Tenth International Symposium on Unmanned Untethered Submersible Technology: Special Session on Bio-Engineering Research Related to Autonomous Underwater Vehicles. September 8 - 11, 1997, New England Center, Univ of NH, Durham NH organized by AUSI and ONR

BIOLOGICAL DESIGNS FOR ENHANCED MANEUVERABILITY: ANALYSIS OF MARINE MAMMAL PERFORMANCE

Frank E. Fish

Department of Biology
West Chester University
West Chester, PA 19383 USA

Abstract - Maneuverability is critical to the performance of autonomous underwater vehicles (AUV) and fast swimming marine mammals which use rapid turns to catch prey. Overhead video records were analyzed for seven cetacean species (29-4536 kg) and sea lions (88-138 kg) turning in the horizontal plane. Powered and unpowered turns were executed by body flexion in conjunction with use of control surfaces, including flukes, flippers, dorsal fin, and caudal peduncle. Banking was used in powered turns and in unpowered turns where major control surfaces were horizontally oriented. Turning radius was dependent on body mass and swimming velocity. Relative minimum radii were 9-17% of body length and were equivalent for pinnipeds and cetaceans. However, *Zalophus* had smaller turning radii at higher speeds than cetaceans. Rate of turn was inversely related to turn radius. The highest turn rates were observed in *Lagenorhynchus* at 453 deg/s and *Zalophus* at 690 deg/s. Centripetal acceleration measured over 3 *g* for small cetaceans and 5.1 *g* for *Zalophus*. While cetaceans are configured for stability, otariid pinnipeds use their relatively large area flippers to produce increased instability with greater turning performance. This work was supported by the Office of Naval Research.

INTRODUCTION

An important consideration in the performance of autonomous underwater vehicles (AUV) is the ability to maneuver or turn. Rapid turns with small radii while maintaining speed are paramount to quickly locating objects, avoiding obstructions in confined and complex environments, and maintaining stability. Animal performance in terms of maneuverability can be superior to manufactured underwater vehicles [1]. Animals, therefore, can serve as effective model systems in exploring body and control surface designs which can be introduced into the design of AUVs to foster increased maneuverability.

Animals rarely move continuously in straight lines. This is especially true in instances where potential prey must out-maneuver a predator or the reverse for a predator to turn fast enough to catch its prey [2, 3]. In addition, the search patterns employed by animals use continuous turning maneuvers. Even the largest of all animals, whales, display considerable proficiency in their maneuverability [4]. Various morphologies within animal lineages have evolved which foster maneuverability. Within the marine mammals there are divergent body designs that suggest differences in turning performance. Of the fastest swimming marine mammals, the pinnipeds (e.g., sea lions, seals) and cetaceans (e.g., whales, dolphins) display considerable variation in both their morphology and propulsive mode [5].

To understand how variation in the morphology of marine mammals can affect maneuverability, consideration should be given to parameters associated with stability. In that maneuverability represents a controlled instability, the possession of morphological characters that deviate from a design which maintains stability is expected to enhance turning performance. Based on analysis of aerodynamics, the following features are associated with stability [6, 7]:

1. Control surfaces located far from the center of gravity

2. Concentration of control surface area posterior of center of gravity

3. Anterior placement of center of gravity

4. Dihedral of control surfaces

5. Sweep of control surfaces

6. Reduced motion of control surfaces

7. Reduced flexibility of body

If we compare the placement and design of control surfaces on sea lions and cetaceans (Fig. 1), we see marked differences between the two groups. The control surfaces of sea lions are represented by fore- and hindflippers with the larger foreflippers near the center of gravity. Because of the high mobility of the foreflippers, both the sweep and the dihedral of the flippers is variable. For the cetaceans, the flippers, flukes, dorsal fin, and caudal peduncle are the control surfaces with the more mobile surfaces distance from the center of gravity. The flippers, flukes, and dorsal fin, when present, can be highly sweep, particularly in the faster species.

Flexibility in the body of cetaceans is generally constrained [8]. In comparison, pinnipeds display significant axial flexibility [9].

Comparison of the morphology between pinnipeds and cetaceans suggests the whales and dolphins have a more stable design than marine mammals such as sea lions. Therefore, it is predicted that pinnipeds will be more highly maneuverable compared to cetaceans.

MATERIALS AND METHODS

To study variation in maneuverability based on differing body and control surface morphologies and propulsive modes, I examined the turning performance of eight species of marine mammals (seven cetaceans, one pinniped) with different swimming capabilities. All were captive animals which were maintained in pools at various research and zoological facilities including Sea World, Pittsburgh Zoo, and Long Marine Laboratory of the University of California Santa Cruz.

For the cetaceans, these included the bottlenose dolphin (*Tursiops truncatus*), killer whale (*Orcinus orca*), Commerson's dolphin (*Cephalorhynchus commersonii*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), false killer whale (*Pseudorca crassidens*), beluga (*Delphinapterus leucas*), and Amazon river dolphin (*Inia geoffrensis*). *Orcinus* was the largest cetacean with one individual of 4536 kg; whereas the smallest at 29 kg was *Cephalorhynchus*. *Pseudorca* and *Lagenorhynchus* are regarded generally as fast swimmers; whereas, *Delphinapterus* and *Inia* are considered to be slow swimmers. *Delphinapterus* and *Inia* are different from the other cetaceans by possessing mobile necks and flippers. *Inia* is capable of a notable degree of lateral flexion. In addition, the dorsal fin is reduced in *Inia* or absent in *Delphinapterus*. The cetaceans all use oscillations of the caudal flukes in the vertical plane for propulsion [4, 5]. Analysis of maneuverability has not been performed previously.

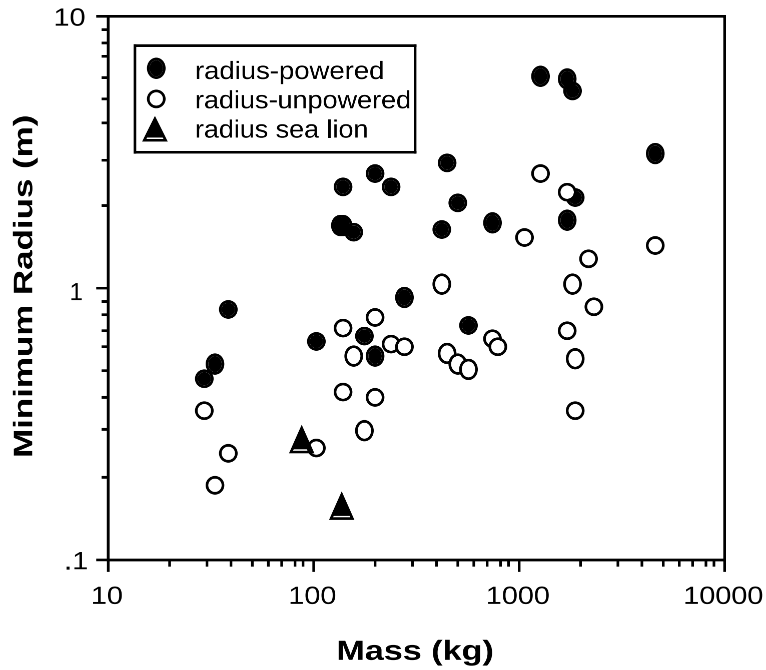

Fig. 2. Minimum turning radius plotted against body mass for individuals. Circles represent cetaceans for powered and unpowered turns and triangles represent *Zalophus*.

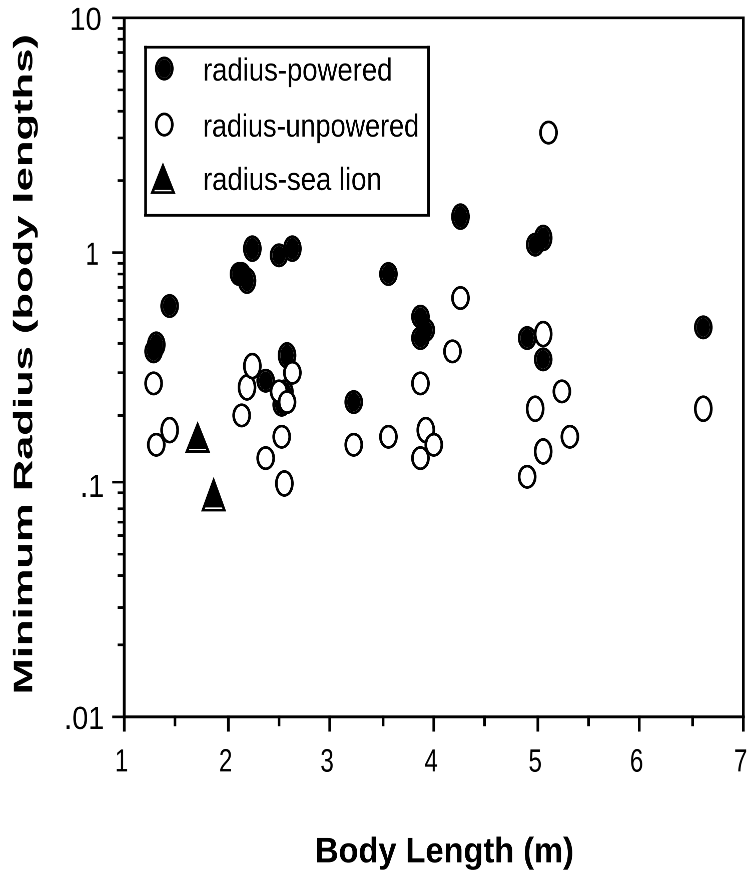

Fig. 3. Minimum length-specific turning radius plotted against body length for individuals. Circles represent cetaceans for powered and unpowered turns and triangles represent *Zalophus*.

The single pinniped species was represented by the California sea lion (*Zalophus californianus*). This animal swims by oscillations of the paired foreflippers [5]. Analysis of turning performance was restricted previously to descriptions of gross movements of the body and appendages during turning [10, 11], but no data were collected on performance capabilities.

Animals were videotaped with a camcorder (Panasonic DV-510) as they executed turning maneuvers at or near the water surface under the direction of their trainers. These maneuvers were observed through a glass wall for a lateral view underwater to detail the motion of the control surfaces. To collect data on turning performance (e.g., radius, turning rate), a dorsal view of the turn was recorded by positioning the video camera above the animal's pool. Distance above the pool varied with the physical layout of the facility and size of the animal. Vertical distance of the camera and observer over the water surface ranged from approximately 2 m to 10 m. Prior to swimming trials, animals were measured and marked with zinc oxide dots, which served as reference points and scale. One marker was placed at the approximate position above or lateral to the center of gravity.

Video records of the dorsal view were analyzed frame-by-frame at 30 Hz with a video recorder (Panasonic AG-7300). Only those records were used in which the animal's body remained horizontal through the turn. The sequential positions of the center of gravity marker were recorded onto transparencies from the video monitor. The center of rotation of the turn was determined geometrically. This technique allowed for determination of the trajectory of the center of gravity, despite distortion in observing the actual position of the marker due to refraction from surface waves. Turning radius, *r*, and average velocity, *v*, were measured, and centripetal acceleration, a_c, in *g*s was computed according to:

$$a_c = v^2/r\ 9.8. \tag{1}$$

Angular displacement was used to calculate the turning rate in deg/s.

RESULTS

Observations of cetaceans showed two turning patterns: powered and unpowered. Powered turns were defined as turns in which the animal was continuously propelling itself by the dorso-ventral oscillations of the flukes; whereas in unpowered turns, the animal glided through the turn without apparent use of the caudal propulsor. Turns were initiated from the anterior of the animal with lateral flexion of the head and rotation of the flippers into the turn. The flippers also were adducted. During unpowered turns, substantial lateral flexion of the peduncle was observed in addition to twisting at the base of the flukes. The twisting action depressed the inner fluke tip. Some inward banking was observed during unpowered turns. Oscillation around the longitudinal axis occurred during powered turns that were associated with the propulsive fluke motions and produced a rolling movement.

Both *Inia* and *Delphinapterus* proved to be exceptions to the general cetacean turning pattern. *Inia* showed no tendency to bank during turns, instead using its flexible body to produce the turn. *Delphinapterus*, without a dorsal fin, would bank 90^o with its ventral surface facing into the turn.

Zalophus used only unpowered turns. As previously described [11], The anterior end of the animal initiates the turn as the sea lion rolls 90^o so that the ventral (abdominal) surface faces the outside of the turn. The body is flexed dorsally. The fore- and hindflippers are abducted and held in the vertical plane. This maneuver brings the full area of the flippers into use. In addition, the position of the foreflippers is set to execute a power stroke and accelerate the sea lion as it comes out of the turn.

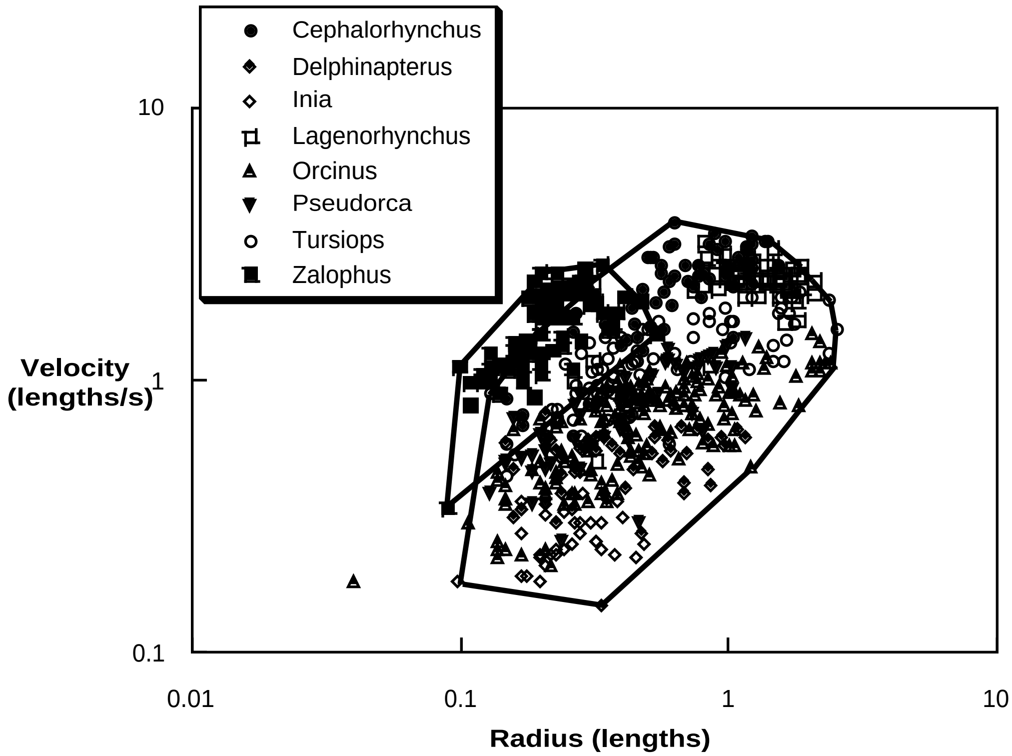

Fig. 4. Average length-specific velocity in relation to length-specific turning radius. Polygons are drawn around data for cetaceans and around data for *Zalophus*. The single point outside the cetacean polygon represents a 1725.2 kg, 5.05 m *Orcinus* which was able to produce a turn radius of 4 % of body length by ventrally flexing the posterior half of the body The flukes were used to pivot the animal around its longitudinal axis.

The force necessary to maintain a curved trajectory of a given radius is directly related to the square of the velocity and the mass of the body [12]. Indeed, minimum turning radius plotted for individuals was associated with body mass (Fig. 2). Unpowered turns for cetaceans had smaller minimum radii than powered turns for the same individuals. When scaled to body length, cetaceans generally demonstrated minimum unpowered turning radii of < 50% of body length (Fig. 3). Minimum radii within each species ranged from 11 to 17% of body length. These results are comparable to maneuvers by fish and penguins [1, 3, 13, 14].

Minimum unpowered turn radii for the two individuals of *Zalophus* were 0.16 and 0.28 m, representing 9 and 16% of body length, respectively. While the length-specific radii were small, they were not substantially different from similar values for cetaceans (Fig. 2, 3).

However, different levels of performance between species were indicated when all the data for turning radius were plotted as a function of velocity (Fig. 4). The cetaceans displayed varying capabilities. *Inia* and *Delphinapterus* produced low-speed, small radius turns. Faster speed but larger radius turns were performed by *Lagenorhynchus* and *Cephalorhynchus* and intermediate performance was displayed by *Orcinus*, *Pseudorca* and *Tursiops*. *Zalophus* was able to make small radius turns while at high speed (up to 4.5 m/s).

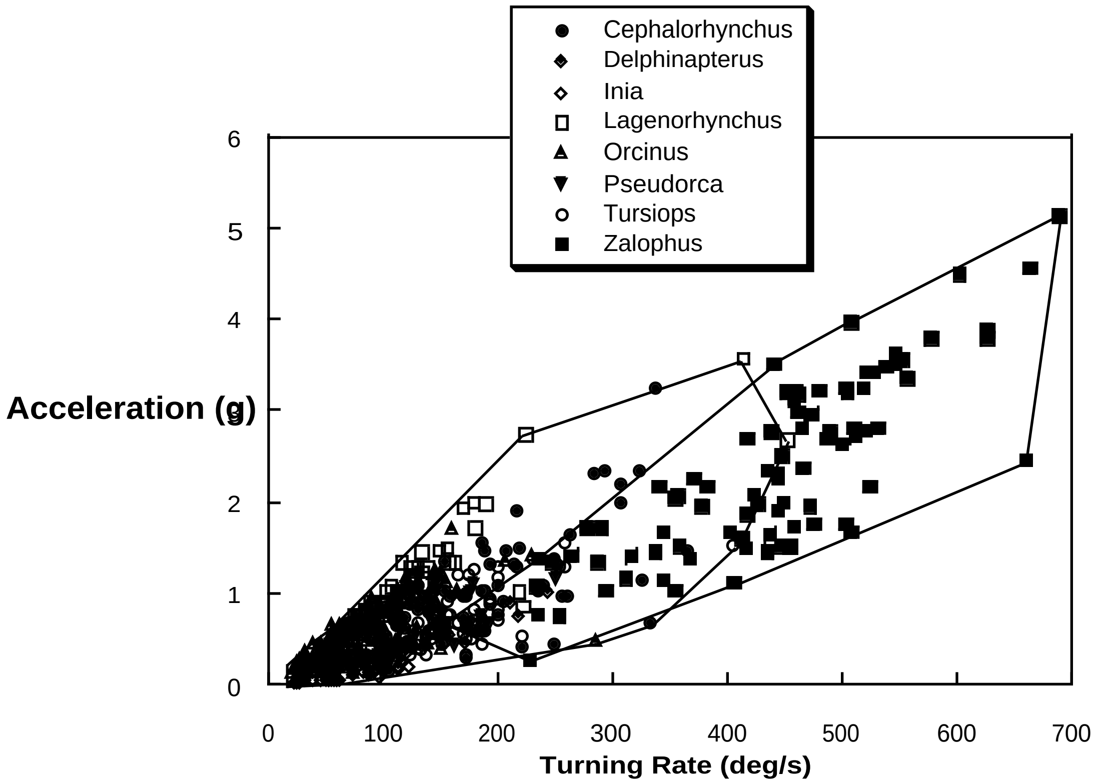

Fig. 5. Relationship between centripetal acceleration and turning rate. Polygons are drawn around data for cetaceans and around data for *Zalophus*.

The performance limits for turning are illustrated in Fig. 5 by a plot of centripetal acceleration and turning rate. Most data for cetaceans is clustered at accelerations < 1.5 *g* with turning rates < 200 deg/s. Individuals of *Cephalorhynchus* and *Lagenorhynchus* were able to exceed these lower values for cetaceans with *Lagenorhynchus* displaying the maximum performance with an acceleration of 3.6 *g* and turning rate of 453 deg/s during unpowered turns. However, *Zalophus* typically exceeded even these maximal performances by cetaceans. One animal was able to execute a 5.13 *g* turn at 690 deg/s.

With the exception of high-performance aircraft (e.g., F-15, F-16) marine mammals meet or exceed the centripetal accelerations of manufactured devices (Fig. 6). However, *Zalophus* was able to achieve an acceleration greater than that experienced during lift-off on the space shuttle, whereas, *Lagenorhynchus* and *Cephalorhynchus* with maximum centripetal accelerations of approximately 3 *g* were equivalent. Other cetaceans exhibited generally lower performance, although still higher than small underwater vehicles [1]. The lowest centripetal accelerations occurred in *Inia* followed by *Delphinapterus* which both swam slowly during testing.

Marine mammals generally show a high level of performance with regard to turning. This performance, however, varies between species and between major taxonomic groups relating to the ecology and the morphology of the animals. Maneuverability by marine mammals is dependent on body size, body stiffness and use of control surfaces. The body stiffness and position and size of the control surface, in particular, determine the stability of the animal when swimming. The sea lion, *Zalophus*, exhibits few adaptations for stability and is able to execute tighter turns at higher rates than cetaceans. The highly flexible body and mobile control surfaces (e.g., fore- and hindflippers) aid in rapidly producing instability for turning. The large area of the flippers aid during the turn by preventing side-slip [11].

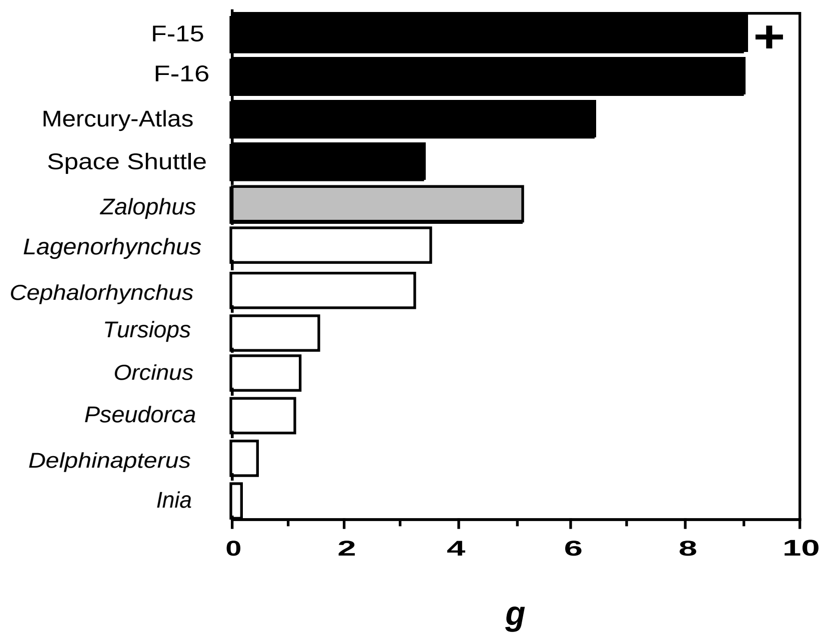

Fig. 6. Comparison of centripetal accelerations, *g*, of high-performance crafts and marine mammals.

Conversely, cetaceans have a morphology that enhances stability thereby constraining turning performance. Cetaceans with flexible bodies and mobile flippers (e.g., *Inia, Delphinapterus*) sacrifice speed for maneuverability, whereas species with more restricted morphologies (e.g., *Lagenorhynchus*, *Cephalorhynchus*) produce faster but wider turns. The dual function of the caudal appendages for both turning and propulsion presents a restriction to simultaneously maintain high speed during tight turns. To produce a small turn radius, cetaceans must use unpowered maneuvers by uncoupling the control surfaces from thrust production and limits speed and acceleration after the turn. During unpowered turns, the peduncle and flukes are diverted from their propulsive orientation and used like a rudder.

The enhanced maneuverability of sea lions thus allows them to operate in restricted, in-shore waters with complex environments, whereas the more stable design of cetaceans limit these animals to swimming and foraging in more pelagic habitats. In addition, the limitations of the cetacean design may be a causative reason for the use of cooperative foraging behaviors by whales and dolphins.

The potential scientific and technological significance of this research is an understanding of the basic turning performance by large aquatic organisms and the use and design of control surfaces. The morphology and turning performance displayed by marine mammals suggest future avenues for the design of faster and more highly maneuverable autonomous underwater vehicles (AUV).

ACKNOWLEDGMENT: I gratefully acknowledge the cooperation and assistance of the personal associated with this project from Sea World, University of California Santa Cruz, Pittsburgh Zoo, Smithsonian Institution, Brown University, and West Chester University. This work was sponsored by ONR under grant #N00014-95-1-1045.

REFERENCES

[1] Bandyopadhyay, P. R., J. M. Castano, J. Q. Rice, R. B. Philips, W. H. Nedderman, and W. K. Macy. 1997. Low-speed maneuvering hydrodynamics of fish and small underwater vehicles. Trans. ASME 119: 136-144.

[2] Howland, H. C. 1974. Optimal strategies for predator avoidance: The relative importance of speed and manoeuvrability. J. theor. Biol. 47: 333-350.
[3] Webb, P. W. 1983. Speed, acceleration and manoeuvrability of two teleost fishes. J. exp. Biol. 102: 115-122.
[4] Fish, F. E., and J. M Battle. 1995. Hydrodynamic design of the humpback whale flipper. J. Morph. 225: 51-60.
[5] Fish, F. E. 1996. Transitions from drag-based to lift-based propulsion in mammalian swimming. Amer. Zool. 36: 628-641.
[6] Weihs, D. 1993. Stability of aquatic animal locomotion. Cont. Math. 141: 443-461.
[7] Smith, H. C. 1992. Illustrated Guide to Aerodynamics. McGraw-Hill, Blue Ridge Summit, PA.
[8] Long, J. H., Jr., D. A. Pabst, W. R. Shepherd, and W. A. McLellan. 1997. Locomotor design of dolphin vertebral columns: Bending mechanics and morphology of *Delphinus delphis*. J. exp. Biol. 200: 65-81.
[9] Gal, J. M. 1993. Mammalian spinal biomechanics. I. Static and dynamic mechanical properties of intact intervertebral joints. J. exp. Biol. 174: 247-280.
[10] English, A. W. 1976. Limb movements and locomotor function in the California sea lion (*Zalophus californianus*). J. Zool., Lond. 178:341-364.
[11]Godfrey, S. J. 1985. Additional observations of subaqueous locomotion in the California Sea Lion (*Zalophus californianus*). Aqu. Mamm. 11:53-57.
[12] Weihs, D. 1981. Effects of swimming path curvature on the energetics of fish motion. Fish. Bull. 79: 171-176.
[13] Domenici, P, and R. W. Blake. 1991. The kinematics and performance of the escape in the angelfish (*Pterophyllum eimekei*). J. exp. Biol. 156: 187-205.
[14] Hui, C. A. 1985. Maneuverability of the Humbolt penguin (*Spheniscus humboldti*) during swimming. Can. J. Zool. 63: 2165-2167.