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Research Article

A New Method to Calibrate Attachment Angles of Data Loggers in Swimming Sharks

Shizuka Kawatsu,[1] Katsufumi Sato,[2] Yuuki Watanabe,[3] Susumu Hyodo,[1] Jason P. Breves,[4] Bradley K. Fox,[4] E. Gordon Grau,[4] and Nobuyuki Miyazaki[1]

[1] *Ocean Research Institute, The University of Tokyo, 1-15-1 Minamidai, Nakano, Tokyo 164-0014, Japan*
[2] *International Coastal Research Center, Ocean Research Institute, The University of Tokyo, 2-106-1 Akahama, Otsuchi, Iwate 028-1102, Japan*
[3] *National Institute of Polar Research, 10-3 Midorimachi, Tachikawa, Tokyo 190-8518, Japan*
[4] *Hawaii Institute of Marine Biology, University of Hawaii, Kaneohe, HI 96744, USA*

Correspondence should be addressed to Shizuka Kawatsu, kawatsusame@ori.u-tokyo.ac.jp

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Recently, animal-borne accelerometers have been used to record the pitch angle of aquatic animals during swimming. When evaluating pitch angle, it is necessary to consider a discrepancy between the angle of an accelerometer and the long axis of an animal. In this study, we attached accelerometers to 17 free-ranging scalloped hammerhead shark (*Sphyrna lewini*) pups from Kaneohe Bay, Hawaii. Although there are methods to calibrate attachment angles of accelerometers, we confirmed that previous methods were not applicable for hammerhead pups. According to raw data, some sharks ascended with a negative angle, which differs from tank observations of captive sharks. In turn, we developed a new method to account for this discrepancy in swimming sharks by estimating the attachment angle from the relationship between vertical speed (m/s) and pitch angle obtained by each accelerometer. The new method can be utilized for field observation of a wide range of species.

1. Introduction

An accurate determination of pitch angle is critical to gain detailed information about the diving and foraging strategies of aquatic animals. For example, air-breathing aquatic animals that forage underwater control pitch angle and allocate their submerged time. In African penguins, steeper ascent angles presumably occur when they have depleted their oxygen stores and must return to the surface more quickly to breathe [1]. In macaroni penguins, pitch angle is significantly correlated with time spent at the bottom-phase of the dive [2]. A steep pitch angle during ascent indicates that they encountered a prey patch and a shallow pitch angle contributes to movement into a more profitable area in the following dive, due to increasing the horizontal distance [2]. While in fish, Nakaya [3] said that scalloped hammerhead sharks (*Sphyrna lewini*) have great maneuverability due to a movable large plate on head. Based on the observation of swimming behavior, it is apparent that sharks make a sharp dorsal turn at the bottom, consume food items, and swim away along the bottom [3]. In this sequence, pitch angle is an important indicator of a feeding event.

Recent advances in the development of animal-borne accelerometers (data loggers) make it possible for researchers to monitor pitch angle of aquatic animals in situ by attaching an acceleration sensor (accelerometer) along the longitudinal axis of the body. When a data logger is positioned exactly parallel to the longitudinal axis of an animal, the calculated angle of the data logger is the same as the pitch angle of the animal. Nonetheless, it is impossible to align the logger exactly parallel to the longitudinal axis of an animal in field studies. A few methods have been previously described to account for the discrepancy between the pitch angle of data loggers and the longitudinal axis in field studies. In one instance, Watanuki et al. [4] designated the attachment angle to the lower back of seabirds as 0° when they were at the water surface, a time in which they were essentially horizontal before release. This methodology is well suited for birds that can be maintained in a horizontal position at the water surface. However, for animals that have a flexible body, it is difficult to keep them positioned horizontally for an extended period of time. In addition, this methodology cannot be applied for obligate swimming fish because of fatal risk for lack of adequate gill ventilation. Another approach to account for the discrepancy between the pitch angle of data loggers and the longitudinal axis was reported by Sato et al. [5] in Weddell seal. In this study, the attachment angle was calculated by using the data logger along with the speed sensor. Sato et al. [5] used the data logger (UWE1000-PD2GT: 22 mm diameter, 124 mm length; 80 g in air; Little Leonardo Co., Tokyo, Japan) which contains a propeller and reported that the attachment angle for a specific dive of Weddell seal could be determined using equations including the number of propeller rotations, surging acceleration (m/s^2), the acceleration of gravity ($9.8\,m/s^2$), and body angle (degrees). This methodology can only be applied for large animals due to the relatively large size of data loggers that have a propeller. Furthermore, this method is only applicable for diving animals that must come to the surface to breathe. Lastly, in a third study, the attachment angle in flatfish was assigned as 0° when they lay on the substrate as reported by Kawabe et al. [6]. This method is only applicable for benthic animals that remain on the bottom. There are currently no reported methods to apply for continuous swimming fish.

The previously described methods are specific for particular species and we therefore anticipated that they might not be suitable for use in hammerhead sharks. Scalloped hammerhead shark pups have flexible bodies and are obligatory swimmers [7]. In addition, their small body size allows only for use of the smallest logger available for field studies that can only record depth, temperature and 2-axes accelerations, but not speed. In this study, we attached data loggers to 17 free-ranging pups with the objective to establish a new method for calibrating the attachment angle of loggers in free-ranging sharks.

2. Materials and Methods

2.1. Field Work. Our field studies occurred in Kaneohe Bay, Hawaii (21.26°N, 157.47°W) in August and October, 2007, and July/August, 2008. Kaneohe Bay is a nursery ground for the scalloped hammerhead shark (*Sphyrna lewini)* during summer months in which pups spend most of their time near the bottom [8]. In this study, juvenile scalloped hammerhead sharks were collected using hand lines with baited hooks. Upon capture, sharks were immediately transferred to the Hawaii Institute of Marine Biology, University of Hawaii, and placed in 3 m diameter tanks with flow-through seawater for 2–3 days. Sharks were fed squid twice a day and usually resumed feeding within 24 hours of capture. Release of the sharks into the field with data loggers did not occur until they resumed feeding in captivity for at least 48 hours. At this time, both total length (TL) and body mass (BM) were measured. For some sharks, BM was estimated from the relationship ($R^2 = 0.45$) between TL and BM of 20 pups from a previous experiment. Prior to release, a data logger was attached immediately anterior to the first dorsal fin using a plastic cable connected to a time-scheduled release system [9]. This cable ran through the soft plastic netting ($3\,cm \times 5\,cm$) attached to the shark with dissolvable suture (Matsuda Medical Kogyo Co., Tokyo, Japan). Techniques used to attach the data loggers were done within a jet of seawater and designed to minimize stress. The time required to attach the data loggers was less than 5 minutes per individual and we let sharks respire forcibly along the way. After which time sharks were immediately released in the bay. All animal experiments were conducted according to the Guideline for Care and Use of Animals approved by the committees of University of Tokyo and University of Hawaii.

2.2. Data Recovery. An automatic time-scheduled release system that allows for loggers to be located and retrieved using VHF radio signals was used because the recapture of instrumented pups in Kaneohe Bay is not possible. The data loggers were attached to a float of copolymer foam (Nichiyu Giken Kogyo Co., Saitama, Japan), in the top of which a VHF radio transmitter with a 45 cm semirigid wire antenna (Advanced Telemetry Systems Inc., Isanti, MN, USA) was embedded. A plastic cable connected to a time-scheduled release mechanism (Little Leonardo Co.) bound the tag to the plastic netting which was attached to the pups. Tag retrieval followed the method reported in Baikal seals [10]. Devices were attached to 17 pups in total, of which we successfully retrieved 16 loggers. Of the 16 loggers, one data logger was released from a pup after 6 hours, 7 were released after 24 hours, 7 were released after 48 hours, and one was released after 72 hours.

2.3. Instruments. Acceleration data loggers (M190L-D2GT; Little Leonardo Co., Tokyo, Japan) were used to examine swimming behavior of pups. Each logger was 15 mm in diameter, 53 mm in length, had a mass of 18 g and recorded depth (1 Hz), 2-axes accelerations (for detecting caudal fin movement and pitch, 32 Hz for eight individuals and 16 Hz for eight individuals), and temperature (1 Hz). The total weight of the instruments deployed on pups, including devices for data recovery (such as float and VHF transmitter), was 50 g with a slight positive buoyancy in seawater. The measuring range for acceleration along two axes was $\pm 29.4\,m/s^2$. Values recorded by the accelerometers were converted into acceleration (m/s^2) with linear regression equations. To obtain the calibration equations, relative values recorded by each logger at $90^\circ$and -90° from the horizontal level were regressed against the corresponding acceleration ($9.8\,m/s^2$ and $-9.8\,m/s^2$, resp.).

2.4. Data Analysis. Two of the sixteen retrieved data loggers were not included in our analyses due to incomplete data records. Loggers were positioned so as to detect longitudinal (surging) and lateral (swaying) accelerations. Loggers attached on the animals measured both dynamic acceleration (such as tail beating activities) and static acceleration (such

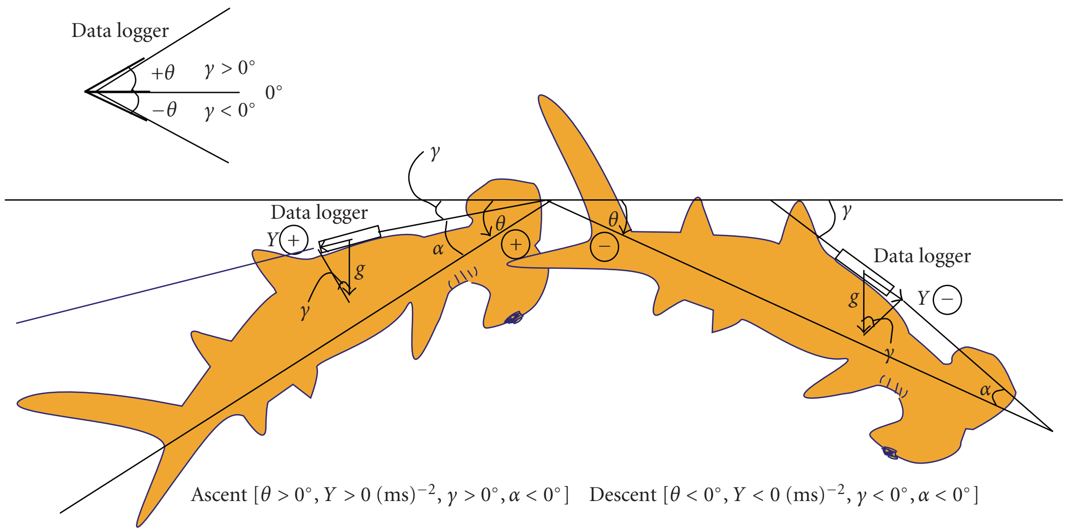

Figure 1: Attachment of a data-logger to the dorsal side of a hammerhead shark. Diagram shows the direction of surging acceleration Y, recorded by a D2GT logger placed on a shark, and gravity g (= 9.8 ms^{-2}), angle of surge axis of the logger to horizon (γ), that of longitudinal axis to horizon (θ) defined as pitch angle (negative as the shark descends), and logger attachment angle (α).

as gravity). The acceleration sensor along the longitudinal body axis can measure acceleration in response to changes in the movements of animals such as stroking and change in pitch angle. High-frequency fluctuations in the surging acceleration records are believed to be caused by caudal fin movements. When the animal is still or moving at a constant speed, the gravity vector will change in response to pitch angle. Together, low-frequency fluctuations in the acceleration along the longitudinal axis (surging acceleration) are used to calculate the pitch angle [5, 11].

To remove the high-frequency component of acceleration caused by the tail beating, we extracted the low-frequency signals on surging accelerations of sharks with a filter in the IGOR Pro software (Wave Metrics Inc., USA; see also [5, 11]). Then, the low-frequency component of longitudinal acceleration (Y) was converted to angle of the data-logger relative to the horizon (γ ranging from $-90°$ to $90°$) as follows:

$$\gamma = \text{a}\sin\left(\frac{Y}{9.8}\right). \qquad (1)$$

Following Sato et al. [5], the body angle of pups against the water surface (θ, Figure 1) can be expressed by

$$\theta = \gamma - \alpha, \qquad (2)$$

where γ is the angle of surge axis of the logger to horizon (degrees), and α is the attachment angle of the logger against the longitudinal axis (degrees). θ and γ while pups were descending (the data logger was tilting in a clockwise direction) were regarded as negative, and when ascending (the data logger was tilting in a counterclockwise direction), θ and γ were regarded as positive.

At first, we estimated an attachment angle (α_1) using a previously reported method [4]. We corrected the values of body angle recorded in a holding tank horizontally for 10–20 seconds to 0°. We held a pup for 10–20 seconds with its body level to the water surface and recorded the time. We assumed the pitch angle during previous recording periods to be flat (0°). Then, we subtracted the recorded angle during previous periods from each individual's pitch angle data over the period of logger deployment. Next, we obtained another attachment angle (α_2) using a new method that estimated the attachment angle from the relationship between vertical

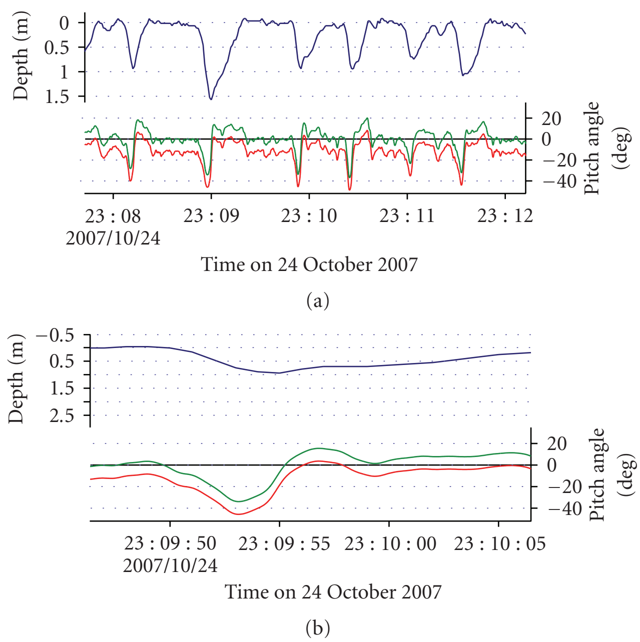

Figure 2: (a) An example of swimming depth (blue line) adjusted pitch angle by new method (green line) and by previous method (red line) of an individual pup (HI0703). (b) Enlarged part of Figure 2 shows that the adjusted pitch angle (green line) changed from a negative to positive value at the moment of ascent.

Table 1: Morphological information and attachment angles of loggers derived from a previous method (α_1) and that following adjustment by a new method (α_2) for each shark.

Shark ID	Sex	Total length (cm)	Body mass (g)	α_1 (degrees)	α_2 (degrees)	Correlation coefficient	Data length (h)*
HI0702	F	54.5	727	−19.6	−43.6	−0.72	6
HI0703	M	58	870	−12.5	−24.3	−0.88	24
HI0704	F	54	935	−2.2	−20.5	−0.71	48
HI0705	F	56	760	−18.0	−36.4	−0.79	48
HI0706	M	55	750	−13.3	−25.3	−0.57	28
HI0707	F	56	780	−12.0	−23.9	−0.77	24
HI0709	M	54	745	−6.9	−19.9	−0.56	20
HI0801	F	54	575	−31.2	−31.9	−0.78	2
HI0802	F	54	575	−19.3	−22.7	−0.83	2
HI0803	—	58	717	−23.1	−40.1	−0.72	19
HI0804	—	58	717	−24.9	−44.1	−0.74	24
HI0805	—	57	681	−26.1	−55.2	−0.60	17
HI0807	M	54	575	−15.8	−40.4	−0.72	17
HI0808	F	57	681	−21.7	−17.3	−0.71	44

*Data length (h) is not necessarily consistent with total recorded hours.

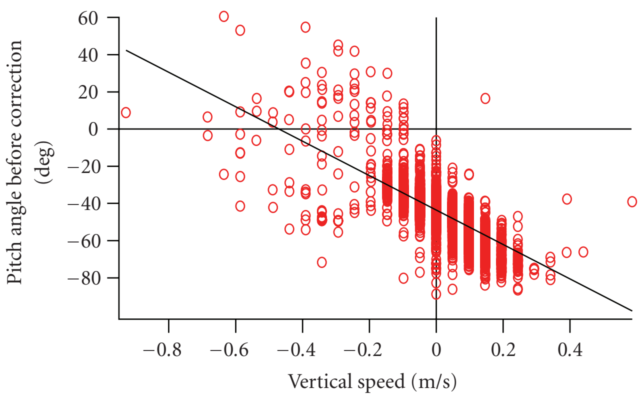

Figure 3: Example of the relationship between raw pitch angle (γ) and vertical speed from an individual pup (HI0702). A negative vertical speed indicates ascent and a positive value indicates descent.

speed (m/s) and body angle. We compared raw pitch angle (γ) with vertical speed per second to find a linear regression from each pup. There are indications that negatively buoyant fishes, such as sharks and sturgeon, may assume a positive pitch tilt during steady horizontal swimming as a behavioral mechanism to increase the total body area generating lift [12, 13]. Nonetheless, it can be assumed that the body axis of an animal is parallel to the direction of movement when the animal swims at a constant speed. With this assumption, we expected a descending pup to have a negative pitch angle while the pitch angle of an ascending pup would be positive. If a pup swims horizontally, the instantaneous pitch angle would be zero. When we analyzed the relationships between raw pitch angle and vertical speed per second, we found a linear regression from each pup. This regression line should pass through the origin coordinate if the logger angle is parallel to the longitudinal axis of the body. We considered the intercept of the regression line to be the attachment angle (α_2 degrees).

To confirm the utility of this new method, we observed instrumented banded dogfish (*Triakis scyllium*) in an experimental tank using a video camera. We attached a data logger (UWE190PD2GT: 22 mm diameter, 124 mm length; 80 g in air; Little Leonardo Co., Tokyo, Japan) using the same method as used for hammerhead pups. After the experiment, we compared the adjusted angle calculated from our new method with the adjusted angle obtained from video observations.

3. Results

As expected, we could not use previously reported methods to adjust pitch angle. Thus, we needed to develop a new method to calculate the attachment angle for hammerhead pups. A modulation of the pitch angle of a swimming shark is expected to correspond to fluctuations in the vertical speed rate (depth changes per second). The depth parameter therefore has the potential to provide information for the correction of pitch angle.

The first method reported by Watanuki et al. [4] provided us an estimated attachment angle (α_1) from 16 pups that varied between −40.9° and −2.2° (Table 1). When we applied this attachment angle to each pup, some individuals showed a negative angle when they ascended (Figure 2, red line). All the scatter plots made from the pitch angle before adjustment and the vertical speed provided a linear regression. A regression line was produced for each pup (Figure 3) with correlation coefficient (absolute value) higher than 0.56 (Table 1). The intercept of the regression line (adjustment angle α_2) varied from −55.2° to −17.3° (Table 1). α_1 and α_2 were regarded as negative when the data logger was tilting in a clockwise direction and positive when the data logger was tilting in a counterclockwise direction. As a result, all the data loggers attached to pups showed negative attachment angles.

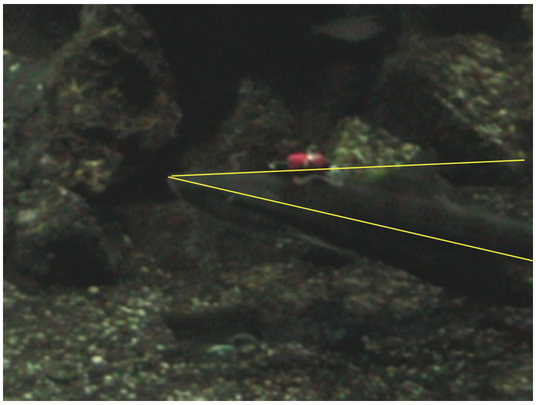

Figure 4: An attachment angle of the data logger on the banded dogfish was 14° from visual analysis and 13.7° from the regression line method.

The attachment angles obtained from our new method differed from values obtained from the first method (Table 1). For example, an attachment angle of one individual (HI0702) from the first method was −19.6° while the new method yielded an angle of −43.6°. Both corrected pitch angles using the above values are indicated in Figure 2. The corrected pitch angle using the new methodology showed that the diving profile became negative during descent and positive during ascent (Figure 2(b)). Even considering the pitch tilt previously cited [12, 13], a negative pitch angle during ascent does not correctly represent the pitch angle of a pup. We concluded that the new methodology corresponds well with the diving profile. In banded dogfish held in an aquarium, the adjustment angle from the regression line method was 13.7°, while the observed tilt angle of the data logger was 14° when analyzed from video observations (Figure 4).

4. Discussion

The new regression line method we report has three advantages over previously described methods. First, the new method provides more accurate information about the correction angle since the corrected pitch angle using the new methodology corresponds well with the diving profile. It is difficult to fix sharks on their flat pitch angle because their bodies are flexible and a seemingly flat angle out of water is not necessarily the same as the rigid flat angle. Indeed, banded dogfish orient their heads slightly upward when resting at the bottom of an aquarium when compared with when they are held out of water. Second, the new method is considerably less invasive than the method that requires holding sharks level at the water surface. Our new method accounts for the fact that hammerhead shark pups are obligate swimmers that can only respire while swimming [7]. Third, it is possible to adjust the pitch angle without speed data. Sato et al. [5] developed another adjustment technique for a logger that contained a propeller so as to record speed in addition to depth, 2-axes accelerations, and temperature in the data logger we used. With this technique, the animal does not need to be fixed flat, but it cannot be applied to smaller animals such as hammerhead shark pups, because a data logger including a speed sensor is too large and would likely impact behavior.

In conclusion, we developed a new method of analysis that enabled us to correct the pitch angle of hammerhead sharks equipped with a small accelerometer. For fish that display changes in pitch angle when making movements up and down in the water column, this new method to correct pitch angle in juvenile sharks can be applied for the acquisition of information in a wider range of species.

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