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Animal-mounted gyroscope/accelerometer/magnetometer: In situ measurement of the movement performance of fast-start behaviour in fish

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ABSTRACT

A novel data logger incorporating a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer was developed and externally attached to Japanese amberjacks, *Seriola quinqueradiata*, to investigate the possibility of using this device for monitoring the movement performance of the fast-start behaviour of fish in the field. Triggered escape behaviours were measured simultaneously by the data logger (500 Hz) and a high-speed camera (200 Hz) in a tank. By using a gyroscope, the data logger accurately reconstructed the gravity-based acceleration, 3-dimensional attitude, dynamic acceleration, and angular velocity of fish during the fast-start movement, which was impossible by previous methods using only an accelerometer and a magnetometer; these variables can therefore be used to assess the distance-related performance and manoeuverability of fish. The escape movements can be categorised into two mechanical types (single- and double-bend) using the obtained locomotor variables, which showed significant differences between movement types. These results indicate the possibility of using this animal-mounted data logger to quantify the movement performance of the fast-start behaviour of fish in nature.

1. Introduction

The ability to move with a sudden acceleration/velocity and a rapid turning rate is important for many animals in a predator–prey context (Domenici and Blake, 1997; Higham, 2007). Kinematics and movement performance, especially those of fast-start movements in fish, have received a significant amount of attention and are usually investigated in laboratory-based settings through the use of high-speed cameras (Domenici and Blake, 1991; Hale, 2002; Harper and Blake, 1990; Lefrançois and Domenici, 2006; Schriefer and Hale, 2008). These studies have identified various types of fast-start behaviours [C- and S-start (Hale, 2002), including single- and double-bend responses (Domenici and Blake, 1991; Jing et al., 2005; Kasapi et al., 1993; Lefranc cois et al., 2005), and slow and fast responses (Domenici et al., 2004)]. However, only a small number of research approaches have investigated the movement performance of fast-start behaviour of fish in their natural environment. In situ measurement of the movement performance of fast-start behaviour should reveal important insights into the physiological adaptations of animals to different environments and their survival strategies in complex natural habitats. This will in turn lead to an improved understanding of the relationship between movement performance and fitness (Domenici et al. 2000; Higham, 2007; Irschick, 2003).

Bio-logging methods, which utilise animal-mounted data loggers, have been used effectively to measure the locomotion of animals in the field (Cooke et al., 2004; Rutz and Hays, 2009). In particular, data loggers including a 3-axis accelerometer and, in some cases, a 3-axis magnetometer have been used to monitor the attitude (pitch, roll, and yaw) and dynamic acceleration of aquatic animals (Davis et al., 1999; Johnson and Tyack, 2003; Mitani et al. 2003; Sato et al., 2003; Elkaim et al. 2006; Wilson et al., 2008). Therefore, bio-logging methods should give researchers the means to assess the movement performance of the fast-start behaviours of fish in the wild. However, only a small number of studies have focused on assessing the movement performance of fast-start behaviour using data loggers (Broell et al., 2013; Noda et al., 2013).

In laboratory-based studies, a number of variables, including maximum acceleration, angular velocity (e.g., turning rate), and movement direction (e.g., turning angle), have been found to be important for assessing the performance of fast-start movements (Domenici and Blake, 1991; Hale, 2002; Harper and Blake, 1990; Lefrançois and Domenici, 2006). Although many studies have used accelerometers to monitor the activities of fish in the wild (Broell et al., 2013; Kawabe et al., 2003; Tsuda et al., 2006; Whitney et al., 2010; Wilson et al., 2008), an accelerometer alone may not be sufficient for obtaining accurate and detailed documentation of the 3D movements of the fast-start

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behaviour of animals because it is difficult to differentiate gravity-based acceleration (which can be converted to pitch and roll movements) from the dynamic acceleration that is included in accelerometer measurements (Fourati et al., 2010; Noda et al., 2012). Furthermore, rotational information, such as the angular velocity and direction of the movement, is lacking in these measurements.

Angular velocity can be directly measured with high temporal resolution (e.g. 100 Hz to 1 kHz) by a gyroscope. Using the gyroscope, if the initial attitude is known, any new attitude (hence, the gravity-based acceleration that would be measured by the accelerometer) can be estimated using the initial attitude and the estimated attitude change calculated from the gyroscope measurements. An accelerometer and a magnetometer can be used in addition to a gyroscope to determine the initial attitude and to correct the error when estimating attitude associated with the accumulation of noise from a gyroscope. In fact, a novel gyroscope data logger (hereafter, gyro logger), which incorporates a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer (for a total of 9 axes), was developed. This device can reconstruct the fine-scale dynamic acceleration, gravity-based acceleration and attitude of animals (e.g. sea turtles), which have not been accurately measured in previous studies that only used an accelerometer (and occasionally a magnetometer) (Noda et al., 2012). Therefore, a gyro logger may be more suitable for monitoring the movement performance of fast-start behaviour in fish.

Given the above considerations, a novel gyro logger was developed and used in this study to investigate the possibility of using an animal-mounted data logger to monitor the movement performance of the fast-start behaviour of fish in the field. Specifically, the gyro logger was applied to measure the fast-start movements of a fish, the Japanese amberjack *Seriola quinqueradiata*, during escapes with a high sampling frequency (500 Hz). The link between escape movements and data logger measurements was thus explored. Although most previous studies have used a relatively low sampling frequency ($\leq$32 Hz) (Føre et al., 2011; Kawabe et al., 2003; Tsuda et al., 2006; Whitney et al., 2010), a higher sampling frequency was used in this study because fast-start movements usually last only a fraction of a second. Our study focused on three questions: 1) Is it possible to accurately define locomotor variables from the gyro logger measurements? 2) Is it possible to define detailed variations in fast-start movements (e.g., single- vs. double-bend) from the gyro logger measurements? and 3) What are the advantages and disadvantages of using a gyro logger over a conventional accelerometer or high-speed imaging for measuring locomotor variables?

2. Materials

2.1. Study animals

The escape movements of five Japanese amberjacks [fork length (FL): 65.9 $\pm$ 0.45 cm, body mass (BM): 4.08 $\pm$ 0.78 kg] (Table A1) were monitored in tank experiments at the Institute for East China Sea Research at Nagasaki University in Japan. The fish were obtained from a local fish hatchery (Nagasaki, Japan) and were maintained in a 300-cm-diameter outdoor tank with flow-through seawater at a temperature of 19.05 $\pm$ 0.84 °C, a depth of 1 m, and a dissolved oxygen level of 84.89 $\pm$ 3.88%. The fish were acclimatised to the tank for at least one week prior to the initiation of experiments; after acclimatisation, the fish were tagged for the experiments.

2.2. Data logger

A gyro logger (LP-BLKU01, Biologging Solutions Inc., Kyoto, Japan) was developed and used to record the 3-axial acceleration, 3-axial magnetism, and 3-axial angular velocity of the fish. This data logger was cylindrical in shape (diameter: 3 cm, length: 17 cm) with a mass of 108 g in air, which includes the attached CR123A battery. The measurement ranges were $\pm$16 *g*, $\pm$100,000 nT, and $\pm$1500 deg s^{-1} for the acceleration, magnetic field, and angular velocity, respectively. The resolution of the measurements was 16 bit (−32,768–+32,768): 4.88×10^{-4} *g*, 3.05 nT, and 4.58×10^{-2} deg s^{-1} for the acceleration, magnetic field, and angular velocity, respectively. The data logger measured and stored all of the sensor outputs in an internal micro-SDHC memory (~32 GB) at a sampling frequency of 500 Hz for a total sample time of 10 h. Furthermore, this device allowed for multiple-scheduled recordings (e.g., 2 h of recording each day). The data logger was covered with an alumite-treated case, which made it waterproof and pressure-proof up to a depth of 300 m. The logger could also record temperature of range of −45–80 °C and depth of up to 30 bar; however, only acceleration, magnetic data, and angular velocity were used for the analysis. A reflective marker was attached to the data logger for the video analysis (see below).

2.3. Measurement of escape responses

One week prior to the escape response measurements, the length and mass of the fish were measured under anaesthesia induced with phenoxyethanol (<0.05%). A plastic plate (3×18 cm^2) was sutured to the dorsal musculature just above the centre of mass (CM; 43% of the TL) using cable ties. The plate formed the base of the data logger. The position of the CM was determined by hanging a dead fish (different fish from those used for the activity measurements, FL = 61.8 cm) using a suture and needle (Lefrançois and Domenici, 2006). The temporary attachment of the gyro logger to the plastic plate base was accomplished using cable ties; the fish were sedated using anaesthesia during this procedure. The mass of the data logger was less than 3% of the body mass of the fish.

For the escape response measurements, gyro loggers were attached to five fish, which were then transferred from the holding tank to an identical and adjacent tank (300 cm in diameter). The water level in the experimental tank was maintained at 0.44 m. The transfer and tagging time, which included the anaesthetising time, was less than 5 min. None of the animals exhibited any signs of stress, and they settled quickly into the experimental tank. The fish were allowed to acclimate to the experimental tank for at least 12 h prior to the start of the escape measurements. The escape responses were triggered by randomly and manually thrusting a PVC pole with a length of 100 cm and diameter of 4.0 cm to the bottom of the tank [thrusting speed = 0.80 (0.34) m s^{-1} for the mean (s.d.), and N = 24] near the position of the fish when the fish were at least one body length from the tank wall. These responses were triggered at intervals of approximately 10 min. Overall, 4 to 11 escape responses were recorded for each fish (Table A1).

The responses were also recorded using two video cameras located 2.85 m above the tank bottom: a 30-Hz standard USB webcam (HD C910, Logicool Co., Tokyo, Japan, with H264 Webcam 3.83 software, Timhillone software Co. Ltd., Nanshan, China) and a 200-Hz high-speed camera (HAS-L1, DITECT Co. Tokyo, Japan). The video cameras were controlled and manipulated using a connected PC. The high-speed camera was calibrated before the experiments by taking a picture of a checkerboard at the bottom of the tank. The relationship between the pixel size in the camera image and the actual distance was obtained by placing multiple markers at known interval distances along the bottom of the tank before the experiments. The clock times of the gyro loggers and the video recording were synchronised using the PC clock before the data loggers were attached to the fish. A reflective marker on the data loggers in the image sequences was digitised using Dipp-Motion PRO (DITECT Co. Tokyo, Japan). The acceleration and turning rate of the markers were derived using a five-point smoothing regression (Lanczos, 1956). The turning rate was obtained using two points: the snout of the fish and the marker on the data logger.