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Measuring the swimming behaviour of a reared Pacific bluefin tuna in a submerged aquaculture net cage

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Abstract – The swimming path of a reared Pacific bluefin tuna, *Thunnus orientalis*, was measured in a submerged aquaculture net cage to understand how reared fish use the space in such a cage. A bluefin tuna (fork length, FL, 0.51 m) was captured by angling in the cage, and two micro data loggers (PD3GT, Little Leonardo; DST Comp-Tilt, Star-Oddi) were attached to its body. The fish was then released back into the net cage. The PD3GT measured its swimming speed and depth at 1-s intervals and recorded these in flash memory. The DST Comp-Tilt measured the magnetic field strength at 1-s intervals and recorded the heading estimated from the magnetic field strength in flash memory. The fish moved through the water in the cage at speeds of 0.7–0.8 $m\,s^{-1}$ and attained a maximum speed of 3.6 $m\,s^{-1}$. Burst swims exceeding 2 $m\,s^{-1}$ were confirmed only after dark and a significant difference was found between the daytime and night-time swimming speeds ($p < 0.001$). The fish moved at depths between 2 and 22 m, swimming near the bottom during the day and at 10–15 m at night, with a significant difference in swimming depth between day and night ($p < 0.001$). The swimming path reconstructed by dead reckoning was visualised using night-time data. For this period, the absolute speed was corrected from 0.75 ± 0.09 $m\,s^{-1}$ to 0.71 ± 0.15 $m\,s^{-1}$ by removing the accumulated error from the reconstruction vector. This study allowed us to examine the behaviour of a tagged tuna in three dimensions and is the first to monitor the behaviour of a bluefin tuna in a submerged net cage. Although only one fish was analysed, this study provides useful information on the space use of reared fish in aquaculture net cages. Future studies must obtain sufficient data to understand the underlying generalities of tuna behaviour.

Key words: Bluefin tuna / swimming path / submerged net cage / aquaculture / data logger / behaviour

1 Introduction

Many sea aquaculture facilities are located in calm areas, such as bays and inshore zones, but increasing development in such areas is causing severe environmental pollution, including the self-contamination of existing aquaculture facilities. It may sometimes therefore be necessary to install aquaculture net cages offshore, where wave and current action are much higher than in inshore areas. Submerged net cages, developed for aquaculture in offshore areas, can be deployed under rough conditions, as they have the capacity to move vertically in the water column. However, the rearing space in submerged net cages can change greatly during these vertical movements, and also decreases due to movement of the bottom net by strong ocean currents (Suzuki et al. 2009).

An evaluatation is necessary of whether offshore submerged net cages are suitable as living spaces for bluefin tuna. To determine this, an examination should be made of the swimming path of the fish and the ways in which vertical movements of the cage and the volume loss caused by ocean currents influence fish behaviour. Examining the behaviour of reared fish in net cages is logistically problematic. Although some studies have already described the behaviour of reared tuna in aquaculture net cages (Kubo et al. 2005; Okano et al. 2006), these reports have only measured one-dimensional behavioural data, swimming depth, acceleration, or feeding behaviour, while three dimensional behavioural measurement is necessary to examine space use properly. It is also necessary to measure behaviour on a fine time scale to fully understand turning behaviour in response to certain structures. Such behavioural studies are possible in a closed space such as a fish tank (Suzuki et al. 2003; Gautrais et al. 2009), but it is difficult

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to measure fish behaviour in a field experiment on a fine time scale in comparison with an indoor experiment.

In recent years, it has become possible to characterise the behaviour of various fish species because of the development of adapted monitoring devices. Scientific understanding obtained using biotelemetry has provided profitable, concrete information on homing behaviour (Mitamura et al. 2005), fish migration (Block et al. 2005), fish behaviour near fish aggregating devices (Ohta and Kakuma 2005; Dagorn et al. 2007), and in aquaculture (Bauer et al. 2004; Kubo et al. 2005; Okano et al. 2006). In the future, biotelemetry will likely play an important role in many research fields including aquatic ecology and fishery and aquaculture sciences.

The two types of biotelemetry generally used to measure the swimming paths of aquatic animals in water are micro data loggers (Wilson et al. 1991; Mitani et al. 2003; Shiomi et al. 2008) and acoustic telemetry (Shin et al. 2003; Anras and Lagardère 2004). Compared with micro data loggers, acoustic telemetry provides a limited type and quantity of information, although it does allow the behaviour of tagged fish to be measured remotely. If scientists want to understand the detailed behaviour of a fish over a short timescale, acoustic telemetry is not recommended, whereas fish behaviour can be measured in detail over a short timescale using micro data loggers. The disadvantage of micro data loggers is that to access the stored data, loggers must be retrieved. Consequently, these tags are usually used to study animals whose homing behaviour ensures a high probability of tag retrieval, such as turtles (Yasuda and Arai 2009), salmon (Tanaka et al. 2005; Tsuda et al. 2006), and mammals (Mitani et al. 2003).

As the receivers cannot be fixed completely, measuring swimming paths using acoustic telemetry is difficult in offshore areas. However, no such problem exists with the attachment of the monitoring device when swimming paths are measured using micro data loggers, and these tags can be easily collected if they are placed on fish in an aquaculture net cage.

Behavioural data on fish grown in submerged net cages would be useful to facilitate the development of net cages that cause less stress to reared fish. An understanding of the ways in which fish swim in net cages under rough conditions might also play an important role in the improvement of offshore net cages. To this end, we measured the swimming behaviour of a reared Pacific bluefin tuna, *Thunnus orientalis*, in an aquaculture net cage, using two types of micro data logger to understand the way in which the fish uses the available living space in the cage. The main goal of this study was to demonstrate a method for determining the swimming path of a fish and to clarify the ways in which reared bluefin tuna swim in a submerged net cage.

2 Materials and methods

2.1 Net cage

This study was conducted in a submerged net cage installed in offshore waters in Kochi Prefecture, Japan. The top of the cage was located at a water depth of 2 m, and the living space within the net was completely submerged. The cage was circular in shape, measured 30 m in diameter and 22 m in depth, and could be lowered to about 10 m below the sea surface to avoid rough conditions such as typhoons, although the cage was not moved vertically during this study.

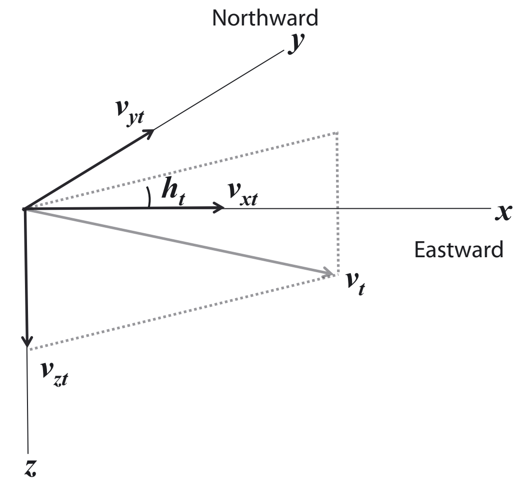

Fig. 1. Schema of the swim vector showing the speed, v_t, heading, h_t, and locomotion vector (v_{xt}, v_{yt}, v_{zt}) of the tagged fish.

2.2 Devices for monitoring fish behaviour

To monitor fish behaviour, two types of micro data logger were deployed in this study: the PD3GT and DST Comp-Tilt. The PD3GT (W190-PD3GT: Little Leonardo, 21 mm diameter, 117 mm in length, weight 75 g in air) measures fish swimming speed through water using a propeller. It can also measure swimming depth, three-axis acceleration and ambient water temperature, although three-axis acceleration and ambient temperature data were not used in this study. In a preliminary experiment, we confirmed that the swimming speed of a tagged fish could be calculated from the number of revolutions of the propeller. The stall speed of the device was determined as 0.2 m s^{-1} in the preliminary experiment but, in the study itself, the tagged fish swam at speeds over 0.28 m s^{-1} without the propeller stopping.

The DST Comp-Tilt (Star-Oddi, 15 mm diameter, 46 mm in length, weight 19 g in air) can record three-axis tilt, swimming depth, ambient water temperature, and the heading of the fish calculated using two-dimensional geomagnetism and the three-axes tilt sensor. Again, in this study, the three-axis tilt, ambient water temperature, and swimming depth data were not used, only the heading data.

2.3 Tagging and retrieving the devices from the fish

A bluefin tuna (fork length, FL, 0.51 m) was captured from within the cage by angling. Two micro-data loggers, inserted into one floating body, were externally attached to the body of the tuna, near the second dorsal fin, using a surgical procedure. The buoyancy of the float was adjusted to slightly more than its underwater weight. The fish was then released back into the net cage. The data loggers were later detached from the fish by a timing device (Little Leonardo) and were collected by a diver.

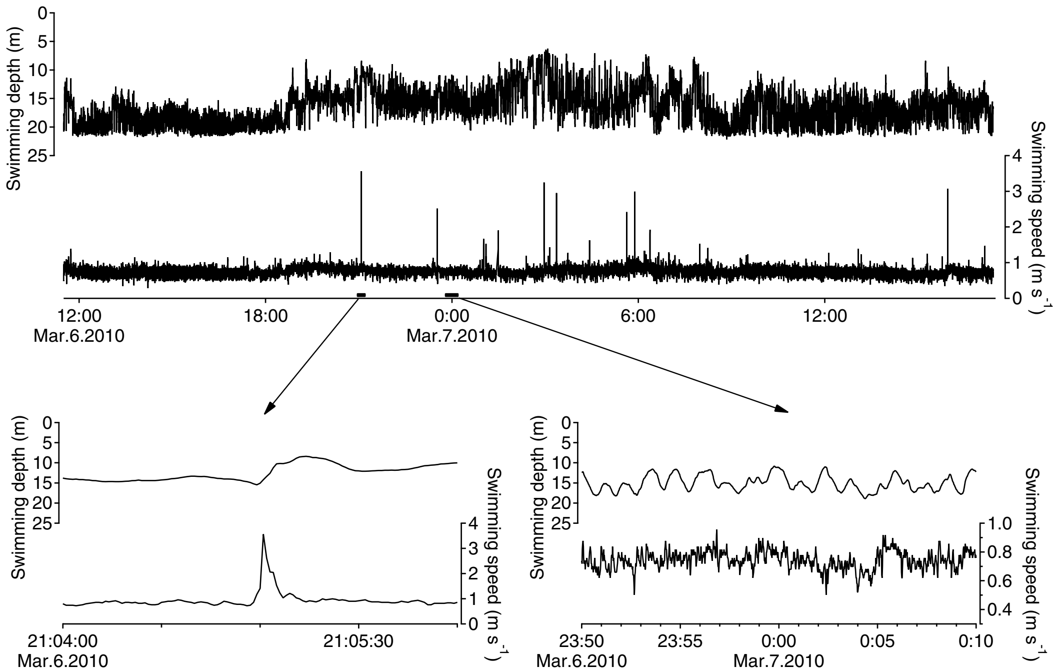

Fig. 2. Top: time series data for the behaviour of the tagged fish showing the swimming depth (top) and speed (bottom). Bottom: the two figures are close-ups of parts of the top figure.

2.4 Data collection

The PD3GT recorded swimming speed and depth at 1-s intervals, saving these data in flash memory from 09:30 on 6 March until 17:30 on 7 March 2010. The DST Comp-Tilt recorded the heading of the fish at 1-second intervals. Due to its limited memory capacity, data from the DST Comp-Tilt were divided into four phases of daily activity: dawn, 05:00–07:00; day, 11:30–12:30; dusk, 17:00–19:00; and night, 23:30–00:30. To monitor the current profile near the net cage, an electromagnetic current meter (Infinity-EM, Alec Electronics) was fixed close to the net cage at a depth of 12 m. The Infinity-EM recorded the current speed and direction and calculated using the two-dimensional velocity at 5-min intervals. Current speeds from 0.2 to 11 cm s^{-1} were observed (mean current velocity, 9.9 cm s^{-1}, 11:30–12:30, 6 March; 6.2 cm s^{-1}, 17:00–19:00, 6 March; 3.0 cm s^{-1}, 23:30–00:30, 6 March; 2.6 cm s^{-1}, 05:00–07:00, 7 March; 2.0 cm s^{-1}, 11:30–12:30, 7 March). No strong ocean currents exceeding 20 cm s^{-1} were measured during the study period that could have reduced the volume of the cage (Suzuki et al. 2009). The current data were not, otherwise, used in this study.

2.5 Path reconstruction

The swimming path was visualised using a dead-reckoning technique (Wilson and Wilson 1991; Mitani et al. 2003; Shiomi et al. 2008) with the night-time data; 23:30–00:30. The swimming path was reconstructed from data on speed v_t, heading h_t and change in depth $d_t - d_{t-1}$. The locomotion vector (v_{xt}, v_{yt}, v_{zt}), was calculated by

$$v_{xt} = \cos(h_t)\sqrt{v_t^2 - v_{zt}^2} \quad (1)$$

$$v_{yt} = \sin(h_t)\sqrt{v_t^2 - v_{zt}^2} \quad (2)$$

$$v_{zt} = d_t - d_{t-1}, \quad (3)$$

where t is time (Fig. 1).

A swimming path can be reconstructed by integrating these vectors. To visualise the swimming path, depth data were used instead of v_z for the reconstructed locomotion vector. An origin point was assigned as the initial condition of the swimming path since the initial conditions were unknown in this study, and the swimming path, v_x, v_y, included a cumulative error (Mitani et al. 2003; Shiomi et al. 2008). In addition, in this study, linear drift was observed when calculating the reconstructed swimming path at night-time, so the path is thought to have included a cumulative error. To correct this, the data for the $x-$ and$y$-components were detrended for the linear component by subtracting the least-squares fit. Since non-linear drift was confirmed at dawn, during the day and at dusk, it was impossible to correct the swimming path by detrending the linear component. Night-time data (23:30–00:30, n = 3599) were used to reconstruct the swimming path.

2.6 Statistical analysis

Average swimming depth and swimming speed of the tagged fish were compared between daytime (06:00–18:00) and night-time (18:00–06:00) using a t-test following an F-test, performed using R version 2.10.0. We first confirmed

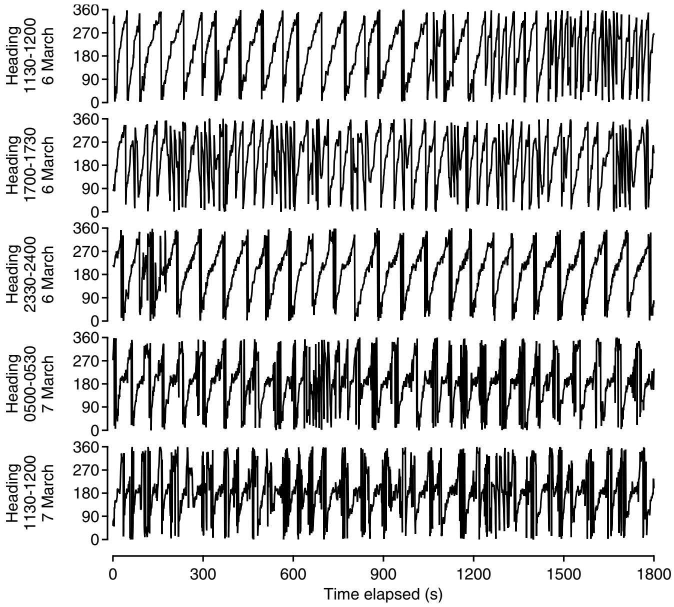

Fig. 3. The time series data showing the heading of the orbiting fish during each period.

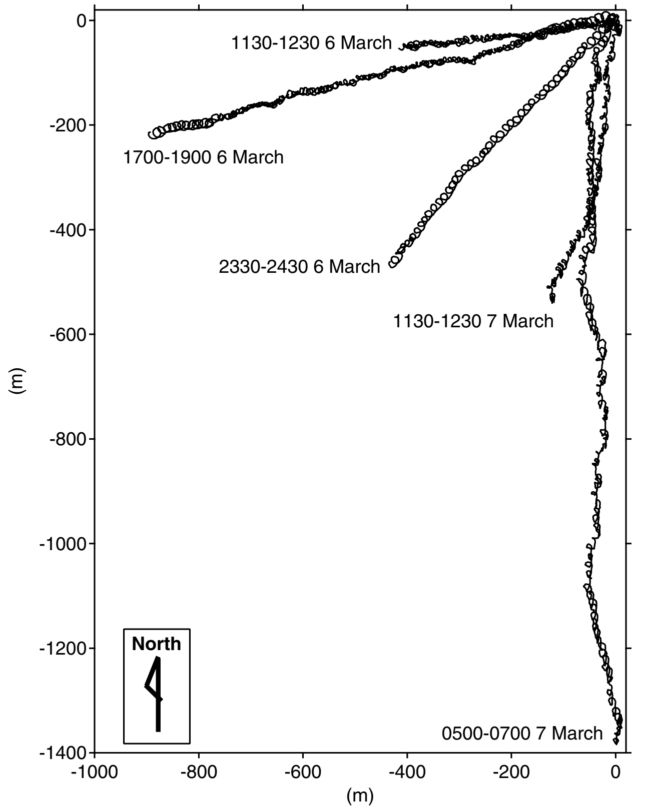

Fig. 4. The swimming path reconstructed for each period using the deadreckoning technique. In the figure, the upwards direction represents north.

the characteristic autocorrelation time to be detected at a speed of 69 s and a depth of 74 s, and doubled this time to take each sampling, then the data at daytime and night-time were compared using a t-test. Autocorrelation function and cross-correlation function were performed using IGOR pro 6.1 (WaveMetrics, USA) to analyse frequency or lag of time series data.

3 Results

A record of swimming behaviour was obtained from the data retrieved over 33 h (Fig. 2). The fish was found to move between depths of 2 and 22 m, swimming in the vicinity of the cage bottom during the day and at around 10–15 m at night, with a significant difference in swimming depth between day (mean ± SD, 17.0 ± 2.6 m; 06:00–18:00) and night (mean ± SD, 14.7 ± 2.9 m; 18:00–06:00) (t-test, $p < 0.001$; F-test, $p > 0.05$). The fish moved at speeds of 0.7–0.8 m s^{-1} (approximately 1.4 FL s^{-1}), with a maximum speed of 3.6 m s^{-1} (7.0 FL s^{-1}). Burst swims exceeding 2 m s^{-1} were observed only after dark (Fig. 2), and a significant difference was found in the swimming speed between day (mean ± SD, 0.73 ± 0.10 m s^{-1}; 06:00–18:00) and night (mean ± SD, 0.77 ± 0.10 m s^{-1}; 18:00–06:00) (t-test, $p < 0.001$; F-test, $p < 0.05$). In general, the fish swam clockwise in the net cage during each period (Fig. 3).

The swimming path reconstructed by dead reckoning was visualised using night-time data from 23:30–00:30 because the accumulated error was the most linear compared with the other periods (Fig. 4), and the error bias in the southwest direction was confirmed (Figs. 4 and 5). The residuals of x (the east component) and y (the north component), calculated to remove the accumulated error, oscillated at less than 15 m, but this was rarely confirmed (Fig. 5). The swimming path was obtained from the data using the east (x) and north (y) components with the accumulated error removed (Fig. 6). The swimming speed was 0.71 ± 0.15 m s^{-1} (1.40 ± 0.30 FL s^{-1}, mean ± SD) corrected by removing the accumulated error. In this period, the speed was 0.75 ± 0.09 m s^{-1} (1.46 ± 0.18 FL s^{-1}, mean ± SD) before it was corrected.

The tagged fish swam rapidly towards the north and west but slowly towards the south and east (Fig. 7). When viewed from the side, the swimming path formed an inclined orbit (Fig. 6). The autocorrelation function of the sine component of the swimming path of the time series data showed a first peak at 74 s. The autocorrelation function of the swimming depth of the time series data also showed a first peak at 74 s. The autocorrelation function of the swim speed of the time series data showed a first peak at 69 s. The cross-correlation function between the swim speed of the time series data and the swimming depth of the time series data showed a first peak at 24 s (Fig. 8).

4 Discussion

This study allowed us to examine the behaviour of a tagged tuna in three dimensions and is the first trial to monitor the behaviour of a bluefin tuna in a submerged net cage. The residuals of x (the east component) and y (the north component) oscillated at under 15 m, but this was rarely confirmed (Fig. 5).

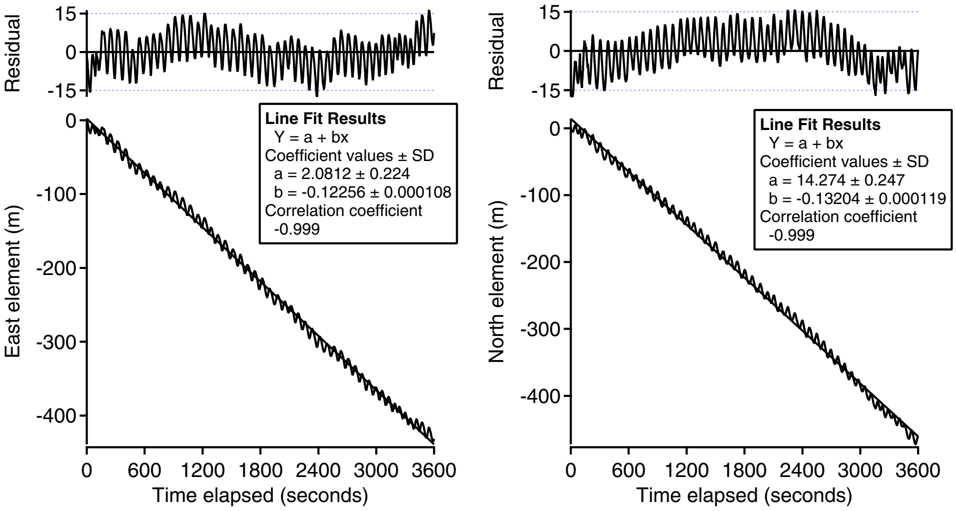

Fig. 5. The liner drift and the residuals of the x- and y-components detrended using the leastsquares method for the swimming path calculated using the dead-reckoning technique. The residuals were detrended by the linear component using the least-squares method from the reconstructed vector of the x- and y-components.

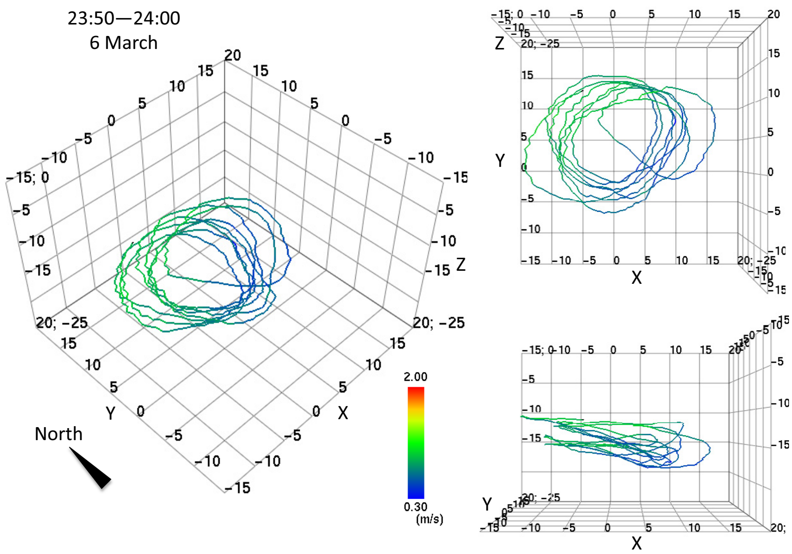

Fig. 6. The swimming path calculated using the dead-reckoning technique during the period from 23:50 to 24:00. The colour of the swimming path indicates the swimming speed.

This means that the fish orbit was more likely to be 30 m, i.e., the diameter of the cage. The examination of the obtained swimming path shows how a fish swims in an aquaculture net cage (Fig. 6). This study serves as a good initial evaluation of whether offshore submerged net cages are suitable living spaces for bluefin tuna.

The fish swam rapidly to the north and west and slowly to the south and east, which suggests that the orbit was unlikely to be circle when the swimming path was viewed from above. The tagged tuna might be swimming in an elliptical orbit. In this case, the swimming speed of the tagged fish measured by the propeller of the PD3GT is the speed through the water, not the speed over the ground. The speed measured using the PD3GT might change depending on whether the fish was moving with or against the current. However, the influence of the current on the swimming speed might be small. In this study, currents of approximately 3 cm s^{-1} were observed at night. The swimming depth of the tagged fish from 23:30–00:30 was about 15 m, which is close to the depth at which the current meter was installed. Other factors besides ocean currents are believed to influence the cumulative error, as part of the measured swimming path went outside the cage. If the accumulated error of the reconstructed swimming path included a current-flow component, the detrending should have removed the ocean current-speed component from the data. Therefore, the results suggest that the linear drift was not related to the

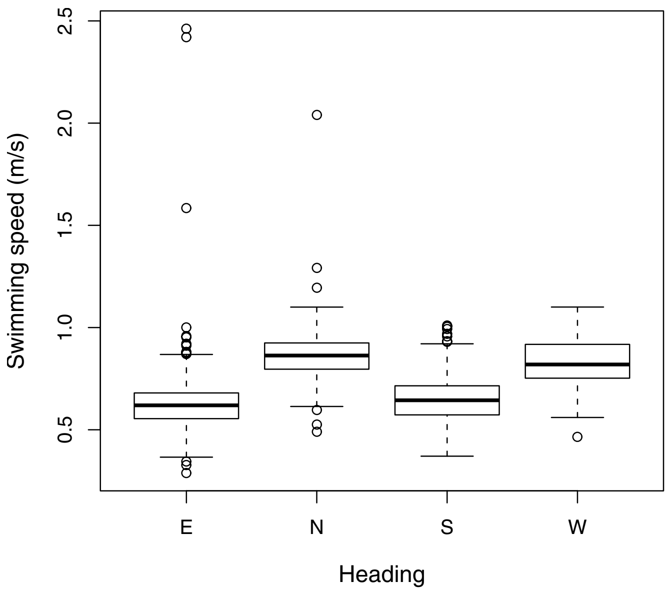

Fig. 7. Box-and-whisker plots of the swimming speed at each heading from 23:30 to 00:30 using the reconstructed swimming path. E, N, S, and W mean that the heading of the tagged tuna was east, north, south, and west, respectively. The thick black lines show the median. The box is draw between the quartiles (Q25, Q75). The dotted lines extend up to 1.5 times the height of the box above and below the vertical box, with points outside the brackets representing outliers.

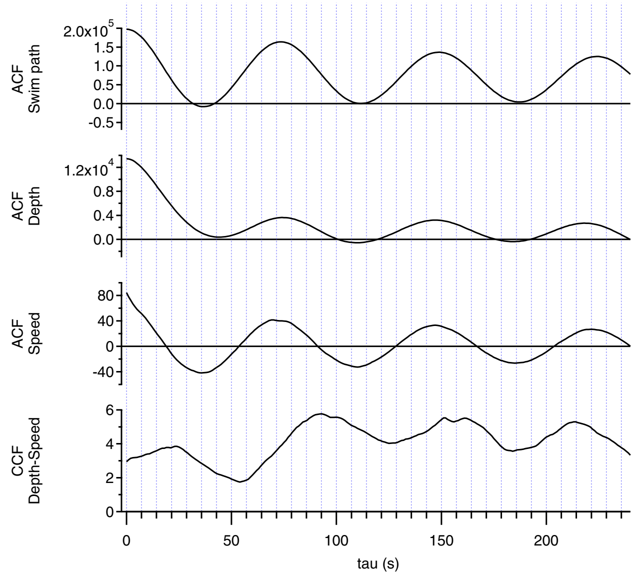

Fig. 8. Autocorrelation function of the sine component of the swimming path, depth, and swimming speed and the cross-correlation function of depth and swimming speed.

ocean current. However, the degree of accuracy of the measurements made with the electromagnetic current meter should be taken into account. Moreover, the current could also change in three dimensions. Using a measurement system similar to the PD3GT used in this study, Shiomi et al. (2008) suggested that the accumulated error was caused by the ocean current and, imilarly, Mitani et al. (2003) emphasised the influence of current flow. A future study should investigate the influence of the drift of the swimming path. As non-linear drift was confirmed at dawn, during the day, and at dusk, it might be impossible to subtract the least-squares linear fit using detrending. If a filter is designed that can correct errors other than linear errors, the accuracy of the measured swimming path will be improved. To achieve this, it is necessary to fully understand what causes the nonlinear drift of the swimming path so that a path including nonlinear drift in other periods can be corrected in future studies.

The gross cost of transport for a bluefin tuna was at a minimum at speeds of 1.15 and 1.3 body length (BL) s^{-1}, after Blank et al. (2007), and bluefin tuna can swim most efficiently within this speed range. The swimming speed of reared tuna was 1.1 BL s^{-1} while cruising (Okano et al. 2006). Marcinek et al. (2000) reported that the mean speed of wild Pacific bluefin tuna was 1.1–1.4 FL s^{-1}. We measured fork length rather than body length; nevertheless, our results showed that the tagged tuna swam at 1.46 ± 0.18 FL s^{-1} while cruising, calculated as its speed through the water. The tagged tuna in our study cruised at a slightly faster speed than that in the previously published study.

Okano et al. (2006) estimated the swimming speed of reared bluefin tuna from tail beat frequency using the formula $U = 0.65\ f$ (refer to Wardle et al. 1989), where U is the swim speed, and f is the frequency of tail beats. However, Pacific bluefin tuna engage in glide swimming, during which they stop beating their tails (Okano et al. 2006) and; it is impossible to estimate the swim speed using beat frequency. In our study, even if the tagged tuna glided while in the cage, we were able to measure its swim speed by using the propeller.

When viewed from the side, the swimming path formed an inclined orbit (Fig. 6). The autocorrelation-function examination of the swimming path indicated that the tagged fish circled at a constant frequency of approximately 74 s per orbit from 23:30 to 00:30 and analysis of the swimming depth indicated that the fish moved up and down at the same constant frequency during the same period (Fig. 8). These results indicate that the swimming path formed an inclined orbit. The autocorrelation function analysis of swim speed indicated that the tagged fish accelerated/decelerated at constant frequency with a period of approximately 69 s from 23:30 to 00:30, which concurred with the frequency of the orbits. The cross-correlation analysis of swimming depth and speed indicated that the tagged fish moved faster near the top of the orbit and slower near the bottom, at a constant frequency and with a period of approximately 24 s from 23:30 to 00:30. This implied that the tagged fish swam rapidly after moving upward and swam slowly after moving downward in the cage.

This study has certain limitations. The actual swimming path would differ slightly from that drawn here, as the initial conditions were unknown and the starting point of the fish was not clear. If the starting point had been identified, the initial conditions would have been understood. However, in this study, it is important to emphasise that the shape of swimming path would not change even if the initial conditions changed. The Comp-Tilt measurement time was limited due to the memory capacity of the data logger. When the measurements were interrupted, the position of the fish could not be specified on resumption of the measurements. Future increases in the memory capacity of data loggers should solve such problems.

The tagged fish swam in the middle layer at night and near the bottom of the net cage during the day. Future studies will need to obtain sufficient data to gain an understanding of the underlying generalities of tuna behaviour. The results of this study demonstrate that behavioural measurements using data loggers are effective in elucidating the behaviour of a tagged fish in a net cage. Although data from only one fish were analysed, this study provides useful information on the spatial use of aquaculture net cages by reared fish and clarifies the manner in which fish swim in such a cage. Theoretically, future studies could examine the turning of fish at a wall (Gautrais et al. 2009) and the movement of fish schools (Suzuki et al. 2003) in outdoor cages by visualising fish swimming paths using the technique developed here.

5 Conclusion

This study demonstrated that behavioural measurements obtained using data loggers are effective for understanding the behaviour of a tagged fish in a net cage. These data were used successfully in this initial attempt at visualising the path of a reared bluefin tuna. The observed path clarified how fish swim in an aquaculture net cage, including the swimming speed, inclined orbit, and swimming depth. Although only one fish was analysed, this study provides useful information on the space use of reared fish in aquaculture net cages. Future studies should now aim to obtain sufficient data to understand the underlying generalities of tuna behaviour. It will be able to obtain a more accurate swimming path by designing the method for removing the accumulative error.

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