

BIOMIMETICS

Climbing robots in a sticky situation

Bruce P. Lee

Mussel-inspired electro-responsive adhesive hydrogels enable robot climbing on conductive surfaces.

Climbing robots mimic the ability of gecko lizards that are able to climb up vertical surfaces (1). These robots have numerous potential applications, which include surveillance, inspection, and maintenance of buildings such as skyscrapers and nuclear storage plants. One of the key challenges associated with the locomotion of climbing robots is attaining strong yet rapidly switchable adhesion for surface attachment and detachment. Existing climbing robots use adhesion mechanisms ranging from suction cup adhesion and magnetic adhesion to nanofibrillar polymers that mimic the adhesion of gecko foot pads (1, 2). However, these adhesive interactions are either limited to a specific surface type or drastically weakened in the presence of moisture. Writing in *Science Robotics*, Huang *et al.* (3) incorporated an electro-responsive adhesive hydrogel onto the feet of walking robots (Fig. 1) and the wheels of a wheeled robot. This hydrogel rapidly switched between its adhesive and non-adhesive states within seconds when exposed to a mild electrical stimulation (applied voltage of 3 to 5 V). The adhesive hydrogel enabled these robots to climb up vertical substrates and traverse along an inverted surface (i.e., upside down).

The key ingredient in the adhesive hydrogel is the adhesive moiety, catechol (Fig. 1). Mussels secrete catechol-containing adhesive proteins that enable these organisms to cling to the rocky shorelines in the turbulent intertidal zones (4). Catechol incorporation is a widely adopted synthetic strategy in designing adhesives for binding to a wide range of wet surfaces, ranging from metal to polymer and tissue surfaces (5, 6). The adhesive strength of catechol is highly dependent on its oxidation state, and tuning the oxidation state of catechol has emerged as an unconventional approach in designing a switchable wet adhesive that is responsive to changes in pH and electrical stimulation (7, 8). However, the oxidized form of catechol is highly reactive and unsuitable for repeated

surface bonding. For that reason, a temporary protecting group in the form of boronic acid is required to prevent oxidative cross-linking of catechol and to preserve its reversibility for repeated redox reaction (9).

Huang and co-workers formulated an electro-responsive adhesive hydrogel consisting of catechol adhesive moiety with boric acid as the protecting group. To integrate the adhesive hydrogel with the feet or wheels of the climbing robot, an electrode is placed on one side of the adhesive. The conductive surface (e.g., steel and copper) that the adhesive is in contact with serves as the counter electrode. Application of electricity generated a pH gradient within the hydrogel through the electrolysis of water (8), which exposes catechol for interfacial bonding. Reversing the applied current resulted in catechol-borate complexation and weakened adhesion (Fig. 1). The maximum adhesive strength of the hydrogel was around 8 to 12 kPa, and this value is reduced by an order of magnitude in the non-adhesive state (<1 kPa). Exposure to less than 5 s of applied voltage was sufficient to tune the adhesive property of the hydrogel. By cycling between the adhesive and non-adhesive states of the hydrogel, a near-50-g robot was able to travel up a vertical wall and move across an inverted surface (i.e., upside down) at a speed of just under 8 cm/min.

Although mussel-mimetic adhesive is potentially suitable for serving as reversible anchors for climbing robots, there are opportunities for improvement. In the existing design, the robots climbed on metal surfaces because of the need to use a conductive surface as the counter electrode during electrochemical stimulation. This potentially limits the wide adoption of the robot. The need to pass electrical current across the interface is also problematic, because the adhesive performance will be highly dependent on the environmental conditions (e.g., pH, ionic strength), surface conductivity, and the surface's stability to electrochemical redox

reaction. In addition, the adhesive exhibited rapid decrease in performance within 100 cycles of electrical stimulations (12% reduction in adhesive strength). This may be due to the physical cross-linked nature of the hydrogel or the irreversibility of catechol

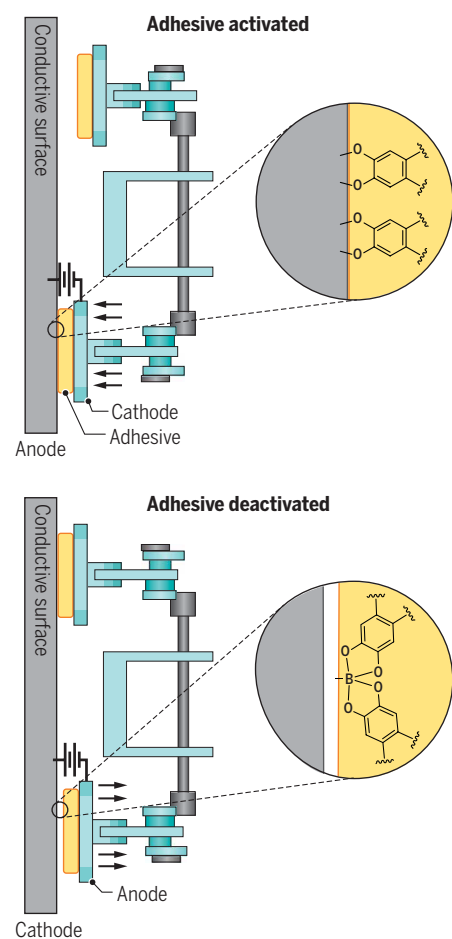


Fig. 1. Schematic representation of the locomotion of the climbing robot on a vertical, conductive metal surface. (Top) When the adhesive is activated by electrical current, the adhesive is bound to the metal substrate. The inset shows the chemical structure of catechol bound to the metal surface. **(Bottom)** Reversing the current weakens the adhesive to enable the robotic foot to be lifted. The inset shows the chemical structure change upon adhesive deactivation, i.e., the result of catechol-borate complexation. The black arrows indicate the direction of movement of the robotic foot.

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after repeated electrochemical oxidation. Last, the reported robot has yet to demonstrate bonding to fully submerged, underwater surfaces, which will cause excessive swelling and reduce mechanical stability of the adhesive hydrogel.

Nevertheless, Huang and colleagues combined the mussel adhesive chemistry with electrochemical stimulation to create a programmable adhesive for climbing robots. This is a practical application of biomimetic chemistry in robotic locomotion. Catechol can adhere to a wide range of surfaces in both wet and dry conditions. With further development, it is potentially feasible to develop climbing robots that can operate on a variety of surfaces and in environmental conditions such as rain. In addition, catechol-based adhesive can potentially enhance the mobility

of automated/unpiloted underwater vehicles and enable their anchoring and detachment to underwater surfaces such as submarines or ship hulls.

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