論文の内容の要旨

論文題目

Quantification of Energy Budgets during Foraging Trips in Pinnipeds using Animal-borne Devices

（動物搭載型記録計による鰭脚類における採餌旅行期間のエネルギー収支定量化）

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It is important to comprehend how much amount of aquatic resources is consumed by pinnipeds for a sustainable usage of natural resources by human fisheries. Pinnipeds are known as high order predators and have been assumed that they consume large amount of aquatic resources with their enormous number of populations. However, the exact amount of their consumption has not been understood well as their foraging events exclusively occur underwater. A key concept to figure out their amount of consumption is "energy budget" during foraging trips. The energy budget is constructed with three components: 1) energetic gain: amount of energy obtained from prey, 2) energetic cost: amount of energy for transportation, and 3) accumulated energy: amount of energy which can be calculated by subtracting the energetic cost from the energetic gain. Although it is difficult to conduct visual observations on their underwater behaviors, recent developments in the technology allows us to obtain their behavioral data using miniaturized animal-borne devices. Using acceleration and swim speed recorders in the experiments on both captive and wild pinnipeds, this study is composed of four contents which contribute to quantify energy budgets during foraging trips in pinnipeds: 1) mandible movements to record feeding events, 2) theoretical cost of transport and optimal swim speed in captive pinnipeds, 3) development of a remote releasing system to retrieve recording devices from free-ranging pinnipeds and 4) selection of swim speed in wild pinnipeds.

1. Mandible movements to record feeding events

A method to detect feeding events using accelerometers was developed using captive pinnipeds. Two accelerometers were attached on the mandible and head of captive hooded seals (*Cystophora cristata, N*=3) at the Department of Arctic Biology, the University of Tromsø, Norway, in August 2007 and February 2008.

The seals were offered two fish species of three different sizes: large (Atlantic herrings, *N*=64), medium (capelins, *N*=69), and small (half-sized capelins, *N*=20), by throwing the fish one by one into the center of an experimental pool. A timing of each feeding events was observed and recorded. Based on the recorded time, accelerations related to feeding events were extracted using a highpass filtering at 3 Hz, which threshold was determined by the Wavelet transformation. All feeding events (*N*=153) were detected using the filtering method.

2. Theoretical cost of transport and optimal swim speed in captive pinnipeds

The cost of transport (COT)—the metabolic cost required to transport the animal's mass over a unit of distance—has been comprehensively discussed to compare energetic costs of animal locomotion (running, swimming and flying) since early 1970's. A recent study developed a theoretical prediction that the optimal swim speed, which minimize COT, is proportionate to the one-third power of the basal metabolic rate divided by drag—and is independent of buoyancy, pitch angle and dive depth in geometrically similar breath-hold divers. An experiment manipulating buoyancy, drag and dive depth was conducted to test this prediction using captive Steller sea lions (*Eumetopias jubatus*, *N*=3) at the Marine Mammal Research Unit, the University of British Columbia, Canada, in July and September 2007. A pair of polyvinyl chloride tubes attached on a harness worn by the animal manipulated the buoyancy and drag conditions, and swim speed recorder was also attached on the harness. A total of 186 dives with the depth up to 50 m were collected from three animals. A generalized linear mixed-effect model (GLMM) was used to test for interaction between swim speed (dependent variable) and five explanatory variables (body mass, buoyancy, depth, drag and dive phases), and swim speed was predicted with two variables (drag and dive phase, AIC=-138.7). This suggests that the optimal swim speed of Steller sea lions is a function of drag, but independent of buoyancy conditions and dive depths. These findings are consistent with the theoretical predictions.

3. Development of a remote releasing system to retrieve recording devices from free-ranging pinnipeds

A radio signal based remote releasing system has been developed through three field experiments on three species of free-ranging Otariidae: South American sea lions (*Otaria flavescence*) in 2010 (*N*=2) and 2011 (*N*=1), South American fur seals (*Arctocephalus australis*) in 2011 (*N*=3) and New Zealand fur seals (*Arctocephalus forsteri*) in 2012 (*N*=5). Accidental dropouts before activating the system occurred in the first two years: 100% (*N*=2) in 2010 and 50% (*N*=4) in 2011, but improvements resulted with no accidental dropout in 2012 (*N*=5). Although only one device in each 2011 and 2012 was successfully detached by the system, a more robust attaching method to prevent accidental dropouts has been established through these field experiments.

4. Selection of swim speed in wild pinnipeds

Mean swim speeds during descent and ascent phases were calculated to examine the theoretical prediction to estimate optimal swim speeds in free-ranging Otariidae. The datasets from New Zealand fur seals (*N*=5) and South American sea lions (*N*=2) were used for the analysis. GLMM was performed to test for

interaction between mean swim speed (dependent variable) and three explanatory variables (body mass, depth and dive phases) with separating the species. Within the fur seals, swim speed was described by dive phases with the minimum AIC=5161, and that within the sea lions was fitted with dive phases and depth with the minimum AIC=422.4. Mean swim speeds of the fur seals in descent was 1.8±0.4 m s^{-1} and those in ascent was 1.7±0.4 m s^{-1} (*N*=3582 dives). Mean swim speeds of the sea lions in descent was 1.7±0.4 m s^{-1} and those in ascent was 1.6±0.4 m s^{-1} (*N*=2641 dives). Assuming that the animals swam at their optimal swim speed in descent and ascent phase, a constant—a ratio of the drag of an active swimmer to that of a passive object—was estimated. The estimated constants were below 1.0 in each species, which was consistent with the most recent study on breath-holding divers, while this constant has been considered to be 1-5 historically. Using the obtained constant, the energetic cost in each foraging trip was estimated with swim speed data, which reflected a linear relation with surface periods. The estimated cost showed that female New Zealand fur seals required approximately 9.5 kiloton of hoki—the third economically important aquatic resource in New Zealand—during three months of nursing period, which corresponds to about 33% of annual catch by fisheries there.