also monitored by a video camera in a small tank (6.0 ¥ 0.5 m; diameter ¥ depth) with the simultaneous use of the acceleration data-logger. 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 28.0 cm/s. Speeds below these values were considered indistinguishable from zero. To calibrate the speed sensor, we examined the relationship between r.p.s. and flow velocity (cm/s) in a water trough. The relationship was linear from 28.0 to 120.0 cm/s and the coefficient of determination was greater than 0.99. Here, the equation of the relationship between the flow speed (V: cm/s) and the propeller speed (R: revolution/s) is:

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V = \frac{120.0}{28.0} R
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\[
V = \frac{120.0}{28.0} R
\]

Table 1 Total length, body length and body weight, and experimental date for two Japanese flounder equipped with an acceleration data-logger

<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>55.0</td>
<td>53.0</td>
<td>2900</td>
<td>22–23 June 2000</td>
</tr>
<tr>
<td>Fish#2</td>
<td>68.0</td>
<td>54.0</td>
<td>3060</td>
<td>22–23 June 2000</td>
</tr>
</tbody>
</table>

Fig. 1 Schematic diagram showing the direction of swaying and surging acceleration recorded by an acceleration data-logger placed on the left side of the body of a trout (black bar).
The trout, which were cultivated by commercial fishermen of Ohata, Aomori prefecture, were transferred from aquaculture net cages into individual tanks where they were lightly anesthetized using 2-phenoxethanol and total length, body length and body weight were measured. The acceleration data-loggers were attached to the left side of the body, below the front edge of the dorsal fin using two nylon straps. The trout were transferred to a recovery tank by submerging them in well-oxygenated seawater where they were allowed to recover for at least 24 h before being released into an aquaculture net cage (12.0 × 12.0 m, 10 m deep).

After retrieval of the acceleration data-logger from the experiment, the data were downloaded into a laptop computer and analyzed using Igor Pro 3.1.4 software (WaveMetrics, Lake Oswego, OR, USA). Statistical analysis was performed using Excel 2000 software (Microsoft Corp., USA). Results are presented as mean ± SD. Videotapes (30 frames/s) were analyzed frame by frame, with a dubbed time interval of 0.033 s. The acceleration profiles of swimming behavior were compared with the visual analysis of the videotapes. The periodic properties of the acceleration signals obtained from the dynamic behavior allowed autocorrelation and fast Fourier Transform (FFT) analysis to be applied, enabling us to determine the frequency of swimming.

RESULTS

We first defined relationships between swaying acceleration profiles and tail beat activity of rainbow trout. During steady swimming, we found that there were sharp, distinct peaks of swaying acceleration (Fig. 2). Figure 3 gives an example of the raw data recorded by Fish#1. A total of approximately 15 h of continuous behavior was monitored by acceleration data-loggers. Minimum swimming depths for the two trout were near the surface (<1 m) and maximum depths were 11.87 m (Fish#1) and 9.67 m (Fish#2). The mean swimming depth for the two trout were 2.28 ± 1.90 m (Fish#1) and 1.65 ± 1.43 m (Fish#2).

Previous studies have demonstrated that tail beat frequency (TBF) can be related to swimming speed. TBF was found to increase linearly with increasing swimming speed (Fig. 4) according to the equation:

\[ U = 0.4 \times BL \times F + 6.1 \]

where \( U \) represents the swimming speed (cm/s), the swimming speed for the body length (BL/s; BL/s is a common unit of measurement for the swimming speed of fish) and \( F \) is tail beat frequency (TB/s). During steady swimming, undulatory cycles (indicating tail beat frequency) using swaying acceleration occurred between 0.90 and 2.67 Hz, with a mean frequency of 1.27 ± 0.40 and 1.40 ± 0.5 Hz, depending on the individual. During much of the time spent swimming (47.8%), the range of frequencies at which the trout chose to beat their tails was between 0.9 and 1.2 Hz (Fig. 5). The trout rarely (0.2%) exceeded frequencies of 3.0 Hz, the highest frequency being 8 Hz for Fish#2. Taking equation (2), we could estimate the swimming speed using the TBF. The trout swam at speeds ranging from 9.9 to 117.8 cm/s (from 0.19 to 2.40 BL/s) and the 'preferred' speeds for the two trout were between 23.7 and 31.5 cm/s (between

Fig. 2 Representative example of a swaying acceleration profile for Rainbow trout while steady swimming, as recorded by an acceleration data-logger. The cycle frequency of swaying acceleration is synchronized with the photo sequences of swimming activity.
0.48 and 0.58 BL/s). The mean swimming speeds for the two trout were 33.0 ± 14.6 and 33.5 ± 15.9 cm/s (0.62 and 0.68 BL/s).

The distribution of swimming speeds for the two trout, recorded by speed sensors, is shown in Fig. 6. For 67% of the time, the swimming speed was <28 cm/s (0.52 or 0.57 BL/s for the two trout). The speed meter of the data-logger could not record below 28 cm/s because of the stall speed of the propeller, as described earlier. In other words, speeds below this value were considered indistinguishable from 0 cm/s (Fig. 7). Assuming that swimming speeds below the stall speed would be 0 cm/s, the mean swimming speed would be estimated at 11.3 ± 16.6 cm/s. However, this value may underestimate the mean swimming speed,
because we do not think that fish will not move and Fig. 3 shows that fish would swim continuously. Thus, assigning 0 cm/s to equation (1) and assuming that the mean swimming speed below the stall speed was 21.2 cm/s, the mean swimming speed was estimated as 25.3 ± 7.7 cm/s. However, the mean swimming speed estimated using the TBF was significantly higher than that using the speed sensor (Mann–Whitney U-test: \( P < 0.0001 \)).

**DISCUSSION**

Firstly, we should briefly comment on the effects of data-logger attachment on the behavior and locomotion of swimming individuals. Tag attachments can adversely affect fish, thus biasing the field data obtained from their movement and behavior. In particular, attachment of external devices to fish and other marine vertebrates can affect their swimming speed because of increased hydrodynamic drag.\(^{12,13}\) Mellas and Haynes conducted experiments to evaluate the effects of external, surgical and stomach transmitter attachment methods on swimming performance and behavior of rainbow trout and suggested that, with all factors taken into account, stomach insertion is the best method of transmitter attachment.\(^{12}\) We had to use external attachment, because our data-logger included a speed sensor. However, we could detect no differences in swimming speed and TBF between instrumented and non-instrumented individuals. Tanaka et al. suggested that migrating adult chum salmon fitted with an externally located data-logger retained their homing motivation and maintained horizontal movement.\(^{14}\) It is, therefore, likely that our instrumented trout retained their swimming performance and behavior in the aquaculture net cage.

The ‘preferred’ swimming speeds of two rainbow trout in our results were between 0.48 and 0.58 BL/s, and for 67% of the time, the swimming speed was <0.52 BL/s (or 0.57 BL/s). It is interesting to compare our swimming speeds, recorded with an acceleration data-logger, with previous laboratory studies concerning swimming speeds of rainbow trout. An estimate of the maximum sustained swimming speed is the critical swimming speed.\(^{15}\) This has been shown to vary with temperature, body length and other factors.\(^{16}\) Webb found the critical swimming speed for a 30 cm rainbow trout to be 1.7 and 2.0 BL/s at 15°C.\(^{17,18}\) By measuring glycogen depletion in the white muscle, Webb...
found that anaerobic respiration occurred at speeds below the critical speed. Hudson confirmed this finding by showing that the white muscle becomes active at 3 Hz, which corresponds to 1.5 BL/s. Our results indicated that our trout swam at a speed at which it had to respire anaerobically or use its white muscle. Similarly, previous studies have indicated that the mode range of swimming speeds of freely swimming flounders was approximately 0.57–0.77 BL/s, which excludes the calculated speed that minimizes the cost of locomotion. These findings suggest that rainbow trout and flounder might need to avoid lactic acid accumulation as much as possible. Another reason, suggested by our results, is that rainbow trout preferred a lower swimming speed than the maximum sustained speeds that have been recorded in some experimental flumes, and that slow swimming may be a way of minimizing the cost of locomotion. The use of an acceleration data-logger makes it possible to study a variety of behavioral variables (such as swimming depth, swimming speed, tail beat activity and body angle) of free-ranging aquatic animals. This has enabled researchers to monitor various activities, such as the porpoising behavior and postures of penguins or the tail beat activity and body angle of free-ranging chum salmon. This acceleration data-logger offers high flexibility for the study of many different marine animals and enables the behavior of the animal to be analyzed precisely under natural conditions.

Most telemetry studies have estimated a fish’s rate of activity or rate of movement (speed over ground) by measuring the distance travelled over fixed time intervals. However, such methodology does not take into consideration fine-scale movements and, therefore, the actual rate of activity may be underestimated. Similar results were made by Gruber et al. and Block et al. using water speed-sensing transmitters to determine instantaneous swimming speeds of free-ranging marine fish. Water speed sensors cannot indicate whether the fish were continually swimming or whether they sometimes glide (or rest) to conserve energy. By placing the data-logger with the speed and acceleration sensor on rainbow trout, we could obtain a continuous record of swimming speeds and tail beats, and estimate activity rates (or rate of movement). Our results indicate that using the acceleration data-logger, researchers can not only record the tail beat frequency of free-swimming trout, but also distinguish between active (swimming) and inactive (gliding and resting) phases. However, our results also indicate that the mean swimming speed values estimated using the speed sensor were different from the values estimated using TBF. Water speed-sensing transmitters and data-loggers, using a propeller or paddle-wheel sensor, have been used to determine the swimming speeds of free-swimming large fish and mammals with some success. However, our results suggest that our speed sensor might underestimate the mean swimming speeds and the rates of activity. The reason for this underestimation is that speeds below the stall speed would be considered indistinguishable from 0 cm/s. Similar observations were made by Tanaka et al. using water speed sensing to determine instantaneous swimming speeds of free-ranging chum salmon. For this reason, we could not estimate the activity rates of slow swimming fish precisely using the water speed sensor.

However, our acceleration data-logger could detect tail beat movement and continuously record the TBF of free-swimming trout. Ross et al. reported the ‘preferred’ tail beat rate of free-swimming brown trout estimated using tail beat transmitter (EMG transmitter) to be 1.0–2.0 Hz and their tail beat rates rarely exceeded 2.5 Hz. This result is quite similar to our results using the acceleration data-loggers. Therefore, continuous measurements of tail beat movement using the acceleration data-logger would be useful for accurately estimating activity rates and swimming speeds. However, can direct measurements of tail beat activity using only tail beat transmitters (indicators) or the acceleration sensor offer a better solution to determining the rate of movement (speed over-ground) of active fish? Kawabe et al. reported that the heaving acceleration values of gliding Japanese flounder were approximately 0 m/s², or occasionally ± 1 m/s² and unchanging. Their results suggested that using the tail beat indicators only could not estimate instantaneous swimming speed and the rate of movement if the fish is gliding. Thus, the present study indicates that these acceleration data-loggers offer the best method to estimate both the rate of activities and movements as simultaneous measurement of the water speed and tail beat activity of free-swimming fish. Future improvements in the design of the logger would help reduce its size and, therefore, allow us to experiment on smaller fish.

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