Mammal Study 36: 55–59 (2011)

Short communication

Swim speed and acceleration measurements of short-finned pilot whales (*Globicephala macrorhynchus*) in Hawai'i

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Over the last few years, studies of top predators in marine ecosystems have benefited from the use of bio-logging systems (Naito 2004; Rutz and Hays 2009). For example, researchers use these techniques to study animal foraging tactics and diving physiology by analyzing acceleration (body angle and stroke), and parameters such as swim depth and swim speeds (e.g., Sato et al. 2003, 2007; Sakamoto et al. 2009).

Short-finned pilot whale (*Globicephala macrorhynchus*), a top predator, is found worldwide in tropical and warm temperate waters. Mature males are from 4.5 to 7 m in length and mature females are from 3.5 to 5 m in length (Bernard and Reilly 1999). Previous studies suggested they are foraging during deep dives which cannot be observed visually. Their primary prey are squid and in Hawai'i they are known to make deep dives (600–800 m) during the day, but also spend considerable periods of time shallow diving or surface resting during the day (Baird et al. 2003). Amano and Baird (1998) recorded deep dives over 100 m off Japan. Soto et al. (2008) recorded sound, depth, and orientation from triaxial accelerometers and magnetometers, and suggested prey chasing behavior by analyzing vertical speed and sound emission during deep dives. For a better understanding of foraging tactics and diving physiology of this species, for example studying prey pursuit in a horizontal direction, stroking patterns and body angle, or assessing behavior by acceleration, we need to record acceleration and swim speed simultaneously. However, swim speed for short-finned pilot whales has not yet been recorded.

We used remotely deployed suction-cup tags for measuring swim speed and acceleration of short-finned pilot whales. The understanding of toothed whale behavior has been advanced by using suction-cup attached data loggers (for a review see Hooker and Baird 2001). There are several types of suction-cup attached tag: one attached with multiple suction-cups that fixed a data logger in place (e.g., Soto et al. 2008), which with a single suction-cup connected to a data logger with a flexible plastic tube (Baird et al. 2005), and one with a single suction-cup that fixed a data logger in place. With removely-deployed tags, it is difficult to set the tag parallel to the water flow. Therefore it would be hard to record swim speed using a propeller with a multiple suction-cup tag. A tag using a flexible plastic tube cannot record acceleration caused by the animal precisely because it is not fixed on the animal's body. A tag fixed on a suction-cup has been demonstrated to record swim speed and acceleration simultaneously in previous studies (finless porpoises, *Neophocaena phocaenoides*, Akamatsu et al. 2005; sperm whales, *Physeter macrocephalus*, Aoki 2008). The purpose of our work was to determine whether this type of suction-cup tag is appropriate for studying swim speed and acceleration in short-finned pilot whales, and whether it was possible to determine behavior types based on the data collected.

Methods

Field operations were conducted as part of a multi-species study of odontocetes in Hawaiian waters (see

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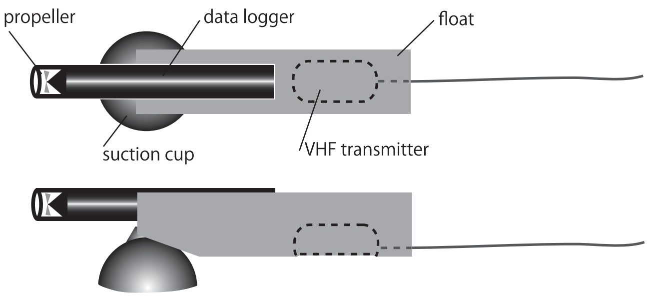

Fig. 1. Tag shape used in the current study.

McSweeney et al. 2007; Baird et al. 2008). Field work was undertaken off the west coast of the island of Hawai'i (19°–20°N, 156°W) over 15 days in May and July, 2008. Long term research on short-finned pilot whales has been conducted in this area (McSweeney et al. unpublished; Shane and McSweeney 1990). A single dedicated research vessel was used. Four or five observers were positioned in order to scan 360° between them. The study area was transited at 15–30 km/h. The tags were attached to pilot whales using a 4.5 or 7 m carbon-fiber pole with clip. The tagged individuals were observed and photographed after tagging in order to assess the angle of the placement of the tag. Age class of tagged individuals was estimated based on body size relative to other individuals, both in the field and in photographs. The tags contained a data logger (W2000-3MPD3GT, Little Leonardo, Tokyo, Japan; diameter, 26 mm; length, 175 mm; weight, 140 g), VHF radio transmitter (ATS, Isanti, MN), suction-cup (Canadian tire, 8 cm diameter) and syntactic foam float (Fig. 1). Depth (1 Hz, resolution of 0.5 m), swim speed (1 Hz), and longitudinal acceleration (32 Hz) parallel with the long axis of the animal body were recorded. Tags were recovered using signals from the VHF transmitters.

The beginning or end of a dive was considered to be the moment when depth was greater than, or less than 3·m, respectively. Surface time was defined as the animal remaining less than 3 m from the surface. Swim speed was calculated using the rotation (revs s^{-1}) of an external propeller. To calibrate the speed sensor, we examined the relationship between number of propeller rotations per second (rev s^{-1}) and the actual speed when the logger was towed from 50 m depth to the surface at 8 different speeds using an electric reel on a vessel. The relationship was linear from 1.09 to 1.92 ms^{-1} for the logger of tag #2 and from 0.99 to 1.68 ms^{-1} for the logger of tag #3, and the coefficient of determination (R^2) for both loggers was greater than 0.99. The angles of the loggers to the longitudinal axes of the animal body may make difference between recorded swim speed and actual swim speed. It was impossible to align the loggers exactly parallel to the longitudinal axes of the animals. Therefore, the adjusted angle was calculated using the method described in Sato et al. (2003). If the adjusted angle was A (degree), recorded speed $V1$ (ms^{-1}) was considered V·cosine A as the component force in a direction perpendicular to the water flow which was actual speed V (ms^{-1}). Therefore, actual speed V was calculated by:

$$V(i) = V1(i)/\cos A(i)$$

Results and discussion

A total of 15 days (120 h) were spent on the water with tagging equipment ready to be deployed. We encountered pilot whales on 9 days and attempted to tag the animals on 3 days. The 3 tags (tag #1, #2, #3) were attached to 3 different whales, two subadults (tag # 1 and 3) and an adult male (tag #2). The tags were successfully attached on the first tagging attempt for tag #1, the third attempt for tag #2, and the second attempt for tag #3. Two of the three tags were retrieved, yielding a total of 37 minutes of data (31 minutes for tag #2, 6 minutes for tag #3, Table 1). One of the tags was not retrieved (tag #1).

The VHF signal of tag #1 was not received during an attempt to locate it 21 hours after tagging, likely due to the tag being underwater and the signal was not able to be received adequately (i.e., the animals was diving). Given that the signal was successfully received on the next attempt (34 hours after the initial tagging), it was assumed that the tag dropped off the animal between 21 and 34 hours after tagging. This is a similar attachment duration to other suction-cup tags deployed on this species in Hawai'i (maximum 24 hours, see Baird et al. 2003).

Although tag #1 and #2 were not initially deployed parallel to the animals' body axes (Fig. 2a, c, e), they shifted to a position almost parallel after several minutes (Fig. 2b, d, f). Tag #1 was observed again 3 hours after tagging, and remained in a position almost parallel to the body axis. We calculated the difference in the angle of the tag and the body-axis angle using the procedure described by Sato et al. (2003). The differences were estimated to be –2.1 degree in tag #2 and –5.7 degree in tag #3. The differences between recorded speed and actual speed were very little (cos (2.1) = 0.9993, cos

Table 1. Summary of swimming data on short-finned pilot whales

	Tag #2	Tag #3
Recording time	31 min	6 min
Number of dives*	7	2
Duration of dive	Max: 367 s, mean. ± *SD*: 136 ± 122 s	128 s
Maximum depth	13.0 m, mean. ± *SD*: 8.2 ± 3.6 m	37.75 m
Swim speed	Max: 5.5 m/s, mean ± *SD*: 1.0 ± 0.4 m/s	Max: 4.2 m/s, mean ± *SD*: 1.2 ± 0.6 m/s
Number of surface time	6	1
Duration of surface time	Max: 281 s, mean ± *SD*: 165 ± 69 s	111 s
Breathing interval during surface time	Max: 22 s, min: 9 s, mean ± *SD*: 14.9 ± 3.0 s	Max: 16 s, min: 8 s, mean ± *SD*: 10.9 ± 2.5 s

* The tags detached during the last drive

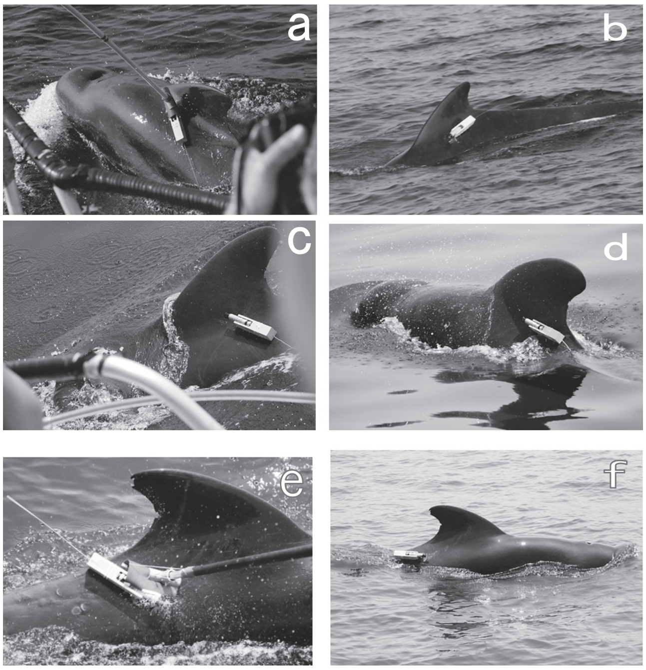

Fig. 2. Attachment of a data logger to a pilot whale using a suction-cup tag (Hawai‘i, USA). a; Tagging using a pole (tag #1). b; 8 minutes after the tagging (tag #1). c; The position of the tag just after tagging (tag #2). d; 4 minutes after the tagging (tag #2). e; The position of the tag at the end of the attempt (tag #3). f; The position of tag #3 after one dive.

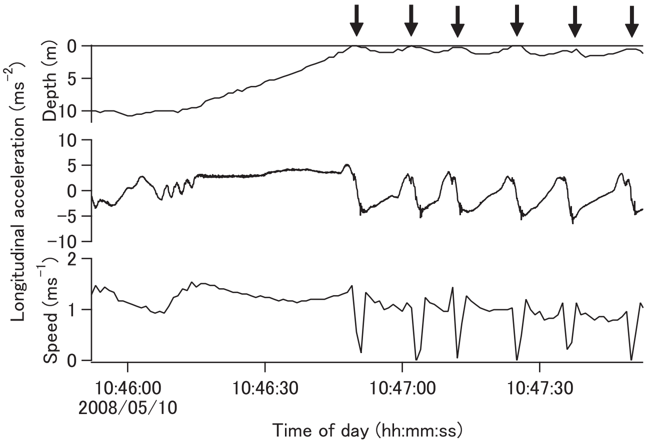

Fig. 3. Breathing behavior of the of the short-finned pilot whale carrying tag #2. black arrows indicate breathing point.

(5.7) = 0.99505). These observations and subsequent analysis suggested that tags became nearly parallel to the animals’ body axes due to the flow of the water. These results suggest that swim speed for this species was measured correctly using this type of suction-cup tag.

Tag #2 recorded 7 dives, and tag #3 recorded 2 dives (Table 1). The animals made shallow dives (maximum depth was 37.7 m) and the average swim speed for both animals were around 1.0 ms^{-1} (tag #2: avg. ± *SD*: 1.0 ± 0.4 ms^{-1}, tag #3: avg. ± *SD*: 1.2 ± 0.6 ms^{-1}). At the moment the tags dropped off, they had recorded the maximum swim speed and acceleration (#2; 5.5 ms^{-1}, 2.1 ms^{-2}, #3; 4.2 ms^{-1}, 1.9 ms^{-2}) and swim depth increased drastically for each animal. The whales were accelerating downward at great speed at that moment.

The swim speed dropped about every 10 to 20 seconds while the animal was close to the surface (Fig. 3). This suggests that the data logger broke the surface of the water at the moment the animal took a breath. Longitudinal acceleration recorded a rapid change of body angle when the animal was breathing (Fig. 3).

A high frequency signal was intermittently recorded in longitudinal acceleration during diving in tag #2 (Fig. 4). In general, high-frequency components of acceleration have been considered as stroking (e.g., Sato et al. 2003, 2007). We tested relationships between high-frequency components of longitudinal acceleration and a change of swim speed. We analyzed only the data when the whale swam horizontally because buoyancy may affect changes of speed during ascent or descent phases (Watanabe et al. 2006). There were 9 periods where we recorded high frequency waves (avg. ± *SD*: 11.6 s ± 5.6) during hori-

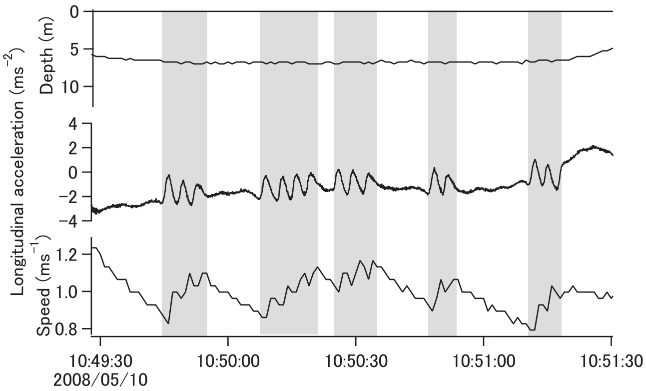

Fig. 4. Stroke and glide swimming of the short-finned pilot whale carrying tag #2. Gray area indicates stroking periods.

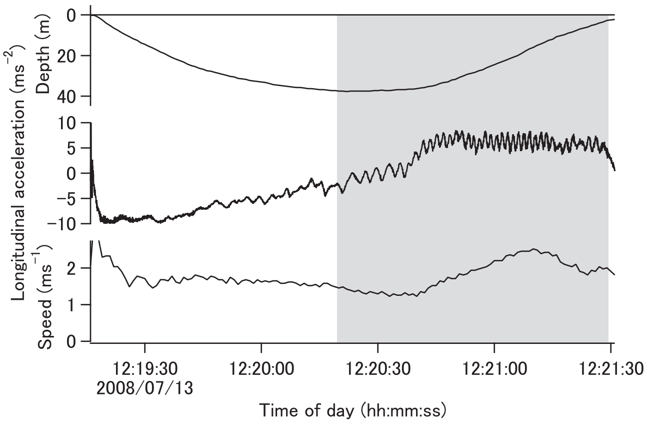

Fig. 5. Continuous stroking of the short-finned pilot whale carrying tag #3.

zontal swim in tag #2. We compared the swim speed of the start point and end point in those periods. For all of these periods the speed of end point was higher than that of the start point (mean difference ± *SD*: 0.18 ms^{-1} ± 0.07). These results suggest that the increases in swim speed were caused by thrust and the high frequency waves indicate stroking. There were 6 periods which did not include stroking (avg. ± *SD*: 10.2 s ± 2.6) during horizontal swim in tag #2. For all of these periods the speed at the end point was lower than that at the start point (mean difference ± *SD*: –0.15 ms^{-1} ± 0.05). This suggests the decline of speed were derived from drag and the animal was gliding during these periods. There was a high frequency signal and the speed increased during the ascent phase of the dive in tag #3 (Fig. 5). This suggests the whale was stroking continuously.

These results show that several behaviors, such as breathing, stroke and glide swimming, and continuous stroking, can be determined using swim speed and acceleration data. By using data loggers for longer periods of time more detailed diving behavior will be revealed in future studies.

Acknowledgments: We would like to thank all volunteer members who assisted us with field work. Field work was funded by the Southwest Fisheries Science Center of NOAA Fisheries and the U.S. Navy (N45). This research was supported by the “Bio-Logging Science of the University of Tokyo (UTBLS)” program led by Nobuyuki Miyazaki. Tagging was undertaken under NMFS Scientific Research Permit No. 731–1774. We thank two anonymous referees for reviewing the manuscript and providing helpful suggestions.

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Received 21 May 2010. Accepted 5 October 2010.