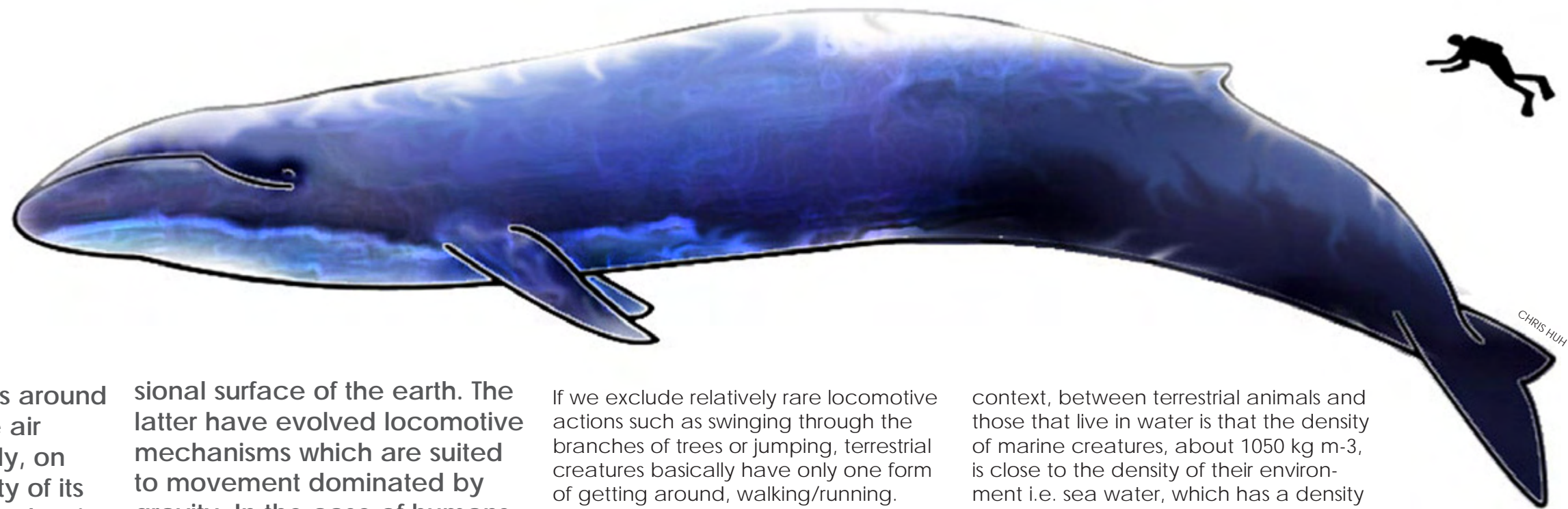


Size and movement style comparison of an average diver and a blue whale (*Balaenoptera musculus*)

Edited by Michael Symes



The way an animal gets around in the sea and or in the air depends, fundamentally, on the density and viscosity of its milieu. Birds use the low density and viscosity of the atmosphere to fly or glide, with the range of their movement being limited only by their endurance and the height to which they can fly. This is similar to the fishes and similar marine creatures who can also move three-dimensionally within their aqueous milieu though unlike the terrestrial creatures which live on the, essentially, two dimen-

sional surface of the earth. The latter have evolved locomotive mechanisms which are suited to movement dominated by gravity. In the case of humans, for example, a two-legged mode of locomotion suited to this situation has evolved. To a certain extent, birds may seem to be independent of gravity as they fly around in the air. However, unlike marine creatures in their aqueous milieu, if they stop flying they immediately crash to the ground – unless, of course, they can glide for a little while.

If we exclude relatively rare locomotive actions such as swinging through the branches of trees or jumping, terrestrial creatures basically have only one form of getting around, walking/running. Marine creatures, however, have several for they live in a three-dimensional world in which they can move more or less at will, with their range of action in this aqueous world constrained only by the upper surface of the oceans and the sea bed. There may be some constraint imposed by pressure differences between the upper water and the depths, but within quite large limits, marine creatures can move around just where they like. Humans have had to invent machines, for example aeroplanes and submarines, to overcome similar restraints imposed by their milieu.

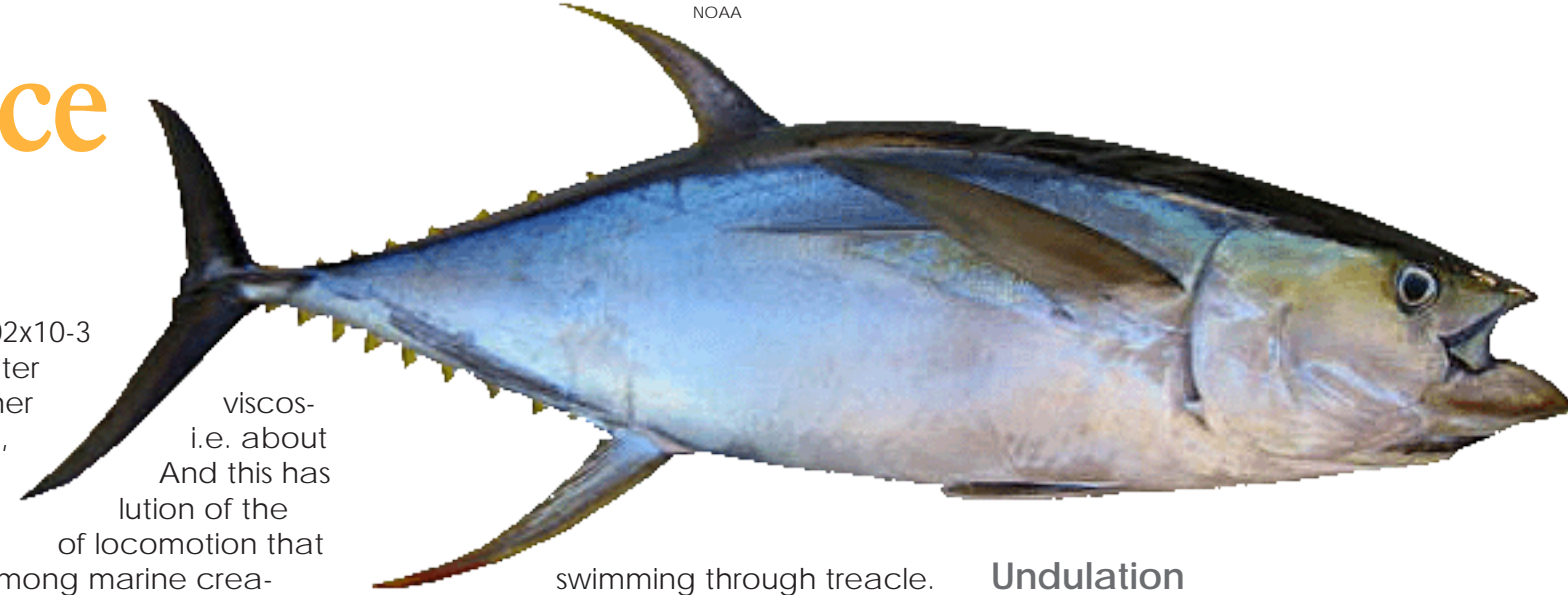
One of the primary differences, in this

context, between terrestrial animals and those that live in water is that the density of marine creatures, about 1050 kg m⁻³, is close to the density of their environment i.e. sea water, which has a density ranging from about 1020 to 1029 kg m⁻³ (although deep in the oceans, under high pressure, it can be 1050 kg m⁻³, or more). This is definitely not the case for terrestrial animals whose milieu is the air with a density of only about 1.2 kg m⁻³ at ordinary temperatures and pressures. This means that, unlike the land-based creatures, the marine creatures can utilise their milieu in their different forms of locomotion whereas, with the exception of birds and some insects, terrestrial creatures do not utilise the atmosphere at all to move around.

A second important difference is the fact that, compared to air with a vis-

Locomotion

How marine animals get around



A Yellow-fin tuna. The tuna family of fish are some of the fastest creatures in the sea with some species clocking in at 100km per hour

viscosity of about $0.02 \times 10^{-3} \text{ Nsm}^{-2}$ at 20°C , water has the much higher viscosity of $1 \times 10^{-3} \text{ Nsm}^{-2}$, 50 times greater. And this has affected the evolution of the different modes of locomotion that are to be found among marine creatures. Unlike for the terrestrial creatures, size plays a great part in what mode of locomotion has been evolved by marine creatures. For even quite small terrestrial creatures, even those down to almost microbial size the viscosity of air places no significant limitation on how these organisms get around. Even the tiniest ant or aphid, for example, does not find the viscosity of air much impedence to their movement. This is in sharp contrast to small organisms in water whose movement is greatly affected by the water viscosity which for humans would seem like

viscosity, i.e. about 50 times greater. And this has affected the evolution of the different modes of locomotion that are to be found among marine creatures.

swimming through treacle. Thus, we see that the two most important factors for the development of types of locomotion of marine creatures are that sea water, relative to air, has both a high density and a high viscosity.

Depending on their size and body construction different strategies have been evolved by the different marine species for getting around in their aquatic environment. Evolution has, as always, ensured that these strategies are the most effective, be it in terms of energy used, manoeuvrability or speed. These strategies are the result of millions of years of evolutionary selection during which the more efficient swimmers will be better at surviving. So, what has evolution produced?

How fish swim

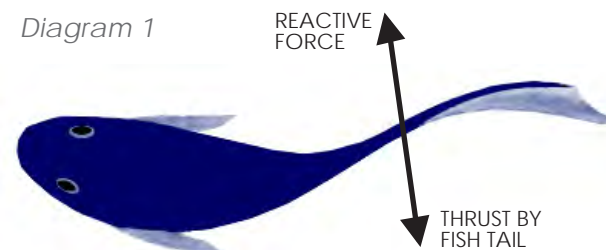
As any swimmer knows, water restrains movement, especially if one tries to move quickly or suddenly. This is due to the viscosity of the water. Divers, especially, will also know that fishes can certainly move rapidly and abruptly in spite of this; and furthermore, unlike the human swimmer, they can move very smoothly.

Marine creatures can move around in a number of ways of which swimming by fishes is by far the most important. Fish swim in basically two sorts of way, either by undulation of their bodies or by using their fins as oars i.e. rowing.

Undulation

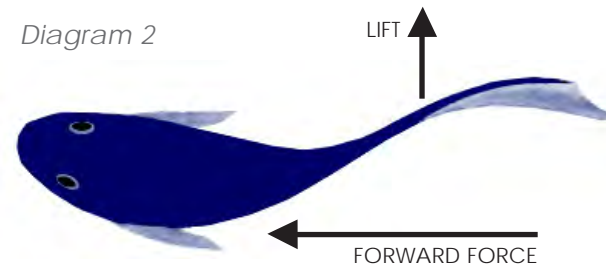
In undulation, a contraction of the muscles down each side of the body in turn causes a sinusoidal wave to pass from the head to the tail. The amplitude of this wave increases as it passes down along the body of the fish. This provides thrust forces, arising from the reaction of the push of the fish against the dense and viscous water, forcing the fish forwards.

Diagram 1



The reactive force can be resolved into (i) a forward thrust in the direction of motion and (ii) a lateral force generally called the lift, although it actually is in the horizontal plane, at right-angles to the direction of motion.

Diagram 2



The lift force, which actually causes a slight transient lateral movement, can-

cells out over one complete stroke of the tail. The fish therefore moves forward by a certain amount for each completed oscillation. The distance travelled in one cycle of undulation is called the stride length. This is a unit of motion analogous to that used to characterise the motion of the legged terrestrial animals.

The resulting forward thrust force is, however, not completely available for moving the fish forward because there are also retarding forces known as the drag forces. There are (i) the pressure drag at the front of the fish as it swims through the dense water (ii) the frictional forces at the skin in contact with the moving water (iii) the vortices formed behind the moving fish.

Diagram 3

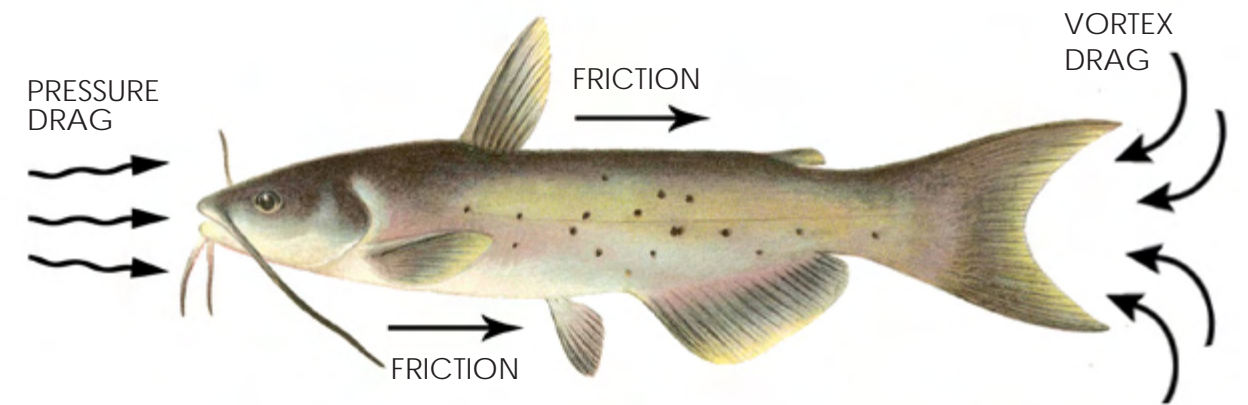
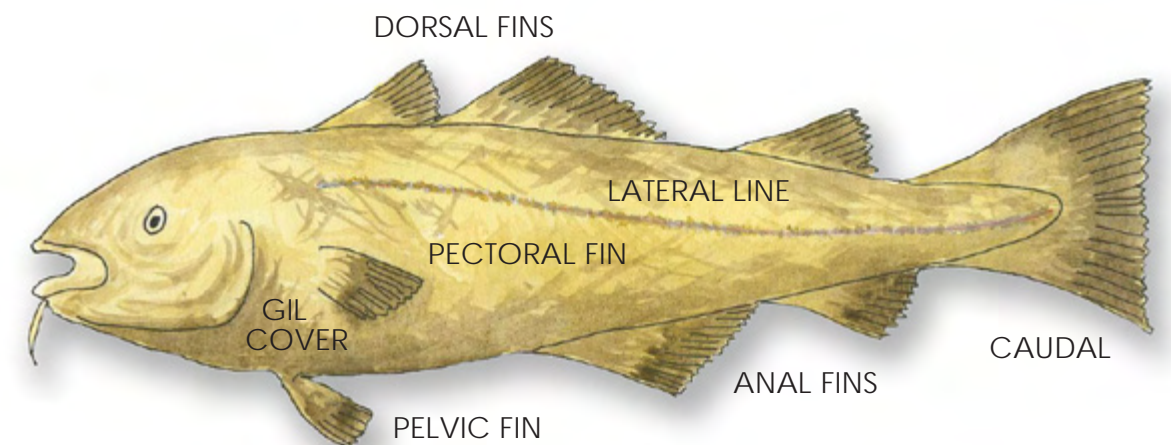


Diagram 4



VISCOSITY

This is the property of a liquid whereby it tends to resist relative motion within itself. If different layers of fluid move with different velocities, viscous forces arise. In SI units, it is measured in Newton seconds per square meter, Nsm^{-2} or Pascal seconds, Pas.

Some people still prefer to use the old nomenclature of poise and centipoise, where one poise is equal to 10^{-1} Nsm^{-2}

Some examples given in centipoise at 20°C .

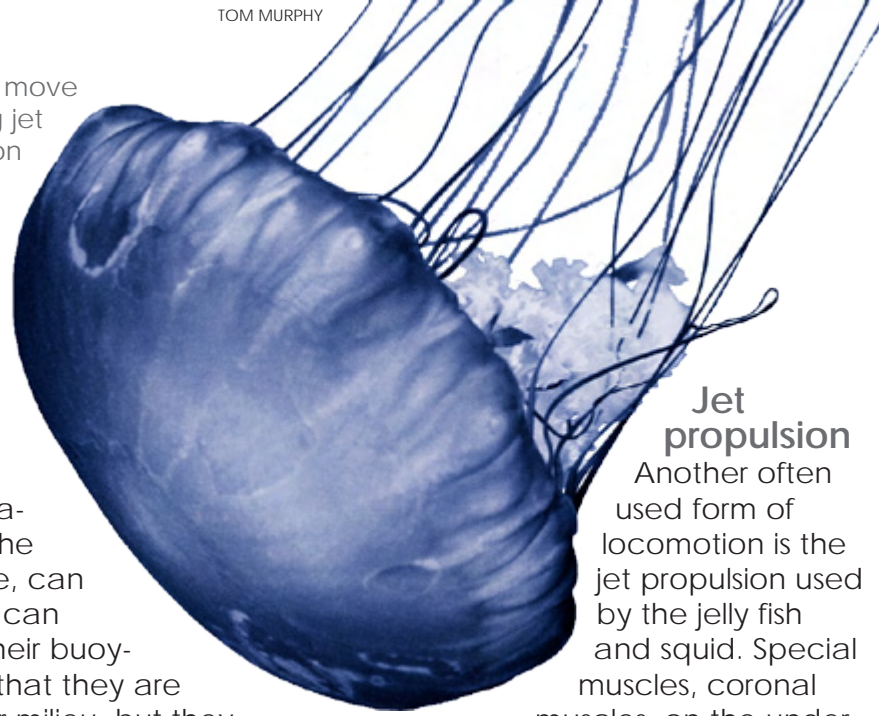
- Air 0.02
- Water 1.0
- Ethanol 1.2
- Olive oil 84
- 75% sucrose solution 2328





The sailfish is considered the fastest fish in the sea at over 110km per hour

Jellyfish move by using jet propulsion



Jet propulsion

Another often used form of locomotion is the jet propulsion used by the jelly fish and squid. Special muscles, coronal muscles, on the under-

side of the bell contract and push water out of the bell. In compliance with the conservation of momentum, the jellyfish move in the opposite direction to the thrust of the water jet. This jet is not very powerful, though, as the expelled water jet has only a low speed; they are therefore not capable of countering the power of oceanic currents and waves.

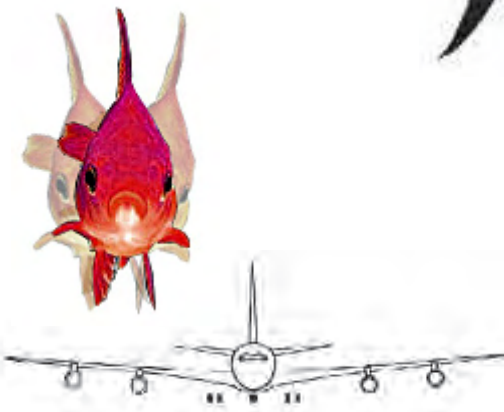
Non-muscular forms of locomotion

The different forms of motion that we have considered above have all been based on muscle power acting on a skeleton. However, invertebrate planktonic larvae such as echinoderms, annelids, and molluscs depend not on muscle power for locomotion but on cilia; and spermatozoa swim using flagella that form their tails. Protozoa move by means of cilia, flagella or pseudopodia. As a curiosity some of the most primitive forms of life, the amoebae, can move at speeds that, relative to their absolute size, are quite impressive. Of course, unlike for other much larger aquatic creatures, the viscosity of water plays a significant role for their locomotion.

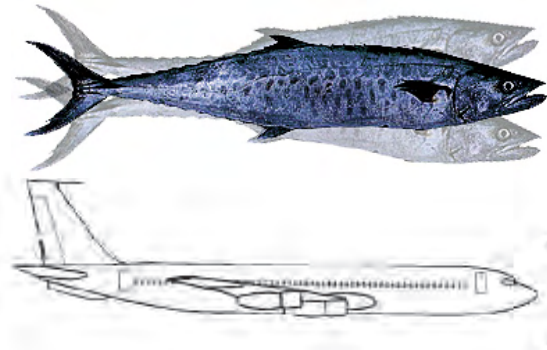
Non-swimmers

Although we have discussed the locomotive behaviour of aquatic creatures, which generally live completely within

Roll:
The control of roll is carried out by the dorsal and anal fins.



Pitch:
Pitch is controlled by the pelvic fins (mostly) and the pectoral fins.



Yaw:
Yaw is controlled by the pectoral fins.



Direction:
As a boat requires some sort of a rudder to control the direction of motion, fish, too, can control their direction with the help of the caudal fin and the pectorals.

'Rowing' with fins

Although the fins are used primarily for control purposes they can also be used for propulsion. Some fish use their pectoral fins as hydrofoils, and others use them to row with. Marine turtles beat their fore flippers to attain speeds of up to 5km per hour. In a similar way whales swim by beating a hydrofoil, in this case, it is the single fin of the tail that beats up and down. This is unlike the vertical tails of tunas that beat from side to side. This is apparently a very effective means of propulsion, for whales can attain speeds of up to 45km per hour and more in sprints while the Black Tuna can attain speeds of more than 100km per hour. (The sailfish is considered the fastest fish in the sea at over 110km per hour.)

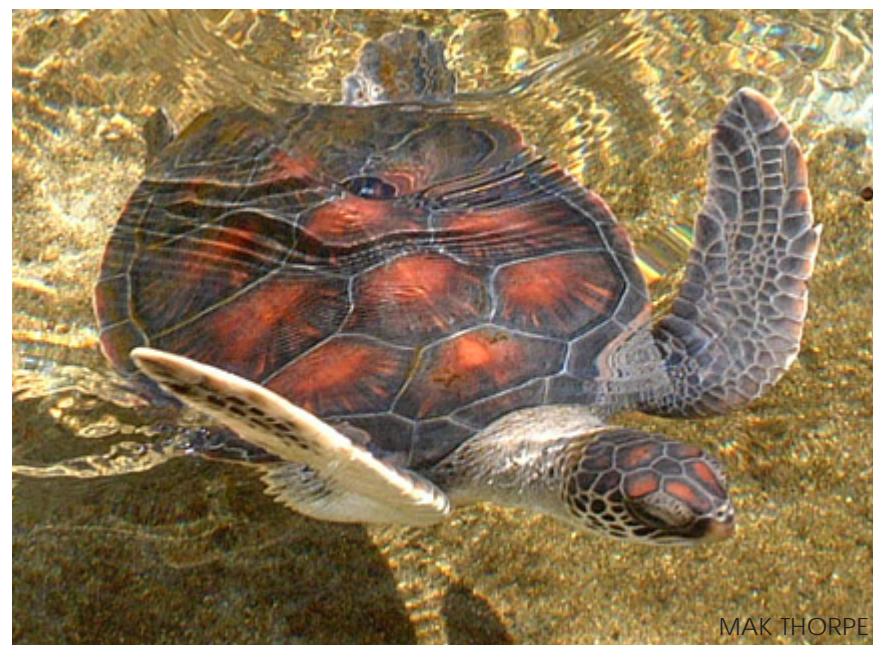
A fish thus needs specialised and strong muscles to move it through the viscous water: it also needs a strong skeleton to support these muscles which can make up to 80 percent and more of the body mass of the fish. And of all the vertebrates the skeleton of a fish is the most complex.

In fish, the body and tail act as a single unit. However, although the cetaceans use the same undulation

movement for propulsion it is only the tail that is involved and not the main body, which takes little part in the locomotion.

The largest of the cetaceans are the whales; the blue whale, for example, can be up to 30m long and can weigh up to 150 tons. Their buoyancy, however, is such that they are nearly weightless in their milieu, but they still have a large inertial mass, which requires a lot of energy to move around. For this, it needs both strong muscles and a correspondingly strong skeleton to attach them to. Not only that, it needs an efficient method of propulsion. This means that like all other creatures, be they marine or terrestrial, it has to be parsimonious in its use of energy.

That whales have adapted to live a weight-free existence can be seen from the fact that when they become beached their bodies tend to collapse under the, for them, unaccustomed force of gravity.



Sea turtles use "rowing" to get around

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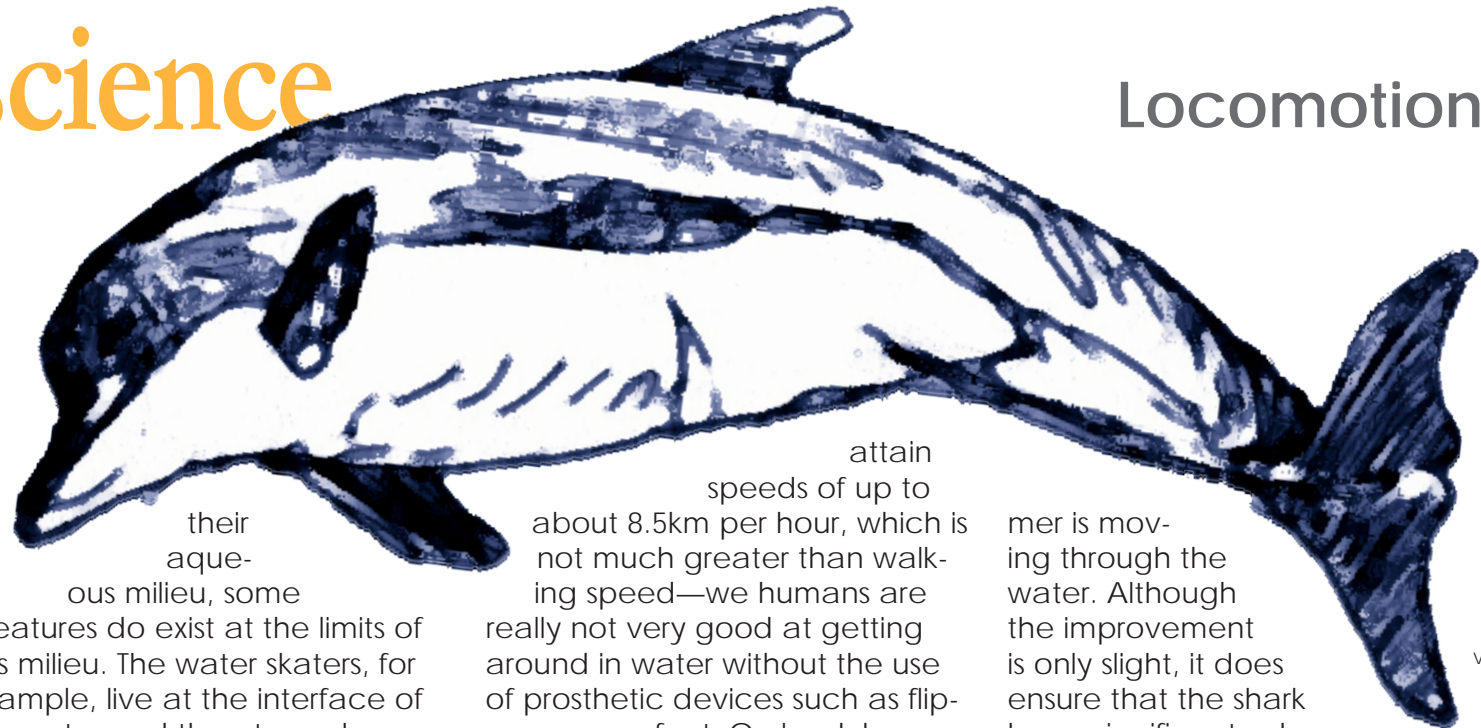
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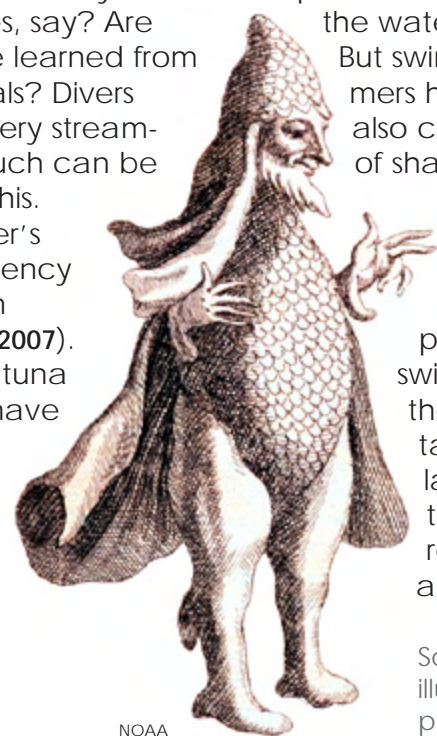
Locomotion



their aqueous milieu, some creatures do exist at the limits of this milieu. The water skaters, for example, live at the interface of the water and the atmosphere (See X-RAY MAG, no.6, 2005). However, these can be considered as walkers on dry land. On the other hand, there are other creatures such as the crustacea which, although they do live completely immersed in the aquatic milieu, move about on the sea bed. In fact, they too, like terrestrial animals live in a 2D world.

Divers

In the context of this article, we can consider divers as aquatic creatures. So how do they compare with the fishes, say? Are there lessons to be learned from the aquatic animals? Divers are certainly not very streamlined, although much can be done to improve this. (See Cedric Verdier's article about efficiency in rebreather kits in X-RAY MAG no. 16, 2007). Compared with a tuna fish which, as we have seen, can swim at speeds of over 100km per hour, olympic swimmers can only



NOAA

attain speeds of up to about 8.5km per hour, which is not much greater than walking speed—we humans are really not very good at getting around in water without the use of prosthetic devices such as flippers on our feet. On land, however, sprinters over 100 meters can attain speeds of up to 37km per hour.

Can divers learn anything from the different forms of locomotion of aquatic creatures? Of course, they have copied the flippers or fins of sea lions and fish to improve their speeds through the water.

But swimmers have also copied the rough skins of sharks, which are covered with thousands of small teeth, to make low-friction swimsuits, for example the new Speedo® swimsuits. These have the function of maintaining a stable thin layer of water close to the body thereby reducing the resistance when the swim-



CLYDE MUIRSHELL

Waterskater

mer is moving through the water. Although the improvement is only slight, it does ensure that the shark has a significant advantage over most of its prey. And so it is with competition swimmers, for it is estimated that

these new suits can reduce record times by up to two percent, which certainly gives the wearers of such suits an advantage. Perhaps

divers could obtain an advantage if wetsuits were designed with such surfaces, for it is clear that energy could be saved.

Reference

For anyone interested in animal locomotion in general, I can recommend *Principles of Animal Locomotion*, R. McNeill Alexander, 2003, Princeton University Press. It is somewhat mathematical but looks at all forms of locomotion on the land and in the sea and air. ■

Scaly wetsuits for divers? How about this model from a 1696 illustration by Johann Zahn, Germany, of a merman complete with scales said to be caught in the Baltic Sea in 1531



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