News & views

Engineering

Soft robot reaches the deepest part of the ocean

Cecilia Laschi & Marcello Calisti

A self-powered robot inspired by a fish can survive the extreme pressures at the bottom of the ocean's deepest trench, thanks to its soft body and distributed electronic system – and might enable exploration of the uncharted ocean. **See p.66**

On page 66, Li *et al.*[1] report a robot made from soft materials that can brave the unexplored depths of the sea. Remarkably, the authors demonstrate that their robot can operate in the Mariana Trench, the deepest part of the ocean. Conventional underwater vehicles require watertight enclosures made of metallic materials to withstand the high pressures of the deep ocean – the thickness and dimensions of these enclosures have to be increased to cope with greater depths. But in Li and colleagues' robot, the delicate electronic components are embedded and distributed in soft silicone, a design that removes the need for pressure-resistant cases.

Largely inspired by living organisms, the field of soft robotics involves making robots from pliable materials. Polymers such as silicone are often used, as well as highly deformable structures such as braids and textiles. Soft robots are intrinsically safer than their conventional rigid counterparts in interactions with humans, and their pliability can boost many capabilities – such as their dexterity when manipulating objects, and their ability to squeeze into tight spaces or to travel across uneven surfaces. Marine species such as squid and octopus were one of the original inspirations for soft-robotics research[2], but soft robotics, in turn, offers a new approach for tackling marine applications of robots. Li and colleagues' work is a powerful demonstration of this.

The authors' robot is designed to have a fish-like body shape and two flapping side fins (Fig. 1). The authors used a well-established mechanism to drive flapping. The fins are attached to 'muscles' on the robot's body; these are made of a soft material that converts electrical energy into mechanical work – when an electric current from the robot's battery is applied to the muscles, they contract. Tiny solid structures mechanically connect the contracting muscles to the fins, making them flap.

One of the challenges faced by Li and co-workers was finding a way to protect the robot's electronic components from high pressures. Taking inspiration from the bones in the skull of the hadal snailfish (*Pseudoliparis swirei*), the authors spaced the electronic components apart, rather than packing them together as is typically done in electronic devices. Laboratory tests and simulations demonstrated that this arrangement reduces the stress at the interfaces between components under pressure. The distributed electronics were then embedded in silicone for incorporation into the robot. This approach is more practical, and cheaper, than other methods for protecting the electronics in deep-sea devices.

Li *et al.* first tested the swimming ability of the robot in the laboratory, in a pressurized water chamber – the robot was connected to a pole, which it swam around in a circle. The machine was then tested in a lake at a depth of 70 metres, where it swam freely at a speed of 3.16 centimetres per second, and then in the South China Sea at a depth of about 3,200 m. It reached a speed of 5.19 cm s^{-1} (equivalent to 0.45 body lengths per second), which is in line with the capabilities of other soft robots[3]. Finally, the flapping movement and pressure resistance of the robot were tested in the Mariana Trench, where it was connected to a conventional underwater robot for support, which also took images of the test.

Several previous attempts have been made to develop soft robots for applications underwater – a realm in which it is challenging for robots to interact delicately with objects, because robotic sensors don't work well in this environment. Soft robotic grippers[4] offer substantial advantages over rigid grasping devices when collecting and handling delicate sea organisms for study by marine biologists. And bio-inspired soft robotic fishes[5]

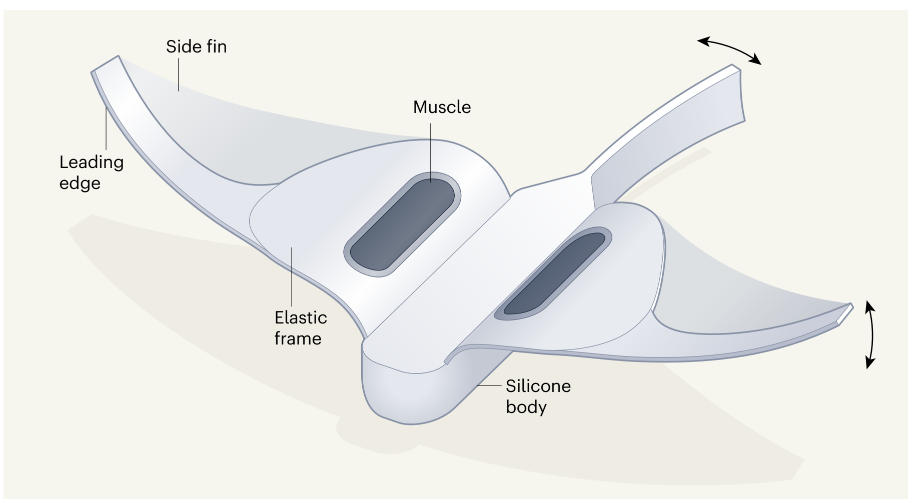

Figure 1 | Designed for the deep. Li *et al.*[1] have developed a robot made from soft materials that is designed to withstand the extreme pressures of the deep ocean. The robot has a fish-like shape consisting of an elastic frame to which two thin flapping side fins are attached; the fins have leading edges made from a stiffer material. 'Muscles' on the frame are made of materials that convert electrical energy into mechanical work, and are attached to the fins (attachment structures not shown). When an electric current from the robot's battery is applied to the muscles, they contract. The electronic components of the robot and the battery are embedded in the central silicone body; their distributed arrangement in the silicone protects them from high pressures.

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can swim among other animals without distressing them, thereby allowing close-up study. Li and co-workers' research now pushes the boundaries of what can be achieved: the replacement of rigid protective enclosures for electronic components by distributed electronics embedded in a soft material paves the way to a new generation of deep-sea explorers.

There is, however, more work to do before the ocean can be populated with robots of this type of design. Li and co-workers' machine is slower than previously reported underwater robots[6], and cannot withstand sizeable disturbances — it could easily be swept away by underwater currents. Its locomotor capabilities will also need to be optimized for practical applications. However, Li and colleagues' approach lays the foundations for future generations of resilient and reliable deep-sea explorers.

In the long term, one can predict avenues of research being opened up for marine biology, in which soft robots safely navigate coral reefs or underwater caves, to collect delicate specimens without damaging them. Swarms of underwater soft robots, with the ability to crawl on the seabed, anchor themselves on to specific structures, or swim over particular areas, could contribute to the development of technologies for various other applications. These might include monitoring the ocean, cleaning up and preventing sea pollution or preserving marine biodiversity. More fundamentally, they could help researchers to explore the vast uncharted depths of the oceans.

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Biochemistry

Active membrane rupture spurs a range of cell deaths

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Rupture of the plasma membrane in different forms of cell death was long thought to be a passive process. The finding that it is an active one, mediated by a specific membrane protein, reveals an unexpected feature shared by dying cells. **See p.131**

Remarkable control mechanisms exist in multicellular organisms to ensure that their cells function normally and are properly removed when necessary. These removal mechanisms include multiple forms of cell death, most of which end in rupture of the cell's plasma membrane. Until now, this breach of the cell's outer layer was generally thought to be a consequence of an uncontrolled influx of water, driven by an ionic imbalance that boosts cellular osmotic pressure. However, Kayagaki *et al.*[1] report on page 131 that this rupture is an active process, mediated by the plasma-membrane protein ninjurin-1 (NINJ1). This protein exerts its effect during the final step of many types of cell death.

Cells of multicellular organisms die in one of two main ways. Either they die passively as a consequence of damage they have incurred, or they die in a well-regulated, programmed manner as part of normal events such as development, homeostasis or the elimination of malignant and infected cells[2].

The defining feature of passive cell death (also known as necrosis) has long been thought to be the loss of integrity of the plasma membrane, which distinguishes necrosis from programmed cell death. As a consequence of plasma-membrane disruption, necrosis resembles a cellular explosion that releases a plethora of intracellular molecules, including proteins, nucleic acids and metabolites. Some of these act as danger signals, known as damage-associated molecular patterns (DAMPs), that alert neighbouring cells to the injury and thus help to induce inflammation. By contrast, apoptosis, the most-studied form of programmed cell death, preserves membrane integrity to enable immunologically 'silent', non-inflammatory removal of dead cells — a process in which they are taken up (engulfed) and dismantled by other cells as the tissue is repaired.

The past two decades have witnessed the discovery[3] of multiple forms of programmed cell death — such as pyroptosis, necroptosis and ferroptosis — that combine a programmed cellular demise with what seems to be passive disintegration of the plasma membrane. A common feature of most of these deaths is the formation of large pores, made of protein, in the plasma membrane[4]. These include, for example, the pores formed by various proteins called gasdermins, which initiate pyroptosis[5]; and the MLKL channel that is assembled in necroptotic cells[6]. Formation of either of these pores is followed by cellular swelling mediated by osmotic pressure, and then rupture of the plasma membrane (Fig. 1).

This rupture was thought to be a passive event, but Kayagaki and colleagues reveal that it is actively regulated. The authors made this discovery by analysing a group of mice with mutations at random genomic locations and examining pyroptosis of macrophage cells of the animals' immune systems. Some of the dying macrophages did not release the enzyme lactate dehydrogenase as usual, indicating that rupture of the plasma membrane was abnormal. Further investigation revealed that these mice had a mutation in the gene encoding NINJ1, which resulted in no detectable production of this protein.

NINJ1 was known to have a role in cell adhesion, but no direct ties had previously linked it to cell death[7,8]. The absence of NINJ1 prevented the dying mouse cells from releasing other large proteins, such as HMGB1, but did not block them from secreting a smaller protein, IL-1α (a member of the IL-1 family of immune-signalling molecules called cytokines), which is small enough to pass through a pore made by gasdermin D.

The lack of NINJ1 had a striking effect on macrophage shape. During pyroptosis, cells normally swell and form ballooning membrane protrusions that eventually rupture[9]. Dying cells deficient in NINJ1 also swelled and made such protrusions, but they didn't burst. Therefore, the rupture that usually occurs is clearly not caused by osmotic pressure, but instead depends on specific events that involve NINJ1. Moreover, Kayagaki and colleagues' data provide evidence that gasdermin-pore-induced cytokine release and cell swelling are distinct processes that can occur independently of plasma-membrane rupture.

Although this finding alone already provides a spectacular twist to a long-studied phenomenon, the big surprise came when the role of NINJ1 was examined in other forms of cell death. NINJ1 also mediated plasma-membrane rupture after toxin-induced cell permeabilization, on the induction of necroptosis, and even during secondary necrosis

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