

Additional observations of subaqueous locomotion in the California Sea Lion (*Zalophus californianus*)

Stephen J. Godfrey

Redpath Museum-McGill University
859 Sherbrooke St. West,
Montreal, Quebec, Canada, H3A 2K6

Abstract

The observations obtained from videotaping the subaqueous locomotion of a California sea lion (*Zalophus californianus*) are not unlike those of English (1976a). Results presented here demonstrate that functional coordination between pectoral and pelvic limbs in subaqueous manoeuvring and directional control are extremely important, especially for tight turning. Swimming speeds and length specific speeds were obtained.

Introduction

The videotaping of a California sea lion (*Zalophus californianus*) was undertaken in an attempt to resolve the long-standing debate as to whether plesiosaurs (Mesozoic aquatic reptiles of the order Sauropterygia) were subaqueous rowers or subaqueous fliers. While studying the functional morphology of the plesiosaur skeletal pectoral girdle and limbs, Godfrey (in press) concluded that they probably did not employ a bilateral dorso-ventral penguin-like 'figure-8' stroke cycle, as had been suggested in the literature (Robinson, 1975, 1977; Taylor, 1981), but rather plesiosaurs probably had a propulsive stroke cycle analogous to that of otariid pinnipeds.

English (1976a) has described the subaqueous stroke cycle of the sea lion pectoral limb, but little has been said about the importance of the pelvic limbs in subaqueous directional control. Sea lions are impressively agile and exhibit a high degree of manoeuvrability subaqueously. This paper is concerned primarily with the contribution of the pelvic limbs to the sea lion's aquatic agility. The results presented here are not complete, but are meant to augment the qualitative and quantitative data dealing with the swimming parameters and locomotor function of the limbs in the California sea lion (English, 1976a, 1976b, 1977; Gordon, 1983).

Methods and materials

A 14 year old, 72 kg female California sea lion (*Zalophus californianus*), measuring 1.67 m long was videotaped in the largest tank at the Montreal Aquarium (Aquarium #5). The sea lion was transferred from the Montreal Zoo to the Aquarium for the one day taping.

The partially glass walled tank (Figure 1) is roughly ovoid, 24 m long, 12 m wide and 4.2 m deep in the centre, tapering gently at the ends to a depth of 3.6 m. 15 cm wide concrete columns support 19, 2.4 m high and 1.1 m wide glass panels. The tank contains 840 000 litres of fresh water and is connected through a channel 1.5 m deep to the reserve tank containing 160 000 litres of water (Ville de Montreal, 1980).

The temperature of the water is usually maintained between 20 to 24°C, however it was lowered to 18°C to promote active swimming. A clockwise

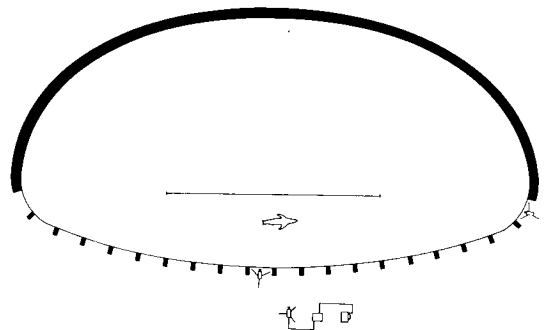


Figure 1. Aerial view of the largest tank (Aquarium #5) at the Montreal aquarium. Video cameras (with monitor and recorder) were placed in a variety of locations to record the aquatic locomotion of *Zalophus californianus*. Solid line in the tank is 10 m long and was used to determine swimming speeds.

current varying between 25 to 39 cm/sec was calculated by timing suspended debris drifting in the water.

Adequate illumination for video was provided by four underwater, as well as numerous surface, spot lights. Two black and white video cameras were placed in a variety of locations around the tank (Figure 1) in order to view the stroke cycle from a number of different angles.

In an attempt to establish swimming speeds (speed and length specific speed) for the sea lion, a cable was suspended lengthwise along the surface of the tank. A 10 m segment (Figure 1) was marked off by eleven 30 cm ropes suspended vertically from the cable. The sea lion was clocked swimming the length of the 10 m segment with a stop-watch. Timings were obtained by having the trainers throw fish to opposite ends of the tank. Length specific speeds were calculated by dividing the maximum speed recorded by the animal's length. For convenience of measurement, body length is taken as the distance from the snout to the end of the tail. Swimming speeds and length specific speeds were also calculated from the videotape by determining the time (see below) required for the sea lion to pass a line perpendicular to its direction of travel.

Analysis of the videotape was performed on a Panasonic editing controller (NV-IA500), two Panasonic editing units (NV-8500) and accompanying video monitors, (CT-110 MCA). This editing equipment permitted a frame-by-frame analysis of the sea lion's aquatic locomotion. A panasonic time generator (WJ-810) was used to delimit time intervals between successive drawings in Figures 2 and 3. The time generator also helped to determine swimming speeds recorded on videotape.

Observations

Analysis of the videotape led to conclusions not unlike those of English (1976a). My observations confirm that (1) the entire stroke cycle of *Zalophus* is usually divided into thrust and recovery phases, although when swimming at high speed thrust may be generated during the recovery phase; (2) the propulsive phase lasts approximately 60% of the entire stroke cycle, while the recovery stroke occupies 40% of the cycle, (cycle duration, 0.5–1.0 sec); and (3) the stroke cycle may be interrupted by gliding, for variable distances, and then resumed. Additional observations demonstrate that the pelvic flippers are essential for the high degree of manoeuvrability seen in sea lions (see below).

During the analysis of the videotape, it was frequently observed that the pectoral flippers crossed as they were swept ventrally during the power phase of the stroke cycle. Figure 2 illustrates a 'typical'

stroke cycle. Figure 2 M, partially demonstrates the crossing of the flippers. I observed this crossing usually after a long glide or after a turn, whenever rapid acceleration was desirable. I could not, however, ascertain which limb crossed ventral to the other, whether the relationship was always constant, or dependent upon some unknown factor. Crossing of the flippers does not usually occur during steady, straight line swimming.

Directional control

English (1976a) reports that the hind limbs and axial skeleton were moved only infrequently during his observations of swimming sea lions. My observations confirm that during straight line swimming (in the 3.0 m/s range) the head moves very little and the pelvic flippers often trail passively, tightly collapsed to minimize turbulence and drag. However, both head and pelvic flippers are functionally essential for turning and are indirectly involved in thrust production.

Figure 3 illustrates the pattern and body form taken by the sea lion in a 180° turn. The turn is initiated by the head, neck and pectoral limbs. In Figure 3, time 0.00, the right pectoral flipper has been rotated laterally (abducted) away from the thoracic wall and angled so that its ventral or volar surface offers resistance to the water. Between 0.00 sec and 0.29 sec both pectoral flippers are protracted. The right flipper continues to lie in the vertical plane until 0.70 sec. To help roll the body longitudinally, the left flipper, between 0.07 sec and 0.15 sec, is angled so that its dorsal surface offers more resistance and deflects more water than its volar surface. The combined action of flipper angling (abduction) and protraction rapidly spirals the body to the left (flippers act as aeroplane ailerons). Once the pectoral limbs lie in the vertical plane, the left flipper changes its orientation so that later (0.29 sec) its volar surface offers maximum resistance to water perpendicular to the flippers direction of travel. The cervical muscles flex to turn the head to the left are held flexed until 0.41 sec, after which they extend the head and neck.

During straight line swimming, the pelvic flippers of the sea lion are often held in an inverted V position with their plantar surfaces lying opposite each other medially (Figure 3A). In this orientation they act as stabilizers, analogous to aeroplane horizontal and vertical stabilizers, preventing undesirable longitudinal roll during a stroke cycle or glide. They are rotated in a horizontal plane, 90 to 100° from their orientation when resting on the ground. At the beginning of the turn (0.00 sec), the pelvic flippers are parallel to one another with, in transverse section, a 90° angle between plantar surfaces (Figure

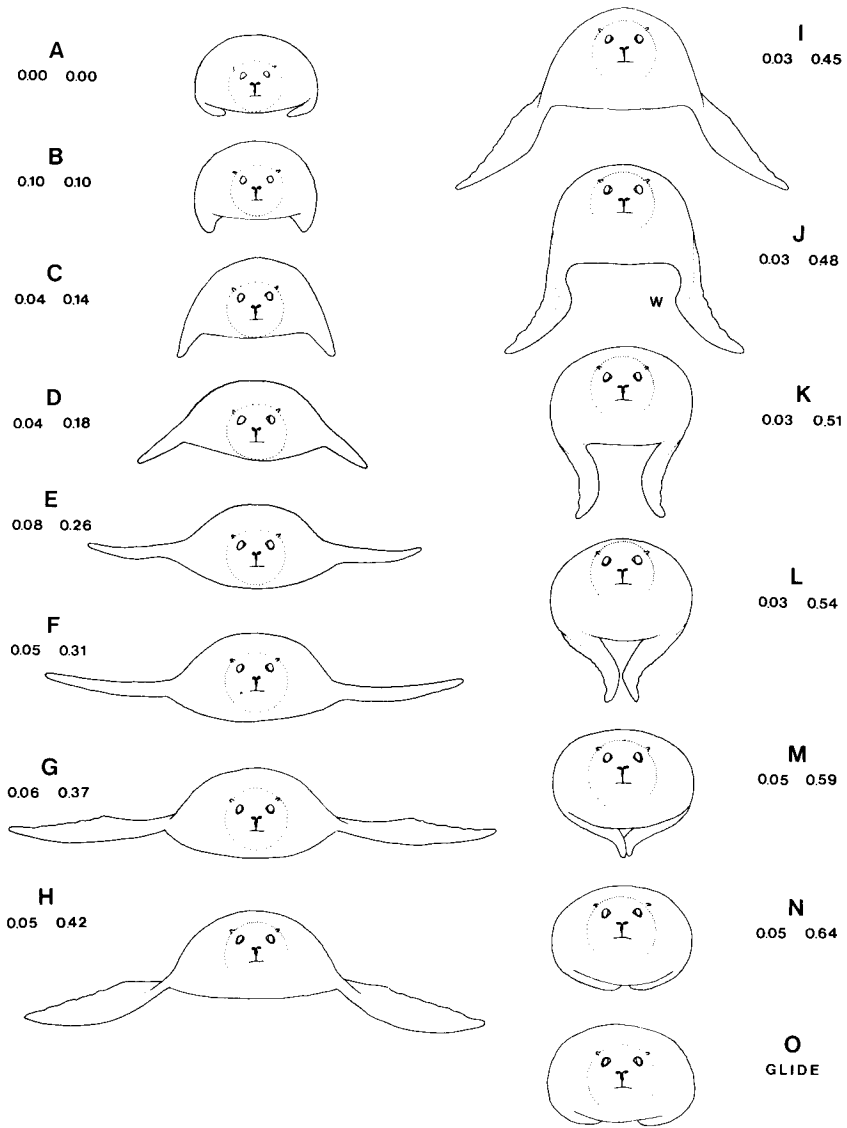


Figure 2. One stroke cycle of *Zalophus californianus* in anterior view. The numbers in the left column are time intervals (1/100 sec) between selected frames, and the right column is cumulative. At 0, the sea lion could glide or begin the cycle again at A. w = Wrist.

3A). At time 0.00, digit 1 on the right pes extends toward the observer, with digit V on each foot juxtaposed. In Figure 3A–H, the plantar surface of the left pelvic flipper is in full view.

As the abdominal surface comes to lie in a vertical plane (on the outside of the turn, 0.29 sec), the pectoral flippers are protracted reaching their maximum at time 0.41. The angle between plantar

surfaces of the pelvic flippers rapidly increases from 90° at 0.00 sec to over 180° in transverse section between 0.75 sec and 0.89 sec. By 0.29 sec, the angle between the plantar surface is 180°, and both flippers are in the vertical plane. To achieve this 180° angle the limbs are rotated laterally or abducted and the knees are seen as bosses in profile (e.g. Figure 3E).

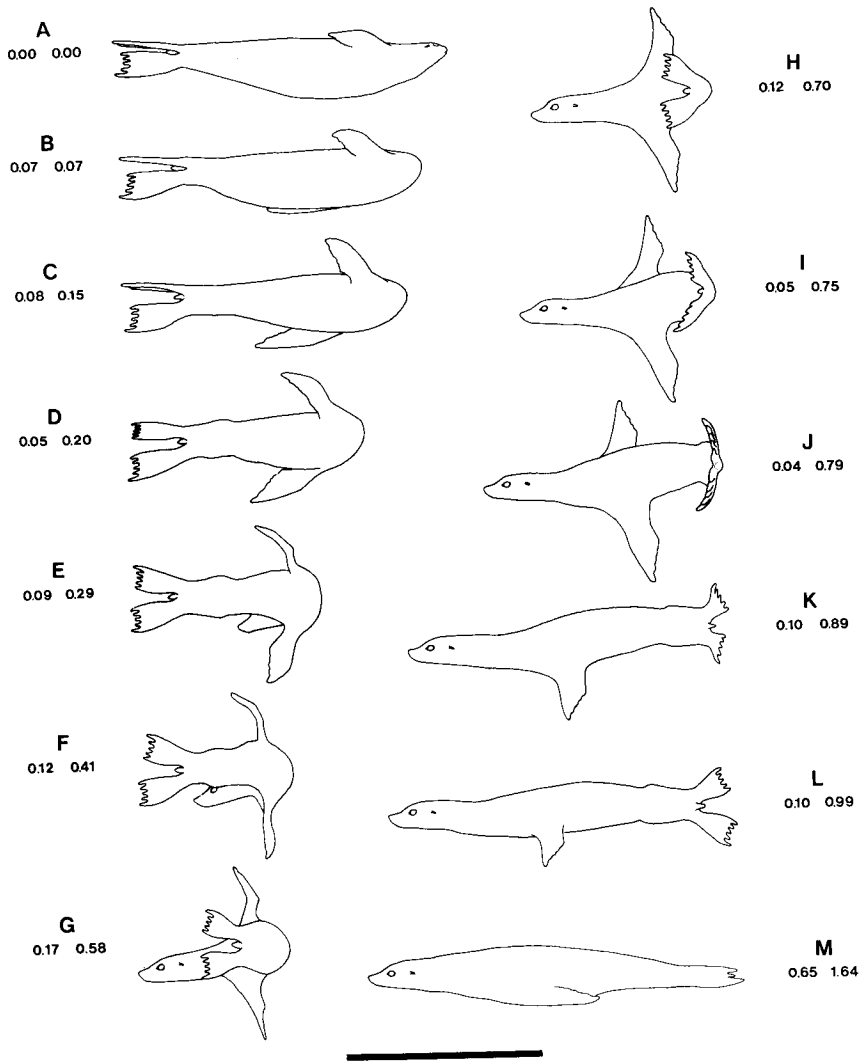


Figure 3. 180 degree left turn by *Zalophus californianus*. The numbers in the left column are time intervals (1/100 sec) between selected frames and the right column is cumulative. In D-F and J-L, the knees are seen as bosses in profile. Scale equals one metre.

Once the pelvic flippers are in the vertical plane they are protracted somewhat and the digits are spread to maximize surface area. They remain in this position until the turn is complete (0.99 sec) at which time they are adducted and folded to form a streamlined body contour.

Sea lions have relatively long flexible necks, enabling the head to remain in its upright position even while the saggital plane of the thorax is 90° from the vertical (Figure 3F and G).

Beginning at 0.70 sec the right pectoral flipper begins to be swept ventrally in a power stroke fashion, while the left pectoral and pelvic limbs remain in the vertical plane, stabilizing against further roll. Gradually the thoracic region is brought back into its upright swimming posture (Figure 3H-L). During this interval, however, the lumbar and pelvic regions remain rotated about 90° with respect to the remainder of the sea lion's body (see Figure 3L). The pelvic limbs are clearly acting as a

rudder or stabilizer, ensuring that the posterior portion of the sea lion's body does not follow a path tangential to the circumference of the turn. Once both pectoral flippers lie in the same horizontal plane (0.99 sec) they are then adducted and retracted in the same manner described by English (1976a).

The pelvic flippers are essential for making tight turns. These flippers are functionally analogous to bird tail feathers. The flippers ensure that forward momentum will not be unduly lost by 'skidding' of the abdominal and pelvic region about a given point, other than the centre of a circle describing the turn of the sea lion. On occasion, and usually at low speeds, the pelvic flippers were not spread as described above. The result was that the hind end of the sea lion 'skidded' about its centre of mass or some other point outside its body, depending on the orientation of its pectoral flippers. On such occasions momentum was dissipated by the skidding action and the sea lion came to rest.

Swimming Speeds

The maximum swimming speed recorded by timing the sea lion over the 10 m segment was 3.2 m/sec, while on videotape a slightly higher maximum speed of 3.5 m/sec was recorded. It should be pointed out that at no time was the sea lion compelled to swim faster than it chose to. Most of the timings over the 10 m clocking segment (Figure 1) were obtained during glides. Burst speeds are believed to be higher, but I did not record speeds as high as those mentioned by Ray (1963), from 6.6–8.0 m/sec (15 to 18 mph).

The top swimming speed recorded is just slightly higher than the maximum speed recorded for swimming penguins (3.35 m/sec by *Aptenodytes patagonica*, King Penguin; Clark and Bemis, 1979). At 3.5 m/sec the length specific speed for the 1.67 m long sea lion is approximately 2.7 body lengths/sec.

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