前肢を欠損したアカウミガメの遊泳能力の評価

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【はじめに】

アカウミガメ *Caretta caretta* は全世界に存在する 7 種のウミガメ類の一種で、温帯から亜熱帯域に繁殖地が分布する。近年、混獲や産卵場所の減少などによりアカウミガメの個体数減少が懸念さている。IUCN のレッドリストでは絶滅危惧種に指定されており、その保全が急がれている。2008 年 6 月、両前肢の約半分を失った雌のアカウミガメ （ID： 悠）が紀伊水道の定置網で混獲された。ウミガメの前肢は、水中で前進するための推進力を生み出したり、産卵上陸の際に陸上を這うことに使われている。両前肢を失った悠の自然界での生存が懸念されたため、一旦人工池ラグーンへ搬送された。その後、人工ヒレを装着することによって悠の遊泳能力を取り戻させる試みがスタートした。本研究では、自然環境下でのウミガメの遊泳能力も調べるため、右前肢を欠損した個体（ID：ヒカリ）および野生個体の遊泳行動測定も実施した。本研究では、人工ヒレを装着する前後での悠の遊泳能力が健常個体と比較してどの程度であるか、さらに右前肢を欠損したヒカリの自然環境下での遊泳能力と比較することを目的に、遊泳速度や、前肢を動かす頻度（ストローク周波数）を記録できる動物搭載型記録計（データロガー）を悠、飼育下健常個体、野生個体の背甲に取り付け、水中で泳ぐ行動を記録した。

【材料および方法】

遊泳速度や、2 または 3 軸の加速度を記録できるデータロガーを悠（標準直甲長, SCL: 77.6 ± 3.3 cm）、飼育下健常個体（n = 2, SCL: 77.1 ± 0.5 cm、84.7 ± 0.2 cm）、およびヒカリ（SCL: 76.0 cm）を含む野生個体（n = 3, SCL: 72.8 - 78.8 cm）の甲羅に取り付け、水中での行動を記録した。得られた時系列データは解析ソフト IGOR PRO (WaveMatrics, Lake Oswego, OR, USA)を使って解析し、健常個体や人工鰭を装着した状態と装着しない状態の間で行動を比較した。全部で 26 タイプの人工ヒレが川村義肢（株）によって制作され、継続して装着できた 6 タイプの人工ヒレについて、遊泳行動を比較した。毎秒のストローク周波数を抽出するため、連続ウェーブレット変換により背腹方向の加速度データのスペクトログラムを算出し、毎秒の変動強度が最大となる周波数を抽出した。これらの計算は「Ethographer」というコンピューターアプリケーションを用いて行った （Sakamoto et al. 2009）。また、個体毎の卓越ストローク周波数を得るために、時系列データ全体からパワースペクトラル密度を描いてピークとなる周波数を調べた。一般化線形モデル（GLM）を用いて、ストローク周波数を説明変数に含む遊泳速度の統計モデルを求めた。モデル式から卓越ストローク周波数やその２倍のストローク周波数における遊泳速度を算出し、遊泳能力の指標とした。また、一回のストロークで進める距離やストロークの効率を表す揚力係数なども、遊泳能力の指標として比較した。悠および飼育下健常個体の遊泳能力測定試験は 2009 年 5 月から 2012 年 11 月にかけて、神戸空港西緑地人工池ラグーンおよび神戸市立須磨水族園内の大水槽で行った。野生個体の遊泳データは 2006 年から 2010 年にかけて岩手県沿岸域で取得した。また、悠の人工ヒレ未装着時、人工ヒレ装着時、および健常個体（n = 32、SCL: 52.2 – 84.7 cm）の前肢面積を PHOTOSHOP （Adobe System, Inc., San Jose, CA, USA)と IGOR PRO を用いて計算し、SCL と前肢面積の関係を示す回帰式を求めた。

【結果および考察】

悠からは 14、飼育下健常個体からは 5、野生個体からはそれぞれ 1 セットの遊泳データを得た。悠と飼育下健常個体の全データから得られた各個体の卓越ストローク周波数の平均は 0.43 Hz となった。野生個体に関しては全ての個体で卓越周波数が 0.31 Hz となった。人工ヒレを装着する前の悠の前肢面積は同程度のSCLを持つ個体の約60%であった。人工ヒレを付けない悠の遊泳速度は、卓越ストローク周波数の時で健常個体の 71%、倍の周波数では 58%しかなかった。また卓越周波数で悠がストロークした際の 1 回のストロークで進める距離は 1.5 体長と、健常個体（1.9 - 2.1 体長）よりも小さく、前肢面積が小さいために遊泳能力が低いことが示唆された。人工ヒレを装着する前の悠は、健常個体と同程度もしくは遅い周波数でストロークしており、前肢面積減少に伴う遊泳速度の低下を高周波でストロークすることで補うといったことはなかった。健常個体を 1 とした時の、悠の相対的な揚力係数は 1.12 と健常個体よりも良い値となった。一般的にウミガメが遊泳する際、主な推力は前肢から獲得されるため、舵取りなどの目的以外で後肢を動かす事は少ない。しかし、悠は遊泳の際に後肢を激しく動かすことが観察されており、後肢を動かし推力を得たことによって、見かけ上前肢をストロークした際の揚力係数が向上したものと考えられる。

人工ヒレ装着直後の悠の遊泳速度は、健常個体の 50 - 60%となり、人工ヒレを装着する前の悠の遊泳速度よりも低くなった。1 回のストロークで進める距離に関しても健常個体の 56 - 68%程度で、人工ヒレ未装着時の悠よりも小さい事から、人工ヒレ装着直後は遊泳能力に向上は見られなかったことになる。一方で、人工ヒレを 1 - 2 ヶ月間長期装着した後の悠の遊泳速度は、健常個体の 71 - 75%となり装着直後よりも高くなった。特に高周波でストロークした際には人工ヒレ未装着時の悠よりも高い速度を獲得することができた。1 回のストロークで進む距離も、高周波でストロークした際には 1.3 体長と、人工ヒレ未装着時の悠の 1.1 体長よりも長くなった。このことから人工ヒレを長期間装着することにより、特に高周波でストロークした際の遊泳能力が向上することが示唆された。長期装着により、悠が人工ヒレに慣れ，効率のよい遊泳を学習した可能性が考えられる。

右前肢を欠損した野生個体ヒカリの前肢面積は同サイズの野生健常個体の約 46%であった。ヒカリの遊泳速度は野生健常個体の 71%で、1 回のストロークで進める距離も健常個体の 71%と小さかった。また、相対的な揚力係数は 1.04 と健常個体とほぼ同等の値となり、ヒカリの遊泳速度は前肢面積減少に応じて低下したものと考えられる。健常個体から得た遊泳速度ヒストグラムでは、0.68 m s^{-1} が最頻値となり、先行研究をもとに推定したウミガメの最適遊泳速度と一致した (Sato et al. 2010)。ヒカリと野生健常個体は同じ卓越周波数でストロークしていたにも関わらず、ヒカリのヒストグラムの最頻値は 0.48 m s^{-1} となり、健常個体よりも低い最適遊泳速度を維持していたことが分かった。前肢面積減少に伴う遊泳速度低下を補うために、高周波でストロークすることはなかったことになる。野生のウミガメは特に高速遊泳を実現したいとは考えておらず、エネルギーコストが最小になる周波数でストロークし泳ぐことの方が大切であるようだ。

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Evaluating the swimming ability of forelimbs-lost loggerhead turtles, *Caretta caretta*

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【Introduction】

Loggerhead turtle, *Caretta caretta,* is one of seven extant species of sea turtles, and their nesting grounds are distributed throughout tropical and temperate regions. Declines of the populations due to human exploitation such as bycatch and declines of spawning grounds have been reported. As of 2012, five out of seven species were listed as either endangered or critically endangered species in the IUCN Red List of Threatened Species, and there has been increasing concerns of conservation of sea turtles in worldwide. In June 2008, a female loggerhead turtle that lost half of its both forelimbs (named 'Yu') was captured in a set net in Kii Channel, Japan. Considering difficulties to survive in the wild without healthy forelimbs that are important for producing thrust for swimming and moving on the ground for nesting, 'Yu' was transported to a closed salt-water lagoon and several artificial fins were equipped to investigate how to recover its swimming ability. The swimming ability of an injured turtle, the right forelimb-lost sea turtle (named 'Hikari'), and sea turtles under natural conditions were also investigated. In the present study, swimming behavior of 'Yu', healthy turtles, and sea turtles under natural conditions were monitored by using data logger to examine the swimming ability of 'Yu' with and without artificial fins, comparing with the healthy turtles and 'Hikari'.

【Materials and methods】

Data logger that was programmed to record swim speed and 2-3 axis accelerations were attached to observe swimming behavior of 'Yu' (standard carapace length , SCL: 77.6 ± 3.3 cm), healthy turtles (n = 2, SCL: 77.1 ± 0.5 cm, 84.7 ± 0.2 cm), and turtles under natural conditions (n = 3, SCL: 72.8 - 78.8 cm), including Hikari (SCL: 76.0 cm). The time-series data obtained from data loggers were analyzed with IGOR PRO (WaveMetrics, Inc., Lake Oswego, OR, USA). In total, 26 versions of artificial fins had been developed by Kawamura Gishi Co., Ltd. and six versions of fins were successfully attached to 'Yu'. Data of 'Yu' with the six versions of fins were used for analysis. Dorso-ventral acceleration was used to calculate stroke frequency. In order to extract stroke frequency in each second, acceleration spectrogram was generated, using continuous Wavelet transformation with computer application, "Ethographer" (Sakamoto et. al. 2009). Dominant stroke frequency of each turtle was also determined by a peak of the power spectral density (PSD) of the entire acceleration dataset of each individual, calculated by a Fast Fourier Transformation. Statistical models of swim speed with stroke frequency as explanatory variable were obtained using generalized linear model (GLM). The swimming ability was evaluated by swim speed at dominant stroke frequency and at high stroke frequency that is twice of dominant frequency. The distance travelled per stroke and relative lift coefficient, which signifies efficiency of stroke, were also examined to evaluate swimming ability. Experiments for 'Yu' and the healthy turtles in captivity were conducted in an artificial lagoon located on west side of the Kobe Airport Island or in a wave tank of Suma Aqualife Park, Kobe City, from September 2009 to December 2012. The data of turtles under natural conditions were obtained along with a coast of Iwate from 2006 to 2009. Forelimbs area of 'Yu' with and without fins and those of healthy turtles (n = 32, SCL: 52.2 - 84.7 cm) were measured from pictures using PHOTOSHOP (Adobe System, Inc., San Jose, CA, USA) and IGOR PRO, and the regression line of area of forelimbs and SCL was obtained.

【Results and discussion】

A total of 22 data was obtained (14 from ‘Yu’, 5 from the healthy turtles in captivity, 1 each from sea turtles under natural conditions). The swim speed at stroke frequency of 0.43 Hz, which was the average dominant stroke frequency of ‘Yu’ and the healthy turtles in captivity, was compared. To evaluate swimming ability at high stroke frequency, swim speed at stroke frequency of 0.86 Hz, which was twice of the average dominant frequency, was also compared. For turtles under natural conditions, since all of them stroked at 0.31 Hz, the swim speed was compared at that frequency. The forelimbs area of ‘Yu’ was about 60% of individuals with similar SCL. The swim speed of ‘Yu’ without fins was 71% at 0.43 Hz and 58% at 0.86 Hz, comparing with the controls. The distance travelled by a stroke at dominant frequency was 1.5 body length (BL), and it was smaller than that of the healthy turtles (1.9 - 2.1 BL). Thus, it was suggested swimming ability of ‘Yu’ was lower than the healthy turtles due to reduced forelimbs area. The dominant stroke frequency of ‘Yu’ without fins was 0.43 Hz, which was similar or lower than 0.43 Hz and 0.55 Hz of the healthy turtles, which signifies that ‘Yu’ did not stroke faster to compensate decreased swim speed caused by decreased forelimbs area. The relative lift coefficient of ‘Yu’ (treating the healthy turtle as 1) was 1.12, and it was higher than the healthy turtle. In general, turtles do not use their hindlimbs unless they were used as steer because main thrust is produced with forelimbs. However, ‘Yu’ was observed to use its hindlimbs while swimming. Thus, it was assumed that relative lift coefficient became higher apparently by producing thrust from hindlimbs.

The swim speed and distance travelled per stroke of ‘Yu’ at beginning of artificial fin application were lower than those of the healthy turtles (50 - 60%, 56 - 68%, respectively), and they were even lower than that of ‘Yu’ without fin. Thus, improvement in swimming ability was not observed at the beginning of the applications of fin. While, after long-term application (one to two months), swim speed of ‘Yu’ increased to 71 - 75% of the healthy turtles. It was higher than that of ‘Yu’ without fins especially at high stroke frequency. Distance travelled per stroke when using artificial fin was also higher than ‘Yu’ without fins at high frequency (1.3 BL and 1.1 BL, respectively). Thus, it was suggested that swimming ability of ‘Yu’ increased at high frequency after long-term application. It is possible that ‘Yu’ learned to swim efficiently by being adapted to use artificial fins throughout the long-term experiments.

Area of a left forelimb of ‘Hikari’ was 47% of total area of left and right forelimbs of healthy similar-seized turtle, estimated from the regression line of forelimbs area and SCL. Swim speed of ‘Hikari’ was 71% of healthy turtles under natural conditions. Moreover, since distance travelled per stroke was also 71% of the healthy turtles, it was suggested the swimming ability of ‘Hikari’ was low due to the lost of right forelimb. However, the relative lift coefficient was 1.04, which was similar with the healthy turtle. It suggests that swim speed of ‘Hikari’ was declined because of the reduced area of forelimb. Histogram of swim speed from the healthy turtle showed a peak at 0.68 m s^{-1}, which accords with the optimal swim speed calculated based on a theoretical research (Sato et al. 2010). Although the healthy turtles and ‘Hikari’ stroked at the same dominant stroke frequency, the histogram of ‘Hikari’ had a peak at 0.48 m s^{-1}. It suggests that turtles adopt a strategy that maintains a particular stroke frequency to optimize cost of transport. Therefore, the optimal swim speed of ‘Hikari’ decreased as a consequence of reduced area of forelimbs. It may be more important for sea turtles to swim at optimal, rather than to swim fast.

【References】

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